Technical and Attitudinal Response Assessment of Fuel Cell Vehicles in Test Fleet Settings

Timothy Lipman, PhD, † Susan Shaheen, PhD, Elliot Martin

ABSTRACT
Hydrogen fuel cell vehicles are one promising vehicle technology for reducing the long-term environmental and energy-use impacts of personal vehicle use. Depending on how the hydrogen is produced, these vehicles can have very low emissions of air pollutants and greenhouse gases while also avoiding the use of petroleum. This paper reports the findings of real-world research conducted by the University of California, Berkeley (UC Berkeley) to assess the energy use/vehicle fuel economy and behavioral response with actual fuel cell vehicle technology. In the behavioral response study, 50 participants drove Daimler “F-Cell” fuel cell vehicles over a period of several months, and were surveyed periodically in three phases regarding their experiences. The overall response to the vehicles was generally positive, with participants reporting that vehicle performance and safety were typically quite good. In the energy use assessment, vehicle fuel economy was measured in terms of miles per kilogram of hydrogen as assessed through refueling log collection and spreadsheet analysis. The results showed considerable variability, consistent with the diverse usage of the vehicle, with an annual average fuel economy of 48 miles per kilogram of hydrogen.

INTRODUCTION
Hydrogen fuel cell vehicles (FCVs) are being produced in prototype production to explore their technical feasibility and potential to reduce the environmental and energy-use impacts of personal vehicle use. These vehicles are currently in a pre-commercial/prototype testing phase but are expected to be produced in larger numbers in the 2009 to 2010 timeframe and may become more fully commercial around 2012 to 2015. Depending on how the hydrogen is produced, these vehicles can have very low emissions of air pollutants and greenhouse gases while also avoiding the use of petroleum. Fully addressing the environmental and energy problems in the transportation sector will require systemic changes, such as greater use of public transit, as well as modifications to vehicle technology. However, improving vehicle technology is important given the dominance of motor vehicle use in many countries and rising “automobility” around the globe.

The primary motivation for alternative fuel vehicles, such as FCVs, today is a combination of concern about climate change, economic security (for oil import-dependent countries), and other environmental issues such as local air pollution and water and soil pollution. Approximately 14% of greenhouse gas (GHG) emissions come from the transportation sector worldwide (Baumert et al., 2005). GHG emissions from transportation are expected to

† All authors are with the Transportation Sustainability Research Center, Inst. of Transportation Studies, University of California – Berkeley, 2614 Dwight Way, 2nd Floor, MC 1728, Berkeley, CA, 94720-1728 Ph: 510-642-4501 / Email: tlipman@tsrc.berkeley.edu, sashaheen@tsrc.berkeley.edu, elliot@berkeley.edu
increase rapidly over the next few decades. Between 2000 and 2030, the International Energy Agency (IEA) projects that energy use and carbon dioxide (CO₂) emissions will increase by approximately 50% in developed countries (IEA, 2003). Transportation supply and demand management strategies are being explored to reduce GHG emissions, particularly with innovative engine and vehicle technologies. However, user response to the latest of these approaches is not well understood given limited vehicle production and availability. To further the understanding of hydrogen FCVs and infrastructure, University of California, (UC) Berkeley researchers partnered with Daimler and the U.S. Department of Energy to test one FCV in a UC Berkeley fleet setting and to conduct an exploratory driver study of 24 Daimler “F-Cell” vehicles deployed in fleet settings in 2006.

This paper reports the results of some recent UC Berkeley FCV investigations. These include a fueling and energy use analysis and the results of the first FCV behavioral study of its kind – a longitudinal behavioral response study to the use of actual FCVs in the field. In the behavioral response study, 50 participants drove Daimler “F-Cell” FCVs over a period of several months, and were surveyed periodically in three phases regarding their experiences. The overall response to the vehicles was generally positive, with participants reporting that vehicle performance and safety were typically quite good. Vehicle driving range – only about 160 kilometers with these vehicle prototypes – was the main drawback indicated by study participants.

**VEHICLE REFUELING AND ENERGY USE ASSESSMENT**

The Daimler F-Cell vehicle is an FCV with a hybridized fuel cell/battery power system that is linked to an electronic motor/power controller propulsion system. This differs from gasoline-electric hybrids where the propulsion system is hybridized. The F-Cell employs a 72-kilowatt (97 horsepower) proton-exchange membrane fuel cell system, a 1.4-kilowatt hour and 15-kilowatt (20 horsepower) nickel-metal hydride battery, an electric motor with torque rated at 210 Newton-meters (156 foot-pounds), and approximately two kilograms of gaseous hydrogen stored at a maximum of 350 bar of pressure (5000 pounds per square inch). The vehicle has a rated 160-kilometer range and a top speed of approximately 135 kilometers per hour.

Daimler has deployed a total of approximately 100 FCVs worldwide. About 25 of the F-Cell vehicles were placed in California with participating for-profit companies, non-profits, governmental agencies, and universities, including one that was delivered to UC Berkeley. The demonstration of the vehicles is supported in part by a five-year U.S. Department of Energy program titled: “Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project.”

Records taken during vehicle refueling events were used to analyze the energy use of the vehicle during 2006. Data and trends shown in Figures 1 through 3 show that: 1) the users experienced fill percentages of just under 90% throughout the study; 2) refilled somewhat less over time per fill; and 3) experienced fluctuating “miles per kilogram of hydrogen” fuel economy levels, apparently depending on the nature of the use and magnified by the relatively small fuel tank of the F-Cell.
The results shown in Figure 1 show that fill percentages averaged just under 90%, with a range from 70 to 95%. Unlike vehicles that are fueled with a liquid fuel, FCVs that run on compressed hydrogen require a storage pressure at the refueling station to be significantly higher than the onboard storage pressure to achieve a complete or nearly complete fill. The F-Cell used at UC Berkeley was primarily fueled at a hydrogen station in Richmond, California that stores hydrogen at a maximum pressure approximately equal to the onboard hydrogen storage pressure. This means that at best the hydrogen fill percentage would be in the low 90% range. Furthermore, the station hydrogen storage is relatively small, meaning that if a vehicle was refueled soon before the F-Cell was refueled, the station pressure could be lower than maximum and the fill level would subsequently be lower as well.
Figure 2 shows a wide variation in hydrogen fueling in terms of kilograms of hydrogen added to the vehicle. The trend shown is for a decrease in the amount of fuel added per fueling episode. The authors hypothesize that this was due in part to a transition in the use of the vehicle, where in the latter part of 2006 the vehicle was used more for long-distance commuting and to attend meetings some distance away, and less for shorter errands. This usage pattern necessitated “topping off” the fuel tank more frequently than was previously the case, to have a full tank for the planned trip, rather than waiting until the fuel level was low before refueling, as would have been possible if the vehicle was used for mostly shorter trips. This “topping off” behavior was necessary due to the relatively short driving range of the F-Cell.

Figure 3: Variation in per-tank estimated miles per kilogram of hydrogen in UCB fleet setting

Figure 3 shows the calculated fuel economy of the vehicle, in terms of miles traveled per kilogram of hydrogen, based on fueling logs filled out by the vehicle drivers. The calculated fuel economy typically ranges from 30 miles per kilogram to 70 miles per kilogram, with an average value of 48 miles per kilogram and a few outlying values. This fuel economy is roughly 50% higher than the gasoline version of the Daimler A-Class vehicle, on a “tank to wheels” basis. The 1.7-liter engine gasoline-powered version of the standard A-Class is rated with a fuel economy of 6.6 liters per 100 kilometers, but in “real world” driving likely achieves more like 7.5 liters of fuel use per 100 kilometers. The average value of 48 miles per kilogram of hydrogen measured with the F-Cell is equivalent to about 4.9 liters of gasoline per 100 miles on an energy basis.

---

2 A kilogram of hydrogen has approximately the same energy content as a gallon of gasoline, so miles per kilogram of hydrogen are analogous to miles per gallon of gasoline on an energy basis.
ATTITUINAL RESPONSE ASSESSMENT
This paper also presents some of the results of a longitudinal survey of the attitudes and perceptions towards hydrogen and alternative fuel vehicles of F-Cell fleet drivers. The study included three survey phases to examine potential trends in F-Cell driver perceptions over a seven-month period. The participant sample was drawn from for-profit companies, governmental agencies, non-profits, and universities in California and Michigan where the vehicles were placed for study. The authors examined safety perceptions, attitudes toward limited driving range, and vehicle performance. The study investigated various hypotheses related to hydrogen acceptance, including those related to changes in perception with greater exposure to the vehicle and refueling, and differences among respondents based on their relative environmental views and “early adopter” tendencies.

As hydrogen passenger vehicles have only recently been introduced to the public to drive and refuel, there is a relatively short research history focused on the observed consumer response to hydrogen as a transportation fuel. Few studies to date have explored the direct interaction of consumers with a fleet of hydrogen personal vehicles over an extended time period. For a review of the few studies that have been conducted, and for more details of the behavioral response study summarized here, please see Shaheen et al., 2008.

The survey population for the 24 F-Cell vehicle behavioral response study in California and Michigan in 2006 included an initial sample pool of approximately 143 participants. The subjects were drawn from for-profit companies in California and Michigan, where 10 vehicles were placed (one of the 10 vehicles was deployed in Michigan), and at governmental agencies, non-profits, and universities in California and Michigan, where another 14 vehicles were deployed (one of the 14 vehicles was located in Michigan). Participant criteria for the F-Cell driver fleet study were established to ensure that drivers had driven the vehicles enough during the course of the study to form an opinion about the F-Cell and hydrogen fueling (but note that not all participants fueled the vehicles). Study criteria required that qualifying participants: 1) drove the F-Cell once or more a month, 2) drove it at least 65 kilometers per month, and 3) were willing to complete the three survey phases.

Many of the initial sample pool (143 individuals) did not meet the study criteria. During the first survey phase, a total of 65 drivers from 15 public and private sector organizations were recruited on a voluntary basis (13 of the participant organizations were located in California and two in Michigan). Not surprisingly, there was some attrition over the seven-month study. Fifty-four participants completed two of the three survey phases, and forty-nine completed all three phases. An initial and final response rate of 45.5% and 34.3%, respectively, was tabulated, based on the total participant pool.

Subjects were recruited with an email solicitation to participate in the study. Volunteer participants were asked to complete and return a study consent form and then were issued a participant identification number that allowed them to complete the first questionnaire. Respondents received a small incentive (e.g., F-Cell coffee mug) after completing each study questionnaire.
**Longitudinal Survey Design**

The longitudinal survey was designed to assess general demographic characteristics of the F-Cell drivers, psychographic characteristics such as their stated level of environmental concern and willingness to experiment with new technologies, as well as their specific response to various F-Cell aspects (e.g., vehicle performance).

The first survey phase consisted of four main categories of questions: 1) function of driver in company (e.g., management, staff, administrative, etc.); 2) experience with alternative fuel vehicles; 3) psychographics (environmental perception and technology adoption among participants); and 4) acceptance of the F-Cell and hydrogen fueling. Psychographic and F-Cell/hydrogen acceptance questions were asked on a five-point “Likert” scale. The authors administered the initial survey in May 2006. The second and third survey phases were shorter and only addressed the response to the F-Cell vehicle and fueling; they were completed in September and November 2006, respectively. The purpose of the second and third phase surveys was to determine to what extent drivers’ views of the FCV and fueling changed over time as they gained more experience.

**Key Results of Longitudinal Behavioral Study**

Some key results of the behavioral response study are presented in Figures 4 through 10.

Figure 4 shows that the overall impression of the F-Cell was rated between “good” and “very good” by the study participants, on average, and was fairly constant throughout the study. The overall impression improved slightly from phase 1 to 2, and then decreased slightly from phase 2 to 3.

**Figure 4: Trend in Response for Overall Impression of the F-Cell**

Figure 5 shows that drivers generally agreed with the statement that they felt safe driving the vehicles, and that this perception of safety increased slightly over the period of the study. A slight increase in this perception was detected between phase 1 and 2, and again between phase 2 and 3.
Figure 5: Trend in Response to “I Feel Safe Driving the F-Cell”

Figure 6 shows that drivers seemed more inclined over time to assess their safety within the F-Cell as comparable to the safety that they feel with a gasoline vehicle. At the end of the study, the average response was just over 4.0, meaning that drivers on balance agreed with the statement that they felt equally safe in the hydrogen vehicle compared with a gasoline vehicle.

Figure 6: Trend in Response to “I Feel Equally Safe in a Hydrogen Vehicle Compared to a Gasoline Vehicle”
Perceptions of refueling safety were positive and relatively stable, as shown in Figure 7, and respondents generally disagreed that refueling was “difficult.” The top line in the figure illustrates the stable trend of feeling safe while refueling, whereas the bottom line illustrates that there is a general disagreement with the statement “Refueling the F-Cell is difficult.”

![Figure 7: Trend in Response With Regard to Refueling Safety](image)

Figure 8 shows a disaggregated assessment of vehicle performance, compared with the overall assessment shown in Figure 4. As shown in the figure, braking, handling, and acceleration where generally rated to be good, with braking performance receiving the highest scores (between “good” and “excellent”), and acceleration receiving the lowest scores of the three categories (between “neutral” and “good”). The responses were relatively stable, with a slight up-tick in the middle of the study with braking and handling and a slight overall trend upward with acceleration.
The study respondents were generally dissatisfied with the F-Cell driving range of approximately 160 kilometers (100 miles), but Figure 9 shows that they suggest that a range of approximately 320 kilometers (200 miles) would be adequate. However, we caution that the vehicles were used in a mix of fleet and personal uses (some but not all drivers were allowed to take the vehicle home on evenings or weekends) and this finding should be interpreted with caution. The expression of the ~320-kilometer driving range being adequate may be more applicable to fleet vehicles than personal vehicles, as this was the dominant use for the vehicles in this study. However, we find this result interesting nonetheless, as a 300-400 kilometer driving range may be much easier to achieve for FCVs given the challenges of onboard hydrogen storage than the 500-600 kilometer driving range that some gasoline vehicles achieve.
Environmental Views and Hydrogen Acceptance

As noted above, the authors explored several hypotheses as part of the behavioral response study. For details of the assessments of the various hypotheses, please see Shaheen et al., 2008. Here we report on the results of one hypothesis investigation, targeted at understanding whether people who had strong environmental views would react to the F-Cell in a manner that was different from other participants. Several questions within the survey probed participants’ environmental sentiments. The question that elicited the greatest diversity in response distinguished those who projected a willingness to change personal behavior for environmental reasons. Those who held stronger environmental views were classified by whether they answered the question “I am willing to reduce my personal auto use to improve transportation and air quality” with “Agree” or “Strongly Agree.”

The results from analysis of these data indicate that enduring respondents who were classified as environmentally sensitive did not respond to the F-Cell in a manner that was different enough from other respondents to be considered statistically significant. For example, the following table illustrates the results from the Mann-Whitney test conducted on the question of safety acceptance of the F-Cell. The asymmetrical significance values are all over 0.20, whereas values of 0.05 or less would be needed to indicate statistical significance at the 95% confidence level. During all three survey phases, those who were characterized as more environmentally sensitive than others did not demonstrate a statistically significant difference in accepting the F-Cell as being at least as safe as a gasoline vehicle.

---

3 This report is available at http://www.imr.berkeley.edu
CONCLUSIONS
This paper presents the results of technical and behavioral assessments of FCVs and supporting hydrogen infrastructure. In 2006, UC Berkeley researchers, in partnership with Daimler, examined the energy use/refueling and behavioral response of “F-Cell” FCV users. The vehicles were made available to UC Berkeley and other host sites as part of a U.S. Department of Energy program to further the development of FCVs as a long-term strategy to reduce motor vehicle petroleum use and environmental impacts.

The energy use and refueling assessment showed that typical fill percentages for the F-Cell operated by UC Berkeley were just under 90% on average, with a range from about 70% to 95%. The lower values were due to operational issues with one of the hydrogen stations used for refueling, where the storage pressure was sometimes lower than its maximum pressure and the fill percentage suffered as a result. The amount of hydrogen added to the vehicle with each refueling event decreased on average over the course of 2006, likely because some drivers felt the need to “top off” the vehicle prior to taking a trip that used most of the maximum available driving range of the vehicle (approximately 160 kilometers). Finally, the average fuel economy of the vehicle was calculated to be about 48 miles per kilogram of hydrogen, with significant variation due to varying driving patterns. This is approximately 50% higher than the real-world fuel economy of the gasoline version of the A-Class, on a “tank to wheels” energy comparison basis.

In the behavioral response study, 65 participants to the F-Cell vehicle and hydrogen fueling over a seven-month period. While there are several limitations to the study (e.g., sample size, self-selection, and generalizability), this does not prevent the use of the dataset to obtain insights into the drivers’ response to the vehicle and fueling. Overall, the F-Cell vehicles were well received by study participants. Key findings include that individuals experienced with alternative fuels express a greater concern for the environment, have higher education levels, and higher incomes. In addition, higher levels of hydrogen exposure (in terms of use and for some participants refueling of the FCVs) are correlated with greater hydrogen acceptance in terms of safety. Environmental consciousness was found to have a positive impact on the impression of respondents initially, but by the end of the study, those with the most favorable impression of the vehicle did not show distinctions in environmental attitude.

Not surprisingly, the limited range and fueling infrastructure posed restrictions on participant behavior. Driving range was considered a limitation, and this lowered the utility of the car for practical purposes. The average desired range was about 322 kilometers throughout the study.
Alternative designs that improve the range by even 50% could help to bring the F-Cell within reach of the mean desired range indicated by survey respondents. Another important insight of the study centers on refueling. While fueling infrastructure remains a challenge, the refueling process was not challenging to those who tried it. Among the participants who actually experienced fueling, an ability to adapt to a new fuel and infrastructure was demonstrated. However, this could reflect some self-selection bias, and it is possible that non-participants of fueling included those who were fearful of this process.

Participants felt safer with the vehicle throughout the study. Early adopters were found to feel safer driving the F-Cell than later adopters. Respondents generally felt safe refueling the F-Cell. Furthermore, as experience with the F-Cell increased, participants felt increasingly safer with the F-Cell.

Furthermore, the F-Cell was considered easy to operate. Vehicle braking was rated highest overall among the F-Cell performance features, followed by handling and then acceleration. Lower vehicle acceleration, however, was a safety concern in a few situations. With the exception of handling, the average assessment of vehicle performance features improved over the course of the study.

We conclude by noting the progress made with FCV technical development over the past fifteen years, where prototype vehicles with good performance are now being tested under real-world conditions. Significant hurdles to FCV commercialization still remain, however, including the cost and durability of fuel cell technology, the development of hydrogen refueling infrastructure, and the challenge on greater onboard hydrogen storage. As these technical and economic challenges are addressed, additional research needs include further assessments of the attitudinal and behavioral response to fuel cell vehicles and hydrogen fuel, and continued efforts to develop more efficient and environmentally desirable methods of hydrogen production and distribution.

ACKNOWLEDGEMENTS
The authors would like to acknowledge Mercedes-Benz Research and Development North America (RDNA) for the opportunity to participate in the F-Cell fleet study as a host organization, and for their generous support of this research. We particularly thank Michele Ventola, Eric Larsen, Jeffra Lyczko, Peter Friebe, Lora Renz, and Taylor Roche. Their assistance with the planning, administration, and conduct of this project was invaluable. Thanks also go to our colleagues at California Partners for Advanced Transit and Highways, who supported the research effort, and all of the participants in the F-Cell fleet study. Finally, we greatly appreciate the support we received for this project from Steve Campbell of the Institute of Transportation Studies at the University of California, 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
