https://doi.org/10.1595/205651320X15826270318193 Johnson Matthey Technol. Rev., 2020, 64, (3), 279–286

JOHNSON MATTHEY
TECHNOLOGY REVIEW

www.technology.matthey.com

Hydrogen Fuel Cell Vehicle Drivers and Future Station Planning

Lessons from a mixed-methods approach

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The market for hydrogen fuel cell vehicles (FCVs) continues to grow worldwide. At present, early adopters rely on a sparse refuelling infrastructure, and there is only limited knowledge about how they evaluate the geographic arrangement of stations when they decide to get an FCV, which is an important consideration for facilitating widespread FCV diffusion. To address this, we conducted several related studies based on surveys and interviews of early FCV adopters in California, USA, and a participatory geodesign workshop with hydrogen infrastructure planning stakeholders in Connecticut, USA. From this mixed-methods research project, we distil 15 high-level findings for planning hydrogen station infrastructure to encourage FCV adoption.

1. Introduction

Hydrogen FCVs are establishing themselves in consumer and fleet markets worldwide, with 11,200 FCVs and 376 hydrogen refuelling stations (HRSs) open to the public and fleets by late 2018 (1). However, the lack of a convenient refuelling infrastructure remains a barrier to greater FCV diffusion.

There is robust discussion regarding network deployment of initial HRSs to address this (2–8), although there is not agreement on how best to geographically arrange stations to do so (9, 10). This area of literature began before the initial market diffusion of FCVs, and relied on surveys of drivers of conventional vehicles about hypothetical station scenarios, or of analogue populations of diesel or natural gas vehicle drivers, to predict FCV adoption and refuelling behaviour (11–15). Since the roll-out of HRSs and FCVs, recent studies have surveyed initial FCV drivers about their station usage (16), but a key outstanding research area is how prospective FCV adopters, accustomed to the ubiquity of gasoline stations, evaluate the spatial arrangement of the full network of HRSs when adopting FCVs. That is the primary emphasis of our National Science Foundation (NSF)-funded research project, which employed a mixed methods research design to address a set of related questions (**Table I**). In this short paper, we distil 15 high-level insights from these studies for regions and companies planning a rollout of HRSs and FCVs. We refer readers to current and future publications and presentations for greater detail on the methods and results than is possible here.

Table I Studies Within our NSF Project in This Paper[a]

Research questions	Research methods	Study area	Study size
Which HRSs were drivers intending to rely on at the time they decided to buy or lease their FCV? How did their list of HRSs change over time?	Online revealed preference survey, network GIS analysis, statistical modelling	California	*n* = 129
How do early adopters describe in their own words how they decided to buy or lease a FCV?	Ethnographic interviews, content analysis	Greater Los Angeles, California	*n* = 12
What decision process do potential early adopters use to decide whether or not to get a FCV?	Ethnographic decision tree modelling	California	*n* = 71 (ongoing)
Where should HRSs be planned to maximize early adoption of FCVs according to industry stakeholders?	Geodesign workshop	Greater Hartford, Connecticut	17 participating stakeholders

[a]Publications and presentation materials are available from Arizona State University (ASU) (17)

2. Mixed Methods Approach

Our mixed-methods research design involved a combination of (a) revealed preference survey research, (b) qualitative ethnographic approaches that analyse consumers' decision-making processes and language and (c) geodesign participatory planning (18–20).

We conducted this research in California and Connecticut. By November 2019 over 7700 FCVs had been sold or leased in California, supported by 42 public HRSs (21), allowing an opportunity to evaluate how recent early adopters evaluated FCVs and HRSs when they got their vehicles. Connecticut is one of eight Northeast US states with Hydrogen and Fuel Cell Development Plans updated in 2018 (22), making it a compelling location to evaluate stakeholder opinions and prospective FCV adoption.

2.1 Survey Research

A web-based survey collected responses from 129 FCV adopters in California in the spring of 2019. To recruit, we posted links on Facebook groups for FCV owners there. Drivers listed HRSs that they intended to use when they decided to adopt their FCV, and using an interactive web map, where they lived, worked and frequently visited at the time, and whether their list of stations changed over time and why.

Using a detailed street dataset, we conducted geographic information system (GIS) network analysis to estimate travel times between stations and respondents' recorded locations. We also computed the deviations required (in miles and minutes) to visit the stations listed as the difference between the fastest direct route from home to destination and the fastest route that included the station as an intermediary stop. We conducted these analyses for stations they initially intended to use, used after experience or did not use. Results were analysed statistically using t-tests and logistic regression, and customer-derived trade areas were estimated in GIS. The GIS and statistical analysis provide insight into the revealed preferences of early adopters, while enabling comparisons with their stated intentions expressed in the survey and their subsequent behavioural changes.

2.2 Ethnographic Content Analysis and Decision Tree Modelling

Ethnography is a qualitative research approach that aims to understand decisions from the subject's individual and culturally specific point of view, and has been used to study automobile purchasing (23). We conducted structured ethnographic interviews of FCV adopters in California to understand their decision-making process. Interviews began with the request to "walk us through your decision-making process," with follow-up prompts for further explanation and reminders to keep responses relevant to the time they were deciding to adopt the FCV. We analysed these data using two ethnographic research methods.

We conducted content analysis using 12 hour-long interviews with FCV adopters in greater Los Angeles (24). All statements in the interview were coded using theoretically derived themes from the FCV adoption literature, and supplemented with additional inductive codes generated after analysing the transcripts. For the ethnographic decision tree model (EDM), we are conducting two rounds of interviews: one for constructing an initial tree model and one for testing and modification. An EDM represents the common or shared decision criteria about this behavioural choice by members of a cultural group (25). The EDM evaluates how most people move through a branching decision-making process to arrive at a yes-or-no decision. This has been used to model automobile purchases (26), but not for FCVs. For both rounds it is essential to sample drivers who (a) ultimately decided in favour of getting an FCV, and (b) seriously considered doing so but decided against it. For the first round, we conducted 25 hour-long interviews with drivers from the Los Angeles and San Francisco Bay regions, and then constructed an initial EDM tree.

Shorter second-round interviews followed, where the interviewer asked about each of the decision factors identified in the first round. In both rounds, the EDM tree was evaluated by the percentage of correctly predicted "yes" and "no" responses.

2.3 Geodesign Workshop

In October 2019, our research team led a seven-hour geodesign workshop in Hartford, Connecticut. In consultation with the host Connecticut Hydrogen-Fuel Cell Coalition and the University of Connecticut, we invited 71 stakeholders from related industries, regional government agencies and local universities. Seventeen participants that included representatives from each of these broad stakeholder groups worked together to propose, vet, negotiate and recommend a plan for a network of HRSs to support the initial rollout of FCVs in the region, following the established geodesign process. Participants worked in breakout groups with an online user-friendly mapping tool (27).

3. Results: Lessons Learned

We distil our findings from this mixed-methods approach into 15 primary lessons.

3.1 Motivations for Fuel Cell Vehicle Adoption

Ethnographic interviewees adopted FCVs for a diversity of reasons, including interest in new technology, perceived social status, free fuel and high-occupancy vehicle (HOV) lane access (24). Given available subsidies, adopters saw FCVs as a more affordable environmentally friendly option than electric vehicles (EVs), with faster refuelling times. FCV adoption also avoided the cost of upgrading residential wiring to accommodate Level 2 EV charging.

3.2 Fit Between Vehicle and Driver

In addition to thinking about whether the FCV would meet their needs, ethnographic interviewees described their degree of fit to the vehicle, in terms of being the type of person who plans refuelling trips, has flexibility due to being retired or has a long commute (24).

3.3 Convenience to Home is the Most Important Factor

California FCV adopters most frequently cited proximity to home as the main reason for choosing their primary intended HRS at the time of purchase. This was true for both the online survey participants (65%) and the ethnographic interviewees (50%).

3.4 Perceived Convenience to Home Varies

Ethnographic interviewees used a broad range of times and distances to describe stations' convenience to home. **Figure 1** shows that 36% of survey respondents planned to rely on HRSs within ten minutes of home because they were "near home" while still others said the same thing for a station an hour or more away.

3.5 Stations Near Work or On the Way Can Substitute for Near Home

Over 35% of survey respondents, and even more in the ethnographic interviews, did not consider their primary HRS to be near home. For primary stations, near work (36%) and on the way to a common travel destination (30%) were the next most important geographic factors.

3.6 Secondary Stations

Early adopters plan to rely on multiple stations to meet their needs when they get their FCV, averaging 2.98 HRSs, while only 18% listed one.

3.7 Station Trade Areas

Trade area analysis for the four HRSs that survey respondents in Southern California

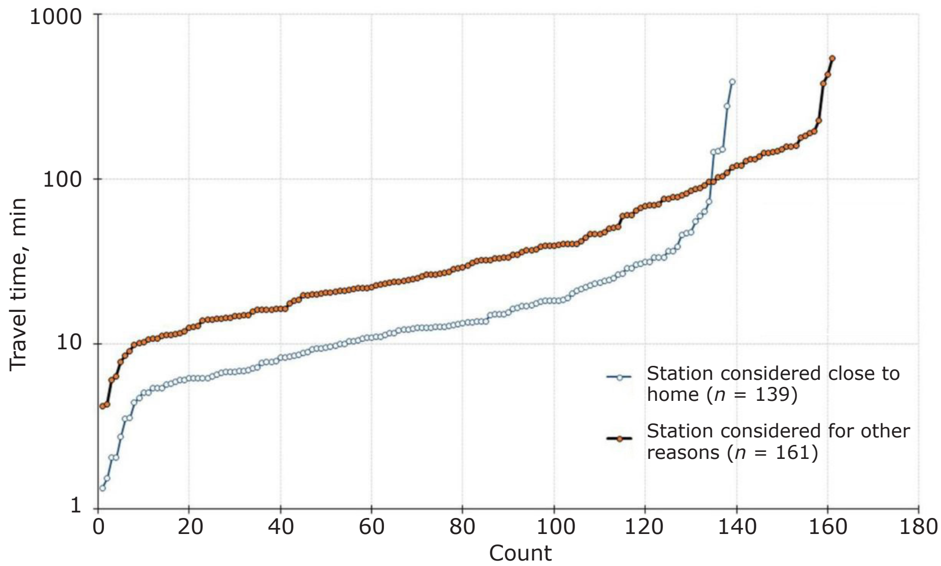

Fig. 1. Ordered estimated shortest travel times between home and hydrogen stations considered (n = 300) by early California FCV adopter survey respondents (n = 124), for stations described by drivers as "near home" and stations considered by drivers for other reasons

Fig. 2. Estimated trade areas for the four stations in Southern California most frequently listed by respondents. These trade areas include the nearest 65% of customers who purchased an FCV intending to rely on these HRSs (customers could list up to five stations)

listed most frequently at the time of adoption encompass a broad area (**Figure 2**), suggesting that respondents living across the region felt comfortable adopting an FCV while intending to use these stations.

3.8 Station Reliability and Backup Stations

Some adopters were aware of HRS unreliability: nearly 50% of secondary HRSs listed by survey respondents were considered to be backup stations. Seven out of 12 ethnographic interviewees required backup stations near home or work.

3.9 Secondary Vehicles

In addition to secondary stations, availability of a secondary vehicle was prominently noted by ethnographic interviewees. These are needed for longer trips and different carrying capacity needs, and to accommodate station reliability issues. Respondents mentioned additional household internal combustion vehicles and EVs, along with rental cars.

3.10 Convenience to Freeways

Ethnography interviewees often cited the proximity of stations to freeway exits near destinations or along routes, and associated time savings, as a reason for frequenting certain HRSs. Stakeholders in the Hartford geodesign workshop prioritised locating HRSs near points of freeway ingress and egress, citing high potential local demand and convenient access and service for New York–New England through-traffic.

3.11 Planned Stations

Ethnographic and survey respondents were willing to adopt an FCV in anticipation of planned HRSs while relying on less convenient, existing HRSs in the meantime, though expressed frustration about HRSs that were anticipated to come online but never did.

3.12 Changing Refuelling Stations

Nearly 60% of survey respondents did not change the list of HRSs that they initially planned to use over time. If their initial list included HRSs conveniently near home, work and along the way to their primary destination, they were less likely to change this list. However, for drivers with an FCV for at least 20 months, more than half did change their list.

3.13 New Stations After Experience

We used logistic regression to analyse the differences between stations that survey respondents initially intended to use when they got the vehicle ($yi = 0$) and those stations added over time that were not initially considered ($yi = 1$). We separately analysed the addition of HRSs that were: (a) available both at the time of adoption and when the respondent took the survey, and (b) planned at the time of the survey that later became available (**Figure 3**). Added HRSs are more likely to be farther from home than those initially considered. Reliability is significant for adding HRSs that were initially available, while shorter deviations are significant

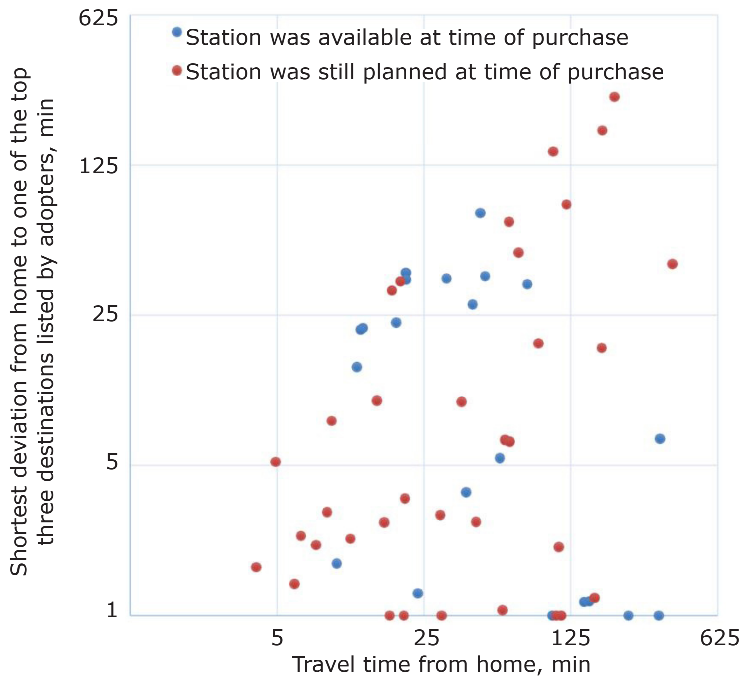

Fig. 3. Stations later added by California FCV adopters to their list of HRSs, that is, HRSs they were not initially intending to use (n = 56)

for adding HRSs that were initially planned and became available.

3.14 Demographics and Stakeholder Priorities for Placing Initial Stations

Geodesign workshop participants suggested placing the first three HRSs near wealthier neighbourhoods to maximise initial FCV adoption. While this reflects conventional wisdom and is consistent with the demographic characteristics we observed in our California ethnographic interviewees, it is possible that those with different demographic characteristics would adopt FCVs if similar outreach, incentives and HRSs were made available to them.

3.15 Sufficient Initial Number of Stations

While further research is needed to reliably predict how many HRSs are needed to encourage regional FCV adoption, there was consensus in the geodesign workshop that adding three new HRSs to the two existing or under construction would be (a) realistic within a few years, (b) sufficient to give potential early adopters several stations they could use and (c) sufficient to satisfy automakers to begin selling FCVs in Hartford (population 1.2 million).

4. Ongoing Research

Finalising the EDM for FCV adoption in California will require completing additional interviews, especially with drivers who seriously considered adopting an FCV but ultimately did not. In addition, we recently completed data collection for the stated preference survey in Connecticut, which prompts respondents to evaluate their willingness to get an FCV given three maps that show different pre-generated spatial arrangements of initial HRSs.

5. Conclusions

The consistent lesson is that these early FCV adopters are diverse in their motivations for wanting an FCV and in the list of stations and refuelling strategies they planned to use at the time of adoption. Drivers consider everything from lifestyle to image, and from incentives to station locations when deciding to get an FCV. A station “near home” is important to many drivers, but it is neither necessary nor sufficient for others. What is subjectively “near home” varies from minutes to over an hour away. Station reliability, secondary stations, freeway access and convenience to a variety of destinations all are important, especially while awaiting the opening of planned stations. Over time, drivers begin using stations they initially did not consider to support travel farther from home, with reliability and short detours also playing important roles.

The key implication is that stations should be located to serve not only ‘targeted’ nearby residents but also others who may visit or pass nearby regularly. Likewise, developers should also locate stations far from these neighbourhoods to benefit the wider travel of these residents and local travel of those who live elsewhere.

Acknowledgements

This work was funded by the NSF, Geography and Spatial Sciences Division, Grant No. 1660514. The authors would also like to thank: Joel Rinebold at the Connecticut Hydrogen-Fuel Cell Coalition for assistance in planning, organising and hosting the geodesign workshop in Hartford; H. Russell Bernard, Director of the Institute for Social Sciences Research at ASU for his recommendation to include ethnographic methods; and Yuhan Ma for GIS assistance.

References

1. L. Munuera and H. Fukui, ‘Tracking Energy Integrations: More Effort Needed’, International Energy Agency, Paris, France, May 2019
2. M. Melendez and A. Milbrandt, “Regional Consumer Hydrogen Demand and Optimal Hydrogen Refueling Station Siting”, Technical Report NREL/TP-540-42224, National Renewable Energy Laboratory, Golden, USA, April, 2008, 40 pp
3. Z. Lin, J. Ogden, Y. Fan and C.-W. Chen, *Int. J. Hydrogen Energy*, 2008, **33**, (12), 3096
4. M. Kuby, L. Lines, R. Schultz, Z. Xie, J.-G. Kim and S. Lim, *Int. J. Hydrogen Energy*, 2009, **34**, (15), 6045
5. S. D. Stephens-Romero, T. M. Brown, J. E. Kang, W. W. Recker and G. S. Samuelsen, *Int. J. Hydrogen Energy*, 2010, **35**, (10), 4652
6. J. Ogden and M. Nicholas, *Energy Policy*, 2011, **39**, (4), 1923
7. J. J. Brey, A. F. Carazo and R. Brey, *Int. J. Hydrogen Energy*, 2014, **39**, (8), 4123

8. J. E. Kang and W. Recker, *Transport. Sci.*, 2014, **49**, (4), 767
9. P. Agnolucci and W. McDowall, *Int. J. Hydrogen Energy*, 2013, **38**, (13), 5181
10. J. Ko, T.-H. T. Gim and R. Guensler, *Transport Rev.*, 2017, **37**, (5), 551
11. J. J. Brey, R. Brey, A. F. Carazo, M. J. Ruiz-Montero and M. Tejada, *Transport. Res. C: Emerg. Tech.*, 2016, **65**, 144
12. S. Kelley and M. Kuby, *J. Transp. Geogr.*, 2013, **33**, 258
13. R. Kitamura and D. Sperling, *Transport. Res. A: Gen.*, 1987, **21**, (3), 235
14. M. J. Kuby, S. B. Kelley and J. Schoenemann, *Transport. Res. D: Transport. Environ.*, 2013, **25**, 84
15. M. Kuby, *J. Transp. Geogr.*, 2019, **75**, 46
16. '2019 Annual Evaluation of Fuel Cell Electric Vehicle Deployment & Hydrogen Fuel Station Network Development', California Air Resources Board, Sacramento, USA, July, 2019, 90 pp
17. Refueling Station Preferences and Adoption of Alt-Fuel Vehicles, NSF Grant 1660514, Arizona State University, USA: https://h2adoptersrefueling.project.asu.edu/ (Accessed on 27th April 2020)
18. S. M. Ervin, *Landscape Urban Plan.*, 2016, **156**, 12
19. T. Fisher, *Landscape Urban Plan.*, 2016, **156**, 20
20. C. Steinitz, *Landscape Urban Plan.*, 2016, **156**, 23
21. 'By the Numbers: FCEV Sales, FCEV & Hydrogen Station Data', California Fuel Cell Partnership, West Sacramento, USA: https://cafcp.org/by_the_numbers (Accessed on 19th November 2019)
22. '2018 Development Plans', Northeast Electrical Energy Storage Cluster: http://neesc.org/publications/2018_roadmaps/ (Accessed on 14th January 2020)
23. EPIC: http://www.epicpeople.org/about-epic/ (Accessed on 24th November 2019)
24. O. L. Jaramillo, R. Stotts, S. Kelley and M. Kuby, *Transport. Res. Rec.*, 2019, **2673**, (9), 377
25. C. H. Gladwin, "Ethnographic Decision Tree Modeling", SAGE Publications Inc, Thousand Oaks, USA, 1989
26. M. Murtaugh and H. Gladwin, *Transport. Res. A: Gen.*, 1980, **14**, (5–6), 337
27. M. Kuby, K. Bailey, F. Wei, J. Fowler, D. Tong, Q. Zhong, O. Lopez and W. Sheaffer, *Transport. Res. Rec.*, 2018, **2672**, (24), 98

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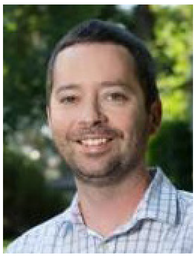

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