Title

Behavioral response to hydrogen fuel cell vehicles and refueling: Results of California drive clinics

Journal

International Journal of Hydrogen Energy, 34(20)

ISSN

03603199

Authors

Martin, Elliot
Shaheen, Susan A
Lipman, Timothy E
et al.

Publication Date

2009-10-01

DOI

10.1016/j.ijhydene.2009.07.098

Peer reviewed

Behavioral Response to Hydrogen Fuel Cell Vehicles in Refueling: Results of California Drive Clinics

International Journal of Hydrogen Energy

Volume 34, Issue 20, Pages 8670-8680

October 2009

Elliot Martin

Susan A. Shaheen

Timothy E. Lipman

Jeffrey R. Lidicker

Martin, Elliot, Shaheen, Susan, Lipman, Timothy, International Journal of Hydrogen Energy. (2009), v.34, pp. 8670-8680

BEHAVIORAL RESPONSE TO HYDROGEN FUEL CELL VEHICLES AND REFUELING: RESULTS OF CALIFORNIA DRIVE CLINICS

Elliot Martin
Graduate Student Researcher,
Transportation Sustainability Research Center
University of California, Berkeley
1301 S. 46th Street. Bldg 190, Richmond, CA 94804-4648
510-665-3576 (O); 510-665-2183 (F)
Email: elliot@berkeley.edu

Susan A. Shaheen, PhD
Honda Distinguished Scholar in Transportation, University of California, Davis, &
Co-Director, Transportation Sustainability Research Center (TSRC)
University of California, Berkeley
1301 S. 46th Street. Bldg 190, Richmond, CA 94804-4648
510-665-3483 (O); 510-665-2183 (F)
Email: sashaheen@tsrc.berkeley.edu; sashaheen@ucdavis.edu

Timothy E. Lipman, PhD
Co-Director, Transportation Sustainability Research Center (TSRC)
University of California, Berkeley
2614 Dwight Way, MC 1782, Berkeley, CA 94720-1782
510-642-4501 (O); 510-642-5483 (F)
Email: telipman@tsrc.berkeley.edu

Jeffrey R. Lidicker
Graduate Student Researcher,
Transportation Sustainability Research Center
University of California, Berkeley
1301 S. 46th Street. Bldg 190, Richmond, CA 94804-4648
510-295-4411 (O); 510-665-2183 (F)
Email: jlidicker@tsrc.berkeley.edu

BEHAVIORAL RESPONSE TO HYDROGEN FUEL CELL VEHICLES AND REFUELING: RESULTS OF CALIFORNIA DRIVE CLINICS

ABSTRACT
Over the last several decades, hydrogen fuel cell vehicles (FCVs) have emerged as a zero tailpipe-emission alternative to the battery electric vehicle (EV). To address questions about consumer reaction to FCVs, this report presents the results of a "ride-and-drive" clinic series (n=182) held in 2007 with a Mercedes-Benz A-Class "F-Cell" hydrogen FCV. The clinic evaluated participant reactions to driving and riding in an FCV, as well as vehicle refueling. Pre- and post clinic surveys assessed consumer response. More than 80% left with a positive overall impression of hydrogen. The majority expressed a willingness to travel five to ten minutes to find a hydrogen station. More than 90% of participants would consider an FCV driving range of 300 miles (480 kilometers) to be acceptable. Stated willingness-to-pay preferences were explored. The results show that short-term exposure can improve consumer perceptions of hydrogen performance and safety among people who are the more likely early adopters.

Key Words: Hydrogen, fuel cell vehicle, drive clinic, behavioral response, safety perception

1. INTRODUCTION
Concerns over air pollution, energy dependence, and now climate change have motivated the exploration of cleaner alternative transportation fuels for several decades. Hydrogen fuel cell vehicles (FCVs) have recently emerged as a zero tailpipe-emission alternative to the battery electric vehicle (EV). Like battery vehicles, FCVs produce no tailpipe emissions (other than water vapor) and also have the potential to be near zero-emission on a full fuel-cycle basis when coupled with renewable energy sources. As the lightest element in existence, hydrogen has several intrinsic characteristics that make it an attractive transportation energy carrier. It has a high energy density by weight, and it can be produced in large quantities from a diverse array of primary energy sources. Furthermore, in contrast to battery recharging, hydrogen can be refueled at speeds comparable to gasoline. These advantages have generated considerable interest in FCVs among governments and the automotive industry. This has led to the controlled deployment and testing of several hundred fuel cell cars and buses around the world.

The techno-economic barriers to FCV deployment are still considerable, but recent progress has been made in several key areas. Remaining issues that require improvement include fuel cell system cost reduction and durability, hydrogen storage, and the costs and technical complexities associated with developing a hydrogen-refueling infrastructure. In addition, and arguably less well recognized, are potential challenges for consumer exposure and acceptance.

Hydrogen FCVs have some important differences from gasoline internal combustion engine (ICE) vehicles. Their recent introduction to US roads presents key questions about consumer reaction and response to their use. Overcoming potential consumer acceptance issues will require an understanding of values and perceptions, as well as the pace at which vehicle users develop their opinions.

This study presents the results of a “ride-and-drive” clinic (n=182) held in August and September 2007 with a Daimler AG/Mercedes-Benz A-Class “F-Cell” hydrogen FCV that is currently in operation in Northern California. The clinic evaluated the reactions of participants to driving and riding in a passenger FCV, as well as witnessing a vehicle-refueling event. In this study, FCV response is measured on a short-term basis through a before-and-after survey taken on the same day. The survey assessed consumer perceptions of safety, vehicle performance in contrast to gasoline vehicles, and willingness-to-pay (WTP) for clean fuel vehicles.

In addition, drive clinic results are compared with the authors’ previous study employing 24 F-Cells by tracking respondents over a seven-month period [1]. This comparative analysis can help discern whether reactions to a new technology occurring over short- and long-term exposures can differ. It can also help corroborate previous study conclusions on exposure to new vehicle technology, given that the two studies used the same vehicle model.

Although extensive research has been conducted on the behavioral response of commercial taxi and bus drivers to hydrogen technology, this study and its predecessor are among the few that contribute to behavioral research on hydrogen passenger cars. Notable work has recently emerged on consumer response to hydrogen buses in Europe and on the acceptability of hydrogen to the public [2, 3, 4, 5, 6]. While customer experience with buses and passenger cars is clearly different, comparisons of this research indicate some similar trends in reaction.

The results of the study are intended to advise policymakers and the auto industry on the relative challenges of introducing a new vehicle propulsion system to consumers who are accustomed to ICEs. This paper consists of four main sections. First, the authors present a background on alternative fuel acceptance research, with an emphasis on electric drive trains and hydrogen acceptance. Next, the study methodology is reviewed. The third section presents the most compelling results of the pre- and post-clinic survey. Finally, the authors conclude by contrasting the results with the previous long-term study as well as discussing the implications of the results for the introduction of new vehicle technology.

2. BACKGROUND

While research on hydrogen FCVs and fuel acceptance has largely coincided with recent vehicle deployment, related work on consumer response to electric vehicles based on battery power systems has been active for nearly twenty years. The two are related in that they both face driving range and infrastructure challenges and both vehicle types rely on an electric motor powered by a unique fuel source. Much of the EV consumer response research occurred during the 1990s. Many of these studies focused on understanding how consumers could address fundamental EV limitations. This included the exploration of the "hybrid household" hypothesis, which considered households that could incorporate EVs in a complementary fashion as part of their personal fleet alongside gasoline vehicles [7, 8, 9]. Other research has used data from EVs that were placed in households for a few weeks to study household travel behavior [10, 11]. Through the analysis of travel diaries, researchers corroborated components of the hybrid household hypothesis in effect. Participants in the vehicle trial were able to use the EV vehicle for much of their daily travel, but they switched to gasoline vehicles on days with longer trips. However, in spite of the demonstrated utility of the EV, respondents still desired driving ranges to be similar to that of a gasoline vehicle [10]. While travel diaries employed in this study suggested that daily trip-making rarely exceeded about 80 kilometers a day, exposure to the EV did not change participant expectations that the vehicle should have a range of 160 kilometers or more [10]. A companion study used data from both a longitudinal survey in California and the same vehicle trial. It focused on the response to EV technology as correlated with opinions on the ability of EVs to bring environmental benefits [11]. Among other things, the authors found that exposure to EVs did not decrease the opinion of participants with respect to the environmental benefits of EVs, but at the same time, those perceived environmental benefits became a lower priority in the stated preference for buying EVs [11]. The range restrictions of EVs have been found to turn off some buyers. In related work, one study in Europe found that interest in owning EVs actually decreases after a few months of use due to concerns over range and daily travel [12].

Consumer interactions with hydrogen buses have been the source of most hydrogen response studies to date. One of the earliest occurred in 1998 when the first hydrogen bus was publicly deployed in Munich. Passengers aboard this bus were surveyed using standard Likert-scale responses. Overall, few barriers to hydrogen acceptance were uncovered. The survey found that direct contact with the technology was correlated with more positive assessments and that concern over negative associations with the Hindenburg dirigible accident in 1937 and the hydrogen bomb were not present [13].

Since that initial deployment, demonstration projects involving hydrogen fuel cell buses began to expand rapidly [14]. These deployments offered multiple opportunities to evaluate passenger response and perception of fuel cell technology. This included hydrogen bus deployments in Luxembourg, Berlin, Perth, and London, which offered an opportunity to explore consumer response on a broader scale. The final report to the European Commission evaluating passenger response to the buses found that safety was not a concern, prior (positive) knowledge of hydrogen increased acceptance, and in contrast to the Munich study, suggested that direct exposure was not necessarily associated with acceptance or willingness-to-pay (WTP) [15].

At about the same time, a study of London taxi drivers operating prototype FCVs found WTP for the technology was correlated with higher education levels, hydrogen knowledge, and air pollution concerns. Taxi drivers also stated that they did not have safety concerns with respect to driving hydrogen-powered cars [16]. Another study based in London evaluated acceptability of hydrogen through a survey of the general public. O'Garra et al. (2005) concluded that knowledge of hydrogen technology was an important determinant of support for wider application in transportation. At the same time, environmental attitudes were not found to be good predictors of support for any transportation technology; this is a finding supported by Ricci et al., (2008) [4,17]. Building on this study, Thessan and Langhelle (2008) conducted a survey using the template established by O'Garra et al., (2005) in the Greater Stavanger region of Norway [6]. Similar to O'Garra et al, (2005), they found that prior knowledge of hydrogen is a key determinant of acceptability of hydrogen. But, in contrast to O'Garra et al., (2005), they found that positive environmental attitudes had a positive influence on acceptability [6].

In addition to these findings, several studies based on the deployment of fuel cell buses in Europe, Australia, and Canada, have significantly expanded knowledge of consumer response to hydrogen vehicles [2, 3, 18, 19]. A recent study of attitudes towards hydrogen buses involved a large collection (3352) of personal interviews across eight cities throughout Europe. These interviews discerned that 77 percent of the respondents would support the substitution of conventional buses for hydrogen buses if the costs and frequency of service was the same [19]. But in the event the price was higher, some studies have found that support drops quickly. Haraldsson et al. (2006) surveyed hydrogen bus riders in Stockholm and found attitudes towards hydrogen were positive, but 64 percent of bus riders were not willing to pay more for using hydrogen buses. Other studies have found a higher proportion of the population to be willing to pay more for hydrogen bus fares. One study [2] reports on a contingent valuation method survey of bus riders in the cities of Berlin, London, Luxembourg, and Perth. The Berlin and Luxembourg surveys asked riders if they would be willing to pay an increased fare to support a large-scale hydrogen bus deployment within their city. The mean WTP of surveyed riders was €0.32 per fare. The London and Perth surveys took a different approach, where both riders and non-riders were randomly surveyed to discern their WTP for hydrogen bus deployment in the form of additional taxes. The researchers found that citizens of London and Perth had a positive WTP for hydrogen bus deployments of €24 and €15 in annual taxes per year, respectively. Across all cities, roughly 85% of respondents were willing to pay an additional fee for hydrogen buses.

Hydrogen vehicle marketing experts have observed that exposure through media stories can impact public acceptance, especially general opinions of safety and quality of the hydrogen driving experience [20]. To better understand potential consumer response to new vehicle types, marketing researchers support test-drives to raise consumer familiarity with new vehicle types, especially driving experience and safety attributes [21]. However, some vehicle features, such as range restrictions and fuel-efficient driving potential, may take more time for consumers to understand and accommodate.

Research addressing consumer response to hydrogen has expanded significantly in the past few years. Almost all of these studies, however, have focused on agents within the public transportation system, including bus passengers, bus drivers, and taxi drivers. Some reveal that a fair portion of public transit riders would be willing to pay higher fares to run buses on hydrogen fuel. Across these studies, it appears that transit riders and drivers generally feel safe with the technology, and passengers overwhelmingly consider hydrogen buses to be as good, or better, than regular buses across a variety of performance metrics. This paper builds on this growing research by exploring similar response metrics among state and university employees in California to passenger FCVs.

3. METHODOLOGY: RIDE AND DRIVE CLINIC

This section provides an overview of the ride-and-drive clinic study methodology, including a description of the surveys and study limitations. The purpose of the ride-and-drive clinic was to gain feedback from a range of individuals who were provided an opportunity to drive the F-Cell vehicle under real-world driving conditions and view a fueling demonstration. After completing a pre-clinic questionnaire, participants drove the vehicle in groups of two on a three-mile route in West Sacramento or Richmond, California with a researcher to direct them. The speed limits along the routes ranged from 30 to 55 miles per hour (48 to 88 kilometers per hour). The route permitted respondents to personally test the acceleration, braking, and handling capabilities of the vehicle. They were not given any written information on hydrogen or the fuel cell vehicle at the clinic or prior to arriving. But they received instruction on what they were going to be doing at the clinic. Their arrivals were staggered so that groups larger than eight participants would not accumulate. Refreshments were provided in a waiting area.

Participants had the opportunity to both drive the vehicle and to ride as a front-seat passenger to maximize their exposure. In addition to driving the F-Cell, subjects were also directed to a hydrogen refueling station where they witnessed the F-Cell being refueled. Some fuel was placed in the vehicle, but the vehicle was not always low on fuel, so in some cases the refueling was approximately half a tank. Once participants had driven the vehicle and witnessed the refueling, they completed a post-clinic questionnaire. During the session, respondents could ask questions about the vehicle, the fuel, or the station. Researchers would explain to participants how certain functions of the vehicle or station worked, but these responses were strictly technical in nature.

Employees from the California Department of Transportation (Caltrans), the California Air Resources Board (CARB), and the California Energy Commission (CEC) participated in the ride-and-drive clinic at the California Fuel Cell Partnership in West Sacramento from August 8 to 17, 2007. University of California, Berkeley (UC Berkeley) employees attended the clinic at the Richmond Field Station and witnessed the fueling demonstration at the AC Transit hydrogen fueling station in Richmond between the dates of September 22 to 27, 2007. Research subjects were recruited from within UC Berkeley, Caltrans, CARB, and the CEC via an email that solicited participation according to the University of California's Committee for the Protection of Human Subjects guidelines. Total participant time ranged between 1.5 to 2 hours. An incentive raffle for a small digital music player was used to encourage participation. In addition, each respondent received a small gift, such as an F-Cell writing pad, upon session completion. A total of 107 individuals participated in the Sacramento drive clinic and 75 in Richmond. Potential subjects who had previously driven an FCV or had extensive knowledge of them were not allowed to participate in the ride-and-drive study.

3.1 Pre- and Post-Clinic Survey Design

Researchers administered questionnaires before and after exposure to the F-Cell and the refueling event. The initial questionnaire assessed experience with alternative fuels, impressions of hydrogen as a transportation fuel, expectations of vehicle performance and hydrogen safety, challenges of hydrogen vehicles, and attitudes toward the environment and experimentation.

The post-clinic questionnaire documented F-Cell impressions including acceleration, braking, handling, fuel economy, and ride comfort; hydrogen vehicle and fuel safety; range acceptability; fueling difficulty; WTP; and questions about participant demographics. When asked to provide their impressions of hydrogen safety, respondents were asked for their assessment relative to their gasoline safety impressions. For example, one question read: "What is your impression of the safety of driving a hydrogen vehicle?" Responses included: "Much less safe than gasoline," "Less safe than gasoline," "About as safe as gasoline," "Safer than gasoline," and "Much safer than gasoline." The benchmarking of the fuel response was done for two reasons. First, the question grounds the answer relative to the vast prior consumer experience with gasoline. Second, it permits a more accurate assessment of impressions to the vehicles and fuel with which hydrogen (and perhaps other technologies) would likely compete. This approach also was employed for assessing consumer response to vehicle performance.

3.2 Ride-and-Drive Clinic Study Limitations

An important limitation of this study is participant self-selection bias due to the restricted study population (i.e., state agency and university employees). The individuals participating in the clinic were volunteers, and hence, the sample is not random. However, only 55% of respondents entered the clinic with a positive impression of hydrogen fuel, with much of the remaining sample classifying their opinion as "Neutral." In addition, only 14% of the respondents had any prior direct experience with hydrogen. The dataset generated for this study reflects an exploratory analysis, but these study limitations do not prevent the use of the dataset to obtain insights into consumer response to hydrogen vehicles and fueling, especially among likely early adopters.

4. SURVEY RESULTS

In this section, the authors present the research results. There are six subsections: 1) demographics, 2) Respondent experience with alternative fuels and hydrogen 3) F-Cell and refueling response, 4) response to vehicle performance metrics, 5) response to range and refueling distance, and 6) Responses to WTP questions.

4.1 Demographics: Sacramento and Richmond Study Populations

Table 1 presents the demographics of the drive clinic participants. They were mostly male (63%) and married (55.2%). The Sacramento clinic was more heavily weighted with males than the Richmond clinic. The difference between the two clinics was not large enough to be statistically significant, according to the Fisher Exact Test. Similarly, while there were perceptible differences between the marital status distributions across the two samples, the relative differences were not statistically significant. However, survey respondents in Richmond had higher education levels (p=0.0038), lower age, and more respondents had relatively low incomes (p=0.025). This reflects the participation of graduate students employed by the university. Clinic demographics are summarized in Table 1. Since differences between the populations were not substantial, researchers have combined responses in the analysis that follows.

In comparison with the general population, the combined sample is not representative of the US or California populations (p<0.001 for all). A summary of the demographic comparisons of the sample with both the US and California appears in Table 1. The study sample has a higher percentage of males, is younger, more often single, more educated, and has a higher household income than either the US or California populations.

TABLE 1 Demographic Attributes of Survey Respondents

Demographic Attribute	Richmond	Sacramento	Total	*p*-value	US 18+	CA 18+	*p* Tot-US	*p* Tot-CA
Gender	N=75	N=106	N=181					
Male	57.3%	67.0%	63.0%	0.21 *	48.6%	49.6%	<0.001 *	<0.001 *
Female	42.7%	33.0%	37.0%		51.4%	50.4%		
Age Category	N=75	N=106	N=181					
22-34	44.0%	25.5%	33.1%	0.0049 **	24.8%	27.3%	<0.001 ***	<0.001 ***
35-49	22.7%	40.6%	33.1%		31.6%	32.7%		
50-59	21.3%	29.2%	26.0%		18.6%	17.7%		
60+	12.0%	4.7%	7.7%		25.0%	22.3%		
Marital Status	N=74	N=107	N=181					
Single	39.2%	29.9%	33.7%	0.094 **	26.9%	30.6%	<0.001 ***	<0.001 ***
Married	55.4%	55.1%	55.2%		50.1%	46.6%		
No Longer Married	5.4%	15.0%	11.0%		23.0%	22.7%		
Education	N=75	N=107	N=182					
Associate Degree or Less	9.3%	10.3%	9.9%	0.0038 **	75.0%	73.5%	<0.001 ***	<0.001 ***
Bachelor's Degree	41.3%	64.5%	54.9%		16.2%	17.4%		
Graduate Professional Deg.	49.4%	25.2%	35.2%		8.8%	9.1%		
Income (HH, $ US)	N=72	N=102	N=174					
Less than $50,000	29.2%	10.8%	18.4%	0.025 **	49.2%	42.4%	<0.001 ***	<0.001 ***
$50,000 to below 75,000	13.9%	20.6%	17.8%		18.9%	18.0%		
$75,000 to below 100,000	18.1%	25.5%	22.4%		12.2%	12.7%		
$100,000 to below 150,000	23.6%	31.4%	28.2%		11.7%	14.6%		
More than $150,000	15.3%	11.8%	13.2%		8.0%	12.2%		

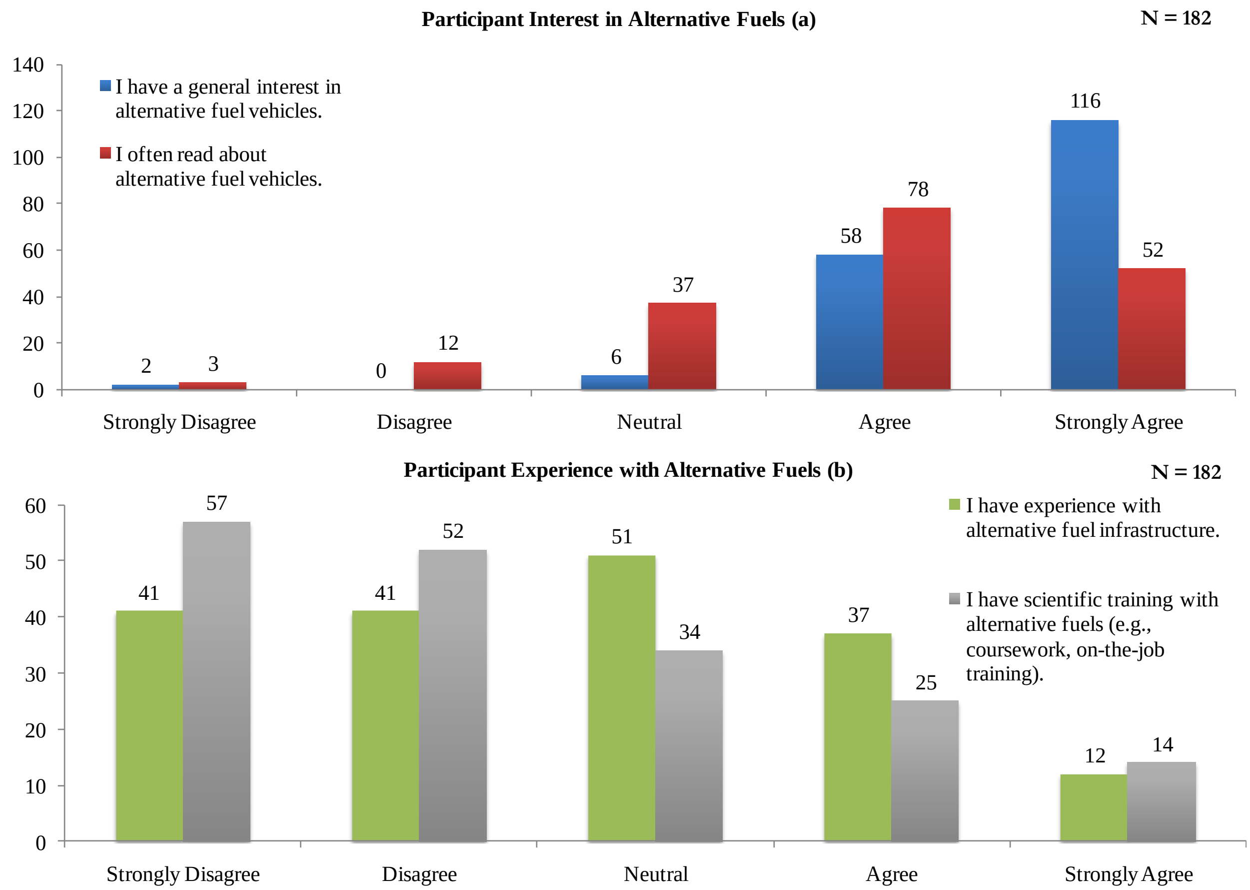
* Fisher's Exact Test
** ANOVA
*** Chi-squared

Source: American Community Survey, 2007 [22]

4.2 Prior Respondent Experience With Alternative Fuels

Questions within the pre-clinic assessed the degree of prior experience that participants had with alternative fuels. Four questions gauged participant interest as well as training in subjects pertaining to alternative fuel vehicles or infrastructure. Not surprisingly, the results found that a significant majority of participants exhibited a strong interest in alternative fuels. However, additional questions found that experience with alternative fuel vehicles and infrastructure was far more mixed. Figure 1 illustrates the self-assessed prior exposure of participants to alternative fuels.

Figure 1 Profile of Participant Interest and Experience with Alternative Fuels



In Figure 1 (a), the distribution of responses show that the questions profiling interest in alternative fuels is markedly skewed to the right. At the same time, interest in alternative fuels did not translate into experience. The distribution of responses in Figure 1(b) illustrate that a majority of respondents did not consider themselves as having significant experience with alternative fuel infrastructure or training in alternative fuels. Those with self-assessed experience were between 20 and 25 percent of the participant population. Though a minority in the sample, this share is likely larger than that of the general population. Such a result would be expected from a sample population recruited from state agencies and a large research university.

While roughly a quarter of respondents were self-classified as having experience with alternative fuels, a far smaller proportion had any direct experience with hydrogen. Therefore, while experience with alternative fuels was present, this did not translate into experience with hydrogen. Among the leading alternative fuels, hydrogen was the least familiar of all fuels to respondents.

During the pre-clinic survey, participants were asked to rate their general experience level with the prevailing advanced or alternative fuel vehicle technologies on the road today. Roughly 86 percent of respondents considered themselves to have no experience with hydrogen. Among the remaining 14 percent, only four percent of the respondents considered themselves to be very experienced with hydrogen fuel. All other fuels had a higher relative level of experience. Not surprisingly, more than half of respondents considered themselves to have had some experience with battery electric hybrids. However, only 10% of respondents considered themselves to be very experienced with these vehicles. Relative to hybrids, respondents were less experienced with battery electric vehicles. But they were more familiar with battery electric vehicles than flex fuel or natural gas vehicles, which were only familiar to a handful of respondents. But all of these vehicles were generally more familiar to the participants than hydrogen vehicles. Respondents usually were highly experienced with only one or two technologies, but a few respondents had some experience with all technologies.

Although California has led the nation in hydrogen deployment, opportunities for respondents to see hydrogen vehicles outside the clinic are limited. Several automakers deployed hydrogen passenger cars with public agencies as part of fleet trials. In addition, the bus agency AC Transit, which operates in Oakland and the East Bay, has been running a hydrogen-powered bus on selected routes for several years. Beyond access to these special situations, obtaining exposure to a hydrogen vehicle would have been difficult for people in the region.

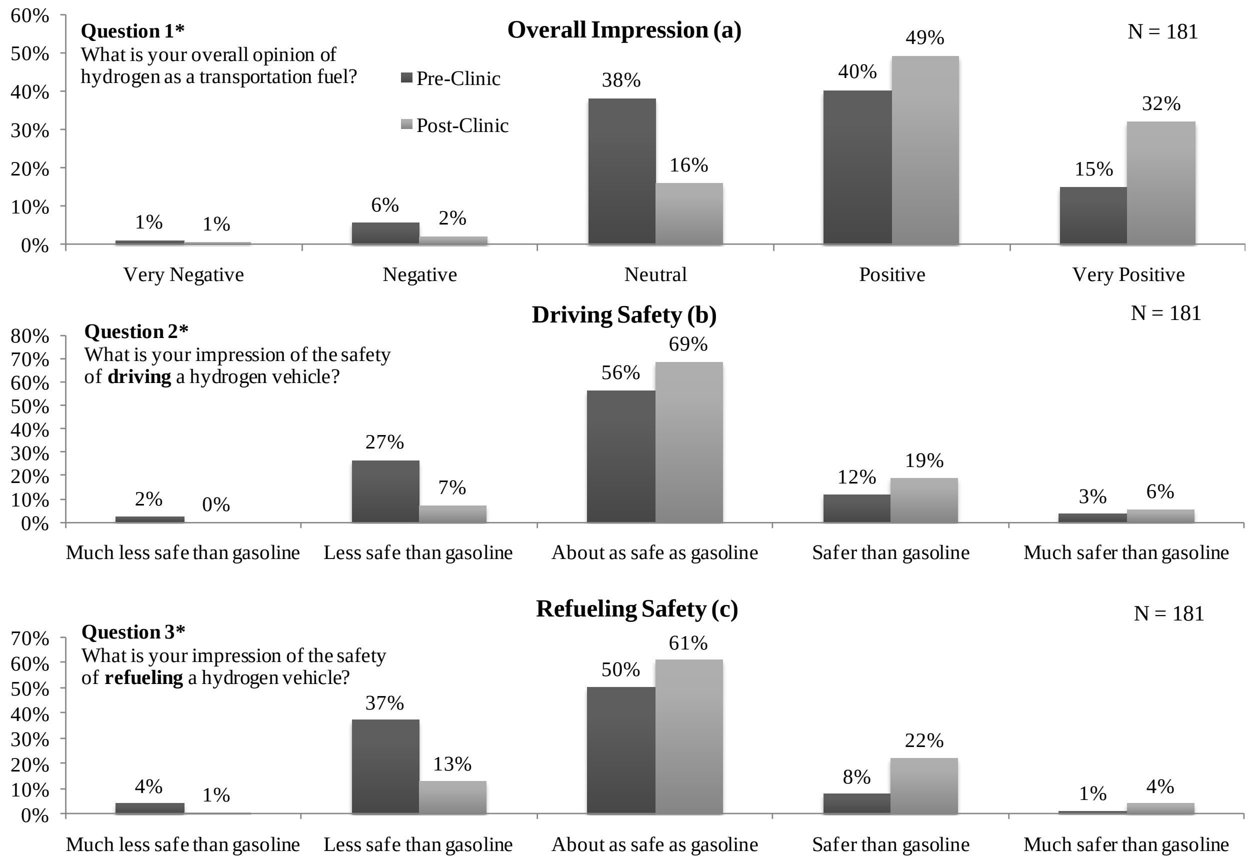
This along with Figure 1 suggest that the study population was generally inexperienced with alternative fuels. However, the proportions of those with some or considerable experience are likely larger than that of the general population. Thus overall, the sample population was a well-educated, well-informed collection of people interested in alternative fuels, but their prior exposure to hydrogen fuel and vehicle technology was limited.

4.3 F-Cell and Hydrogen Refueling Response

The response of drive clinic participants to the F-Cell was evaluated from several perspectives. Pre-clinic survey questions were designed to assess preconceptions of the hydrogen fuel, hydrogen vehicles, and refueling. Post-clinic survey questions discerned how impressions shifted as a result of direct exposure to the vehicle and refueling process. The post-clinic survey also elicited respondent opinions of vehicle safety and operation. By the end of the clinic, most participants left with a good impression of the F-Cell. When asked of their opinion given the options of “Very Negative,” “Negative,” “Neutral,” “Positive,” and “Very Positive,” roughly 95% of respondents finished the clinic with either a positive or very positive impression of the F-Cell. When asked of their overall feelings of vehicle safety, 89% reported that they “felt safe” with the F-Cell. Finally, 85% who witnessed the F-cell refueling considered it to be safe, and 82% did not consider it to be difficult.

To gain insights into short-term exposure impacts, the survey sought to measure whether technology exposure during the clinic had any effect on respondent safety and hydrogen fuel impressions. With respect to safety, respondents were asked to give their opinion of hydrogen safety relative to gasoline safety. Results indicate that short-term exposure to hydrogen technology can shift hydrogen and fuel safety opinions. Figure 2 illustrates the before-and-after response distributions to three paired questions. Sample size is indicated within each figure for the appropriate question. Sample sizes vary slightly due to missing or invalid responses from a handful of respondents.

FIGURE 2 Before-and-after vehicle and refueling safety response



* Paired Sign Test significant at ($p < 0.001$)

The pre-clinic and post-clinic distribution of each question within Figure 2 is evaluated with the "Sign Test." The Sign Test is a nonparametric statistical test that permits the evaluation of differences in distributions. These paired distributions illustrate several important points. Question 1 assesses respondents' before-and-after opinions of hydrogen as a transportation fuel. The pre-clinic survey distribution illustrates that a small majority (55%) entered the clinic with a favorable view of hydrogen, while the remaining respondents either had negative or neutral opinions. The shift after the clinic is evident from the post-clinic survey response distribution, which skews to the right. More than 80% of participants finished the clinic with a positive overall hydrogen impression. When applied to the distributions of Question 1, the Sign Test generates a z-score of -5.8 ($p < 0.001$), indicating that the opinion shift is statistically significant.

Question 2 evaluates respondent safety impressions of driving a hydrogen-powered vehicle. The answers to this question were posed relative to gasoline as a familiar benchmark.

The distribution of pre-clinic survey responses better approximates a normal distribution, with roughly 70% believing that hydrogen is equally safe or safer than gasoline. However, the remaining 30% believed that driving a hydrogen vehicle is less safe than gasoline. The post-clinic survey reveals a considerable impression shift, as the proportion of respondents feeling less safe with hydrogen than with gasoline dropped to 7%. Opinions mostly shifted towards the belief that gasoline is as safe as hydrogen, with some gains in the opinion that hydrogen is safer than gasoline. The comparison of the distributions of Question 2 had a z-score of -4.9 ($p < 0.001$) with the Sign Test, meaning that the difference between the distributions is statistically significant.

Finally, Question 3 illustrates a similar assessment of hydrogen refueling safety normalized to the impressions of gasoline refueling safety. Here, stronger safety reservations exist in the pre-clinic survey prior to exposure, as over 40% considered hydrogen refueling to be less safe than gasoline. As with the driving assessment, responses shifted in the post-clinic survey, with only 15% leaving the clinic with the impression that hydrogen refueling is less safe than gasoline refueling, while 60% felt that it was as safe and 25% believed it was safer. The z-score of the Sign Test on the paired responses for Question 3 was -6.7 ($p < 0.001$), also showing statistical significance. Thus, the response shift exhibited in Figure 2 illustrates that short-term exposure to hydrogen vehicles and refueling can make at least some people feel more comfortable with hydrogen fuel.

4.4 Response to Vehicle Performance Metrics

Participants were asked to assess their opinions of several hydrogen vehicle performance metrics. As with the questions in Figure 2, researchers designed the performance questions to assess response metrics calibrated to participants' gasoline vehicle perceptions. In the pre-clinic survey, respondents were asked to provide their hydrogen vehicle performance expectations in comparison to a typical gasoline vehicle with the following metrics: acceleration, braking, handling, and ride comfort. Respondents were asked whether they anticipated that the hydrogen vehicle would perform worse, better, or about the same as a typical gasoline vehicle. In the post-clinic survey, participants were asked to assess whether the vehicle had met, exceeded, or failed to meet their expectations. Table 2 illustrates the cross-tabulation of responses to two key metrics: acceleration and braking.

TABLE 2 Before-and-After Survey Responses to Vehicle Performance

Acceleration						
Pre \ Post	Greatly Disappointed	Slightly Disappointed	Met Expectations	Slightly Exceeded	Greatly Exceeded	**Total**
Much Worse	0%	1%	2%	1%	1%	**4%**
Slightly Worse	0%	5%	9%	12%	7%	**34%**
About the Same	1%	11%	16%	5%	9%	**42%**
Slightly Better	0%	3%	5%	4%	1%	**13%**
Much Better	0%	2%	3%	1%	1%	**7%**
Total	**1%**	**23%**	**35%**	**23%**	**19%**	**100%**

Braking						
Pre \ Post	Greatly Disappointed	Slightly Disappointed	Met Expectations	Slightly Exceeded	Greatly Exceeded	**Total**
Much Worse	0%	0%	0%	0%	0%	**0%**
Slightly Worse	0%	0%	1%	1%	0%	**2%**
About the Same	1%	3%	55%	21%	8%	**88%**
Slightly Better	0%	1%	6%	0%	1%	**7%**
Much Better	0%	1%	1%	0%	1%	**3%**
Total	**1%**	**4%**	**64%**	**22%**	**9%**	**100%**

[i]Pre-Survey Question: How do you expect the hydrogen vehicle to compare to a typical gasoline vehicle within the following performance categories?

[ii]Post-Survey Question: How did the following attributes meet, fail to meet, or exceed your expectations?

The cross-tabulation illustrates both the distribution of respondent expectations prior to exposure and how those relative expectations were met or unmet by the vehicle. The bold numbers within the table represent the aggregate distribution of responses to each question. The interior numbers of the cross tabulation illustrate how respondents with specific prior expectations changed after exposure to the vehicle. As a performance metric, "acceleration" illustrated the widest distribution of prior expectations, with nearly 40% of respondents expecting the vehicle to perform worse than a gasoline vehicle, and 20% expecting it to perform better. The results of the post-clinic survey revealed that 25% of respondents considered acceleration to perform below their expectations, while the expectations of roughly 40% were exceeded. Braking exhibited far less variance in expectations as most respondents anticipated braking to perform about the same as gasoline vehicles. A little more than 30% found braking to exceed expectations, far more than the 5% that indicated disappointment in braking performance.

The results suggest that expectations of vehicle performance and how those expectations were met may play a role in the respondent's overall impression of hydrogen. As shown in Figure 2(a), Question 1, the impressions of hydrogen as a transportation fuel improved among a large share of participants in the clinic. Of the 182 participants, 46 percent (84) reported an improvement in impressions, 41 percent (75) reported no change in impressions, and 13 percent (23) reported a decline in impressions. The change in the respondents' impressions of hydrogen may be linked to how they perceived the performance of various vehicle attributes relative to their prior expectations. Table 3 illustrates the distribution of responses to the before-and-after performance questions as categorized by how the participant's impressions changed as determined by their pre- and post-clinic responses to Figure 2(a), Question 1.

TABLE 3 – Performance perceptions as categorized by change in hydrogen perception

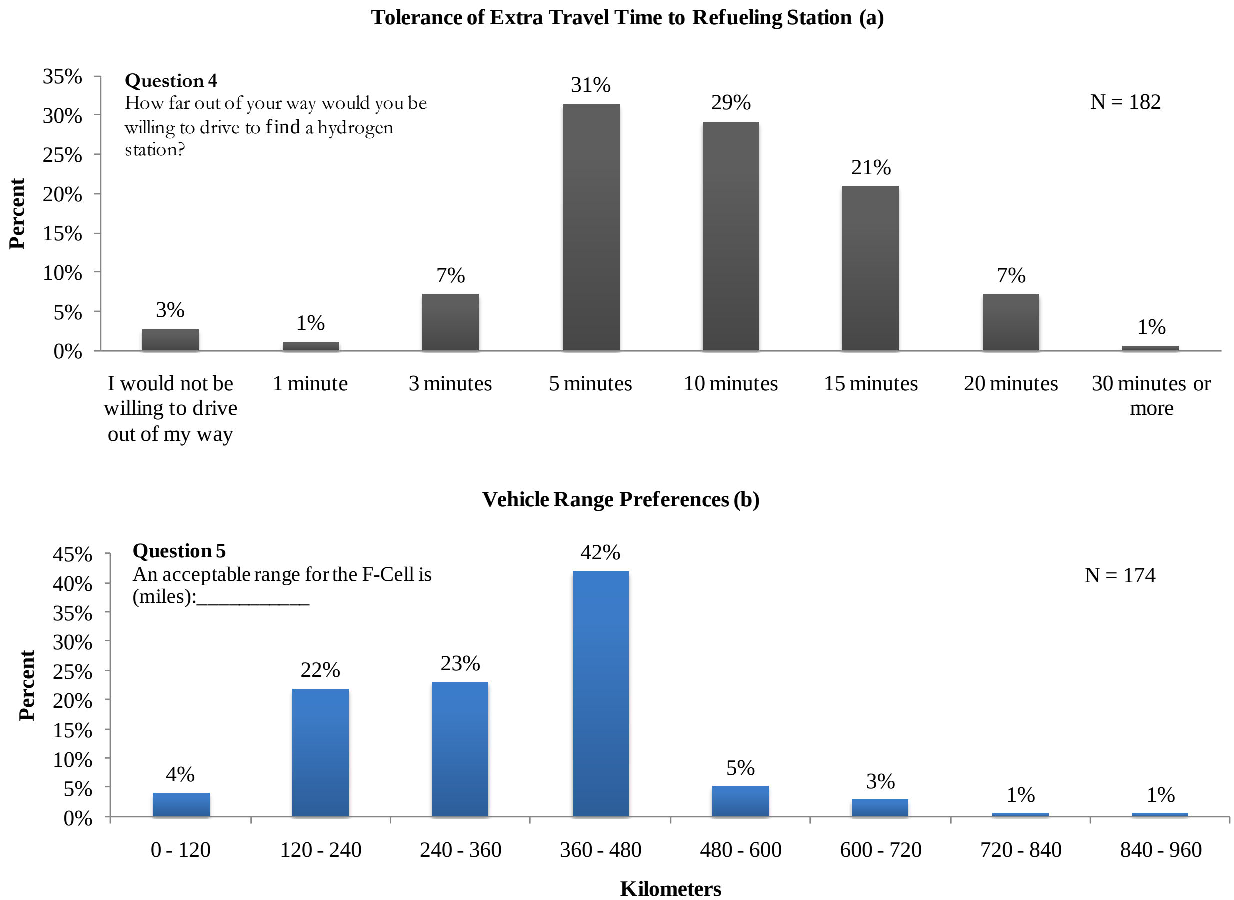
PRE-SURVEY	Negative Overall Change in Opinion			Neutral Overall Change in Opinion			Positive Overall Change in Opinion		
	Acceleration	Braking	Handling	Acceleration	Braking	Handling	Acceleration	Braking	Handling
Much worse	4%	0%	0%	4%	0%	0%	5%	0%	0%
Slightly worse	22%	0%	17%	33%	3%	9%	37%	2%	8%
About the same	48%	83%	78%	44%	89%	82%	39%	88%	83%
Slightly better	17%	13%	4%	15%	5%	7%	11%	7%	6%
Much better	9%	4%	0%	4%	3%	1%	8%	2%	2%
POST-SURVEY	**Negative Overall Change in Opinion**			**Neutral Overall Change in Opinion**			**Positive Overall Change in Opinion**		
	Acceleration	Braking	Handling	Acceleration	Braking	Handling	Acceleration	Braking	Handling
Greatly Disappointed	0%	4%	0%	0%	0%	0%	2%	0%	0%
Slightly Disappointed	48%	4%	9%	27%	7%	1%	12%	2%	4%
Met Expectations	35%	78%	70%	33%	61%	52%	37%	62%	57%
Slightly Exceeded	4%	9%	17%	24%	23%	32%	26%	25%	20%
Greatly Exceeded	13%	4%	4%	16%	9%	15%	23%	11%	19%

Table 3 shows the response to acceleration, braking, and handling. As mentioned earlier, the expectations and reactions to acceleration illustrated the widest distribution of response. Considering just the acceleration responses, the pre-survey shows that those ending the clinic with a negative overall change in hydrogen impression came into the clinic with a symmetric distribution of expectations of acceleration performance. A larger share of those with neutral and positive changes in impression entered the clinic with lower expectations of acceleration performance. The post survey shows the opposite trend. Among those whose impressions of hydrogen as a fuel declined, almost half were disappointed with the vehicle's acceleration. In contrast, a larger share of those whose impressions of hydrogen did not change or improved had their expectations of acceleration exceeded. The attributes of braking and handling illustrate similar trends, but the movements are not as pronounced. Between 80 to 90 percent of respondents, regardless of how their opinions changed, entered the clinic with expectations that the vehicle would brake and handle about as good as a typical gasoline vehicle. But nearly 40 percent of those with improved impressions of hydrogen had their expectations of braking and handling exceeded. This share is far lower among those whose opinion of hydrogen declined. It is important to emphasize that the majority within all cohorts had their expectations met or exceeded with respect to performance attributes. But, these shifts in impression, as divided by changes in overall opinion of hydrogen, suggest that key performance attributes of hydrogen vehicles will influence people's acceptance of the fuel.

4.5 Response to Range and Refueling Distance

Participants also were asked about driving range and refueling perceptions. Both aspects are jointly important as restricted driving range and limited refueling infrastructure have long hindered the adoption of alternative fuel vehicles by consumers. Results of two questions from the survey illustrate a distribution of preferences across these two parameters. In the post-clinic survey, respondents were asked to write-in a vehicle range (in miles) that they would consider acceptable for the F-Cell (which at the time had a range of 100 miles/160 kilometers). Additionally, respondents were asked to characterize their tolerance in terms of extra travel time to drive to a fueling station. The response distributions to both questions are illustrated in Figure 3.

FIGURE 3 Distribution of range and refueling preferences



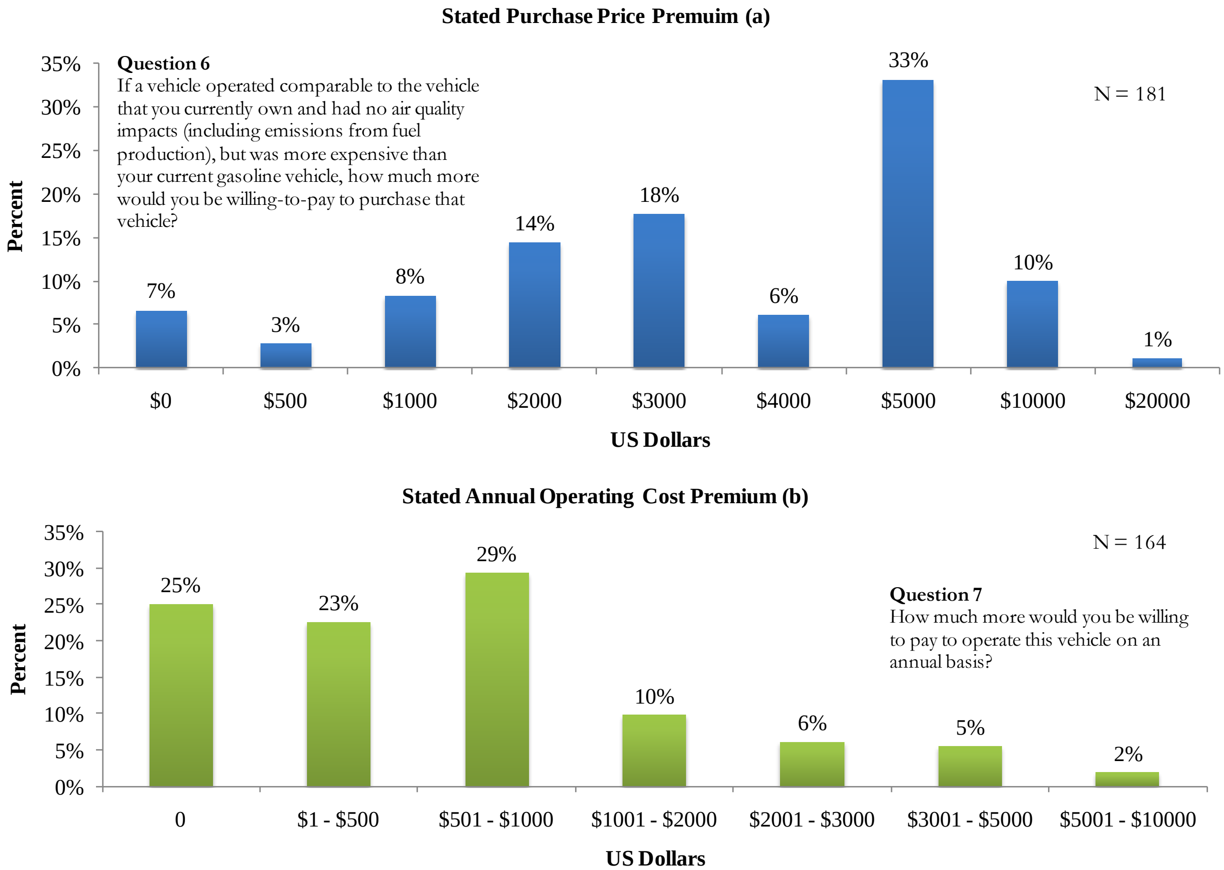
Question 4 illustrates the refueling distribution and reveals that the majority of respondents would be willing to travel five to ten minutes out of the way to find a hydrogen station. A sizable minority also expressed a willingness to drive at least 15 minutes to find a station. This information is useful for informing time-distance tolerances for planning potential station networks. The distribution also can be helpful for gaining a preliminary probabilistic assessment as to the share of people willing to access stations at a certain distance from their home or work.

Question 5 presents the distribution of range preferences and shows that roughly 90 percent of the respondents would consider a vehicle with a range of between 225 to 300 miles (360 to 480 kilometers) to be acceptable for a vehicle like the F-Cell. This result is consistent with the range preferences of respondents within a previous study conducted with the F-Cell [1].

4.6 Evaluation of Willingness-to-Pay (WTP) Responses

The ride-and-drive clinic offered a forum to query respondents about their WTP for vehicles powered by clean fuel technology. Participants were made aware (if they did not already know) that hydrogen is only as clean as the primary energy sources from which it is made. Survey questions sought to gauge a more generalized personal valuation with respect to clean vehicle technology. The post-clinic survey queried respondents about the purchase price premium they would be willing-to-pay for a vehicle and fuel that were emission free, such as an FCV powered by hydrogen generated from renewable resources. Not surprisingly, there is a practical limit to the degree to which consumers are willing to pay to offset environmental externalities (e.g., air pollution and greenhouse gas emissions). To explore this issue, respondents were asked the purchase price premium that they would pay for an emission-free car similar to their own, as well as their annual operating cost premium. The questions were asked sequentially, leading with the purchase price premium. Figure 4 illustrates the response distribution of both questions.

FIGURE 4 Response distribution to WTP questions



The WTP distribution suggests several points about how consumers value the benefit of clean vehicles and fuels. In terms of purchase price premiums, 50 percent of respondents indicated that they would be willing to pay at least $4,000 in premium over a similar gasoline vehicle. The mode is $5,000, and WTP drops off significantly at greater values. The distribution for the annual operating cost premium suggests that consumers have a higher stated aversion to paying more for operating costs than purchase price premiums. A quarter of respondents stated a WTP of zero, and 75 percent indicated that they would pay no more than $1,000 per year to operate a cleaner vehicle over what they would pay to operate a conventional vehicle. The drop in sample size observed in Question 7 is due to the fact that some respondents interpreted the question in percentages rather than absolute terms (e.g., "10% more"); therefore, their responses were not included in the analysis for this question.

The main objective of assessing WTP is to explore the difference in price and anticipated operating costs that would have to exist between conventional and cleaner vehicle options for consumers to consider such alternatives. Stated WTP, reflecting the responses given here, is distinct from empirically revealed WTP, which is observed through actual behavior. Revealed WTP is preferred when data is obtainable, but stated WTP is useful when the product in question either does not yet exist or is not widely available. Respondents answering these questions are not held to their answers or accountable to actual financial circumstances. Rather the stated WTP offers a proxy as to the range of additional expenses that would be conceptually tolerable to the consumer.

5. CONCLUSIONS

These study results indicate that short-term exposure to FCVs and refueling can improve a variety of impressions among participants. It is encouraging that impressions of FCVs improve with exposure as opposed to decline for the future of FCV acceptance. The positive reaction to hydrogen vehicles is a result that is consistent with many previous studies. Over the past decade, a strong consensus has emerged within the literature that the perceived safety of hydrogen fuel is not a concern for consumer deployment. However, many of the past studies have been conducted in the context of hydrogen vehicles in public transportation, including taxis. This study exploring fuel cell powered passenger cars finds similar results with respect to the safety perception of hydrogen. The results from this study reveal similar reactions as those found in a previous longitudinal study with the same vehicle [1]. In both studies, exposure improved perceptions of safety and found that respondents considered the performance of the vehicle (in terms of acceleration, braking and handling) to be acceptable. The longitudinal respondents faced greater exposure to range limitations, but interestingly, both sets of respondents had similar desires for an acceptable range of the FCV. In addition, both sets of respondents did not consider refueling to be exceptionally difficult. The participants of this study experienced refueling via witnessing the process, while participants of the longitudinal study actively refueled the vehicles themselves [1].

A sizeable minority of 30% of drive-clinic participants entered the study believing that driving with hydrogen was less safe than gasoline. After exposure to the vehicle, this proportion had dropped to 7%. A similar result was found with the safety perception of refueling as more than 40% of participants entering the study considered refueling with hydrogen to be less safe than gasoline. After exposure to refueling, only 13% considered it to be less safe. These trends not only indicate that perceptions of safety may not be a major inhibitor to hydrogen, but that consumer exposure to the hydrogen vehicle environment can help to improve hydrogen acceptance among populations that may harbor reservations. It is important to note this these results exist at a time when the safety record of hydrogen has been demonstrated to be quite good.

Additional results provide potential parameters for station network planning of dedicated fuels outside of gasoline. In the clinic, most respondents were willing to travel five minutes out of their way to find fuel, and a sizeable proportion appeared willing to drive at least 15 minutes. In addition, range considerations indicate that vehicles designed to travel around 250 to 300 miles (400 to 480 kilometers) on one tank would meet the needs of most respondents. Finally, WTP parameters illustrate that consumers might pay more to drive a vehicle that emits less air pollution. The WTP distribution of the stated purchase price premium suggests that half the participants would be willing to pay $4,000 or more for a zero-emission vehicle that is similar to their own. This distribution offers some proxy of the limits that private consumers would place on premiums to purchase a vehicle that eliminates personal air emissions on behalf of the public. Premiums on operating costs are understandably lower. Interestingly, nearly a quarter of all clinic respondents indicated no tolerance for operating cost premiums. Operating cost premiums exceeding $1,000 per year would be unattractive to 75% of the respondents.

An important caveat to the results of this study pertains to the participant population. The sample population within this study is not random, nor is it demographically reflective of the public. This is an obvious limitation to the generalizations that can be made with respect to the survey results and the broader sentiments of the consumer public with respect to hydrogen. The sample population is more reflective of the population of likely early adopters of alternative fuel vehicles.

Overall, we conclude that for dedicated fuels such as hydrogen to succeed, some pre-exposure could assist in educating the public and improving impressions. Adaptation strategies that account for exposing the public to vehicles in a neutral setting may help to expand the potential market. Of course, other techno-economic challenges that address driving range, limited infrastructure, and vehicle cost still must be addressed. The information provided in these studies offers an early proxy of vehicle and infrastructure specifications that would be required for the successful proliferation of FCVs and other dedicated alternative fuel vehicles in the future.

6. ACKNOWLEDGMENTS

The authors would like to thank the California Department of Transportation (Caltrans) and California Partners for Advanced Transit and Highways (PATH) for funding this research. In particular, Randell Iwasaki, Larry Orcutt, Nancy Chinlund, Lindsee Tanimoto, and Marcus Evans of Caltrans made this study possible. Our deep appreciation also goes to Mercedes-Benz Research and Development North America, Inc. for the opportunity to employ the F-Cell in this study. In particular, we thank Eric Larsen, Katerina Tsasis, Michele Ventola, Peter Friebe, Rosario Berretta, and Lora Renz. Thanks also go to Catherine Dunwoody, Juan Contreras, and Chris White at the California Fuel Cell Partnership and to Jaimie Levin and Mallory Nestor at AC Transit for making the hydrogen-fueling demonstrations possible. We also thank our research team at the Transportation Sustainability Research Center and the Innovative Mobility Research group of UC Berkeley for their tireless efforts in supporting the ride-and-drive clinics, including Rachel Finson, Denise Allen, Charlene Kemmerer, Melissa Chung, Keith Brown, Judy Liu, Cynthia Phan, Kate Reimer, Jaako Immonen, Amanda Chou, Dan’l Martinez, and Tagan Blake. Finally, we greatly appreciate the support we received for this project from Steve Campbell of the Institute of Transportation Studies at UC Berkeley. The contents of this paper

reflect the views of the authors who are responsible for the facts and the accuracy of the data presented.

REFERENCES

1. Shaheen, S.A., E. Martin, and T.E. Lipman. Dynamics in Behavioral Response to A Fuel Cell Vehicle Fleet and Hydrogen Fueling Infrastructure. Transportation Research Record: Journal of the Transportation Research Board 2058; (2008): 155-162.

2. O'Garra, T., S. Mourato, L. Garrity, P. Schmidt, A. Beerenwinkel, M. Altmann, D. Hart, C. Graesel, and S. Whitehouse. Is the public willing to pay for hydrogen buses? A comparative study of preferences in four cities. Energy Policy 2007; 35: 3630-3642.

3. Saxe, M., A. Folkesson, and P. Alvors. A follow-up and conclusive repot on the attitude towards hydrogen fuel cell buses in the CUTE project - From passengers in Stockholm to bus operators in Europe. International Journal of Hydrogen Energy 2007; 32: 4295-4305.

4. O'Garra, T., S. Mourato, and P. Peterson. Analysing awareness and acceptability of hydrogen vehicles: A London case study. International Journal of Hydrogen Energy 2005; (30): 649-659.

5. Haraldsson, K., A. Folkesson, M. Saxe, and P. Alvfors. A first report on the attitude towards hydrogen fuel cell buses in Stockholm. International Journal of Hydrogen Energy 2006; (31): 317-325.

6. Thesan, G. and O. Langhelle. Awareness, acceptability and attitudes towards hydrogen vehicles and filling stations: A Greater Stavanger case study and comparisons with London. International Journal of Hydrogen Energy 2008; (33): 5859-5867.

7. Kurani, K., T. Turrentine, and D. Sperling. Demand for Electric Vehicles in Hybrid Households: An Exploratory Analysis. Transport Policy 1994; (1)4: 244-256.

8. Kurani, K., T. Turrentine, and D. Sperling. Testing Electric Vehicle Demand in 'Hybrid Households' using a Reflexive Survey. Transportation Research: Part D 1996; (1)2: 131-150.

9. Turrentine, T.S. and K.S. Kurani. Adapting interactive stated response techniques to a self-completion survey. Transportation 1998; (25)2: 207-222.

10. Golob, T., and J. Gould. Projecting use of Electric Vehicles from Household Vehicle Trials. *Transportation Research: Part B* Vol. 32, No.7, 1998, pp. 441-454.

11. Gould, J., and and T. Golob. Clean Air Forever? A Longitudinal Analysis of Opinions about Air Pollution and Electric Vehicles Transportation Research: Part D 1998; (3)3: 157-169.

12. Gärling, A., 'Paving the way for the electric vehicle', VINNOVA 2001.

13. Altmann, M. and C. Graesal. The Acceptance of Hydrogen Technologies. Report for HyWeb, LBST. 1998.

14. Saxe, M., A. Folkesson, and P. Alvors. Energy system analysis of the fuel cell buses operated in the project: Clean Urban Transport for Europe. Energy 2008; (33): 689 – 711.

15. O'Garra, T. Comparative Analysis of the Impact of the Hydrogen Bus Trials on Public Awareness, Attitudes and Preferences: A Comparative Study of Four Cities. Report for the ACCEPTH2 project, European Commission Fifth Framework Programme. 2005.

16. Mourato, S., B. Saynor, and D. Hart. Greening London's Black Cabs: a Study of Driver Preferences for Fuel Cell Taxis. Energy Policy 2004; (32): 685-695.

17. Ricci, M., P. Bellaby, R. Flynn. What do we know about public perceptions and acceptance of hydrogen? A critical review and new case study evidence. International Journal of Hydrogen Energy 2008; (33): 5868-5880.

18. Hickson, A., A. Phillips, and G. Morales. Public perception related to a hydrogen hybrid internal combustion engine transit bus demonstration and hydrogen fuel. Energy Policy 2007; (35): 2249 - 2255.

19. Heinz, B. and G. Erdmann. Dynamic effects on the acceptance of hydrogen technologies – an international comparison. International Journal of Hydrogen Energy 2008; (33): 3004 - 3008.

20. Zachariah-Wolff, J. and K. Hemmes. Public Acceptance of Hydrogen in the Netherlands: Two Surveys That Demystify Public Views on a Hydrogen Economy. Bulletin of Science, Technology & Society 2006; (26)4: 339-345.

21. Gärling, A. and J. Thøgersen. Marketing of electric vehicles. Business Strategy and the Environment 2001; (10)1:53-65.

22. US Census Bureau. American Community Survey 2007. US Census Bureau, Washington DC. http://www.census.gov/acs/www/