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U.S. Fuel Cell Vehicle Learning Demonstration: Status Update and Early Second-Generation Vehicle Results

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Abstract

The National Learning Demonstration is conducting an integrated field validation to examine the performance of fuel cell vehicles and their supporting hydrogen infrastructure. NREL has now analyzed data from over four years of the six-year project, including 140 vehicles and 20 refueling stations, resulting in over 346,000 vehicle trips across 1,900,000 miles and over 90,000 kg of hydrogen produced or dispensed. Public analytical results from this project are presented in the form of composite data products (CDPs), which aggregate individual performance to protect the intellectual property and the identity of each company, while still publishing overall status and progress. In the spring of 2009, the National Renewable Energy Laboratory (NREL) published the latest set of CDPs, making a total of 60 individual results and many new analyses publicly available. Highlights from the vehicle results include meeting the 250-mile driving range program milestone with 700-bar hydrogen storage tanks, stacks that have demonstrated almost 2,000 hours without repair, maintenance categorization from the powertrain and fuel cell system, and fuel cell stack usage data on trips/hour and time at various voltage levels. Infrastructure results include well-to-wheel greenhouse gas emissions calculated using actual fuel economy and production efficiency and a deep-dive into refueling rates. The project is continuing into 2010, with a significant number of vehicles planned for daily use through the end of the project. Results will continue to be published by NREL every six months and a final report is planned at the end of the project.

Keywords: hydrogen, PEM fuel cell, car, demonstration, ZEV

1 Introduction

Hydrogen fuel cell vehicles (FCVs) are being developed and tested for their potential as commercially viable and highly efficient zero-tailpipe-emission vehicles. Using hydrogen fuel and high-efficiency fuel cell vehicles provides environmental and fuel feedstock diversity benefits to the United States. Hydrogen can be derived from a mixture of renewable sources, natural gas, biomass, coal, and nuclear energy, enabling the United States to reduce emissions and decrease its dependence on foreign oil. Numerous technical barriers remain before hydrogen fuel cell vehicles are commercially viable. Significant resources from private industry and government are being devoted to overcoming these barriers.

The "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," also known as the Learning Demonstration, is a U.S. Department of Energy (DOE) project started in 2004. The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. The DOE's National Renewable Energy Laboratory (NREL) has now analyzed data from over four years of the six-year project. During this time, over 140 vehicles have been deployed, 20 project refueling stations have been placed in use, and no fundamental safety issues have been identified. We have analyzed data from over 346,000 individual vehicle trips across 1,900,000 miles and over 90,000 kg hydrogen produced or dispensed. Public analytical results from this project are in the form of composite data products (CDPs), which aggregate individual performance to protect the intellectual property and the identity of each company, while still publishing overall status and progress [1].

2 Auto Industry and Refueling Infrastructure Partners

Automotive original equipment manufacturers (OEMs) are leading three of the four project teams, and an energy provider is leading the fourth. The major companies making up the four teams are:

- Chevron and Hyundai-Kia
- Chrysler and BP
- Ford Motor Company and BP
- General Motors and Shell.

Figure 1 shows the teaming arrangement of the four teams along with their first- and second-generation fuel cell vehicles. In addition to data from the four Learning Demonstration teams, data from another DOE project called the California Hydrogen Infrastructure Project (CHIP) has also been analyzed and included in the infrastructure results to further broaden the available data set. Figure 2 shows the five regions of the United States on which this project is focused (green circles) along with other stations (white triangles). The total number of hydrogen stations in the U.S. is currently 58; one-third are from this project.

Figure 1: Four Learning Demo project teams and their two generations of vehicles.

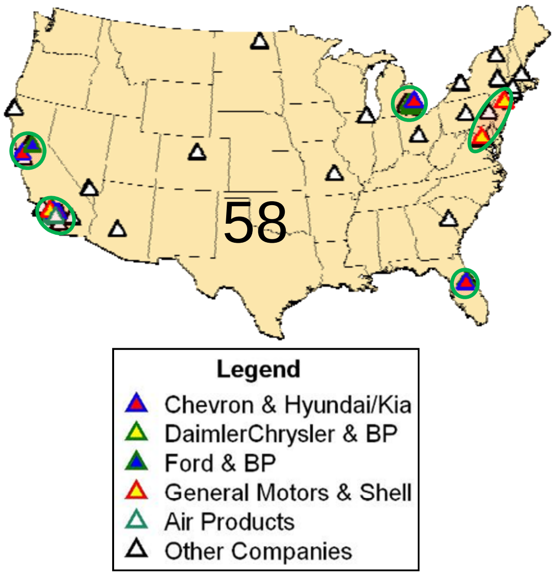


Figure 2: Hydrogen refueling stations in the US; the five project regions circled in green.

3 Data Analysis Approach

NREL's approach to accomplishing the Learning Demonstration's objectives is structured around a highly collaborative relationship with each of the industry teams. We are receiving raw technical data on both the hydrogen vehicles and refueling infrastructure that allows us to perform unique and valuable analyses across multiple companies and technologies. Our primary objectives are to feed the current technical challenges and opportunities back into DOE's Hydrogen Fuel Cells and Infrastructure Technology (HFCIT) research and development program and assess the current status and progress toward targets.

To protect the commercial value of these data for each company, we established the Hydrogen Secure Data Center (HSDC) to house the data and perform our analyses. To ensure value is fed back to the hydrogen community, we publish CDPs twice a year at technical conferences and in journals [2-3]. These CDPs report on the progress of the technology and the project, focusing on the most significant results. Additional CDPs are conceived as trends and results of interest are identified. We also provide each individual company with detailed analytical results from their data to maximize the industry benefit from NREL's analysis work and obtain feedback on our methodologies. These individual results are not made available to the public.

To process such a large data set (second-by-second data from over 346,000 vehicle trips) we have created a specialized analysis tool at NREL called the Fleet Analysis Tool (FAT). This tool enables us to convert the data into a common MATLAB format, perform all of the predefined analyses, and then study the results graphically. The tool is unique in that it lets us quickly compare data from within a team (stack to stack) or between teams. It also is the mechanism by which we create our CDPs, which pull individual results from each team into aggregate results.

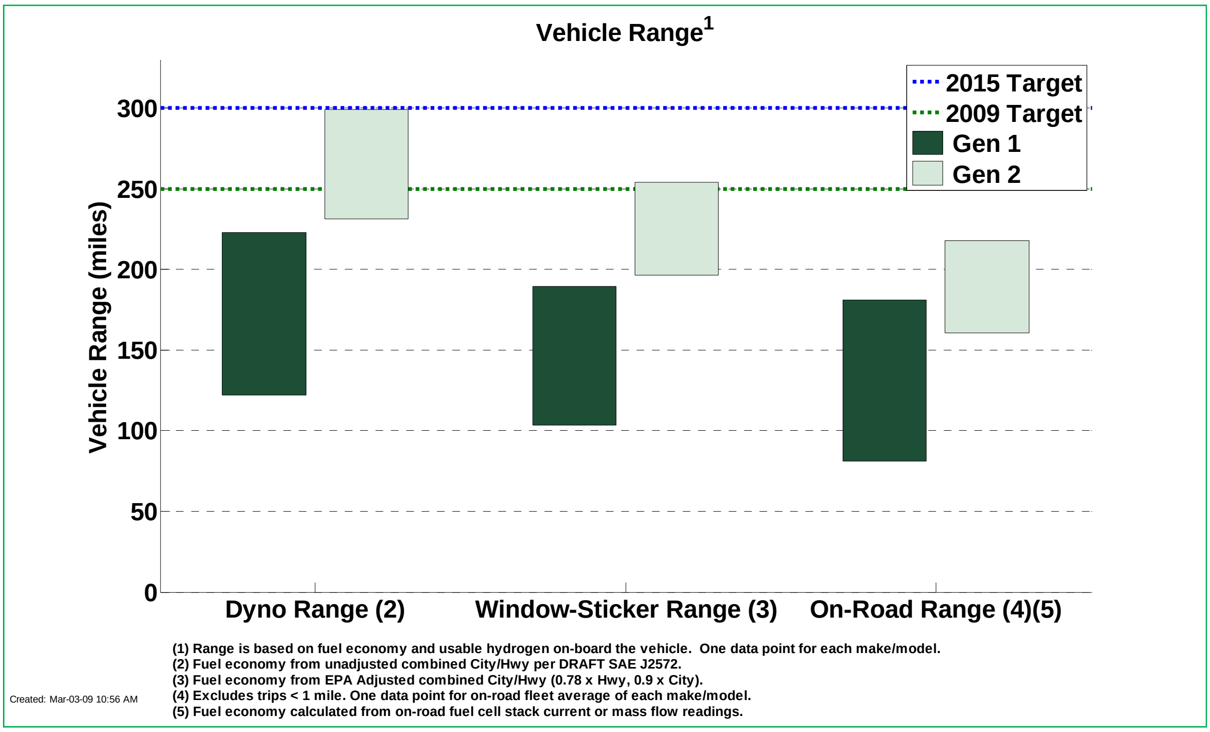
4 Fuel Cell Vehicle Results

4.1 Fuel Economy

The ranges of fuel economy between the first-generation and second-generation vehicles did not significantly change. For example, the range of fuel economy for first-generation vehicles (Environmental Protection Agency window-sticker values) was between 42 and 57 miles/kg, whereas the range for second-generation vehicles was 43 to 58 miles/kg. All of the second-generation vehicles were still conversions of conventional internal combustion engine (ICE) platforms, and could not benefit from the "designed around hydrogen" synergies that some of the more recent prototypes and demonstration vehicles have employed.

4.2 Driving Range

Driving range has significantly improved between the first-generation and the second-generation vehicles (Figure 3). This is due to the switch to 700-bar hydrogen storage tanks from 350-bar tanks. We can see that the window-sticker driving range increased from 103-190 miles up to 196-254 miles. This exceeded DOE's 2009 target of 250 miles and met a major project milestone. Note that future generations of vehicles that are designed around hydrogen should be able to meet the 2015 target of a 300 mile range.

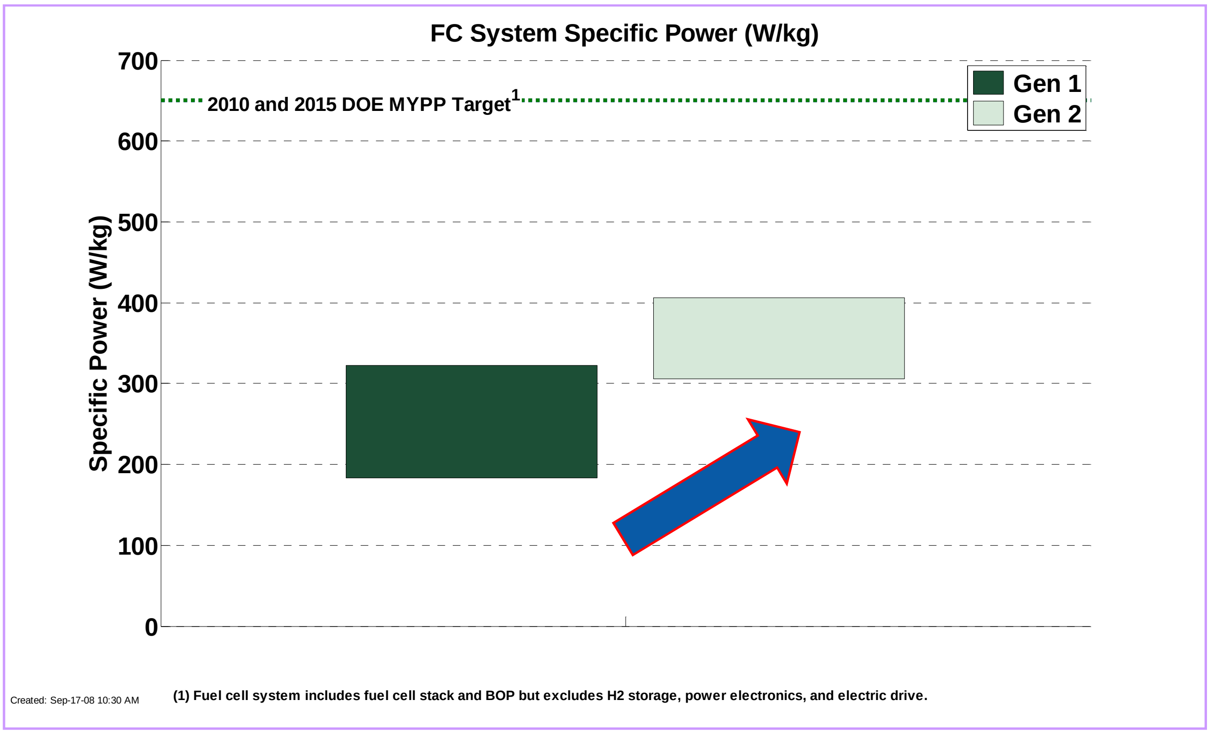


(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.

Figure 3: Comparison of driving range between first-generation (dark green) and second-generation (light green) vehicles.

4.3 Fuel Cell System Specific Power

One measure of the capability of a fuel cell system is its specific power, calculated as the ratio of its peak power divided by the system mass (Figure 4). Consistent with DOE's definition, the fuel cell system includes fuel cell stack and balance of plant, but excludes the hydrogen storage, power electronics, and electric drive.



(1) Fuel cell system includes fuel cell stack and BOP but excludes H2 storage, power electronics, and electric drive.

Figure 4: Improvement in specific power (W/kg) between fuel cell generations.

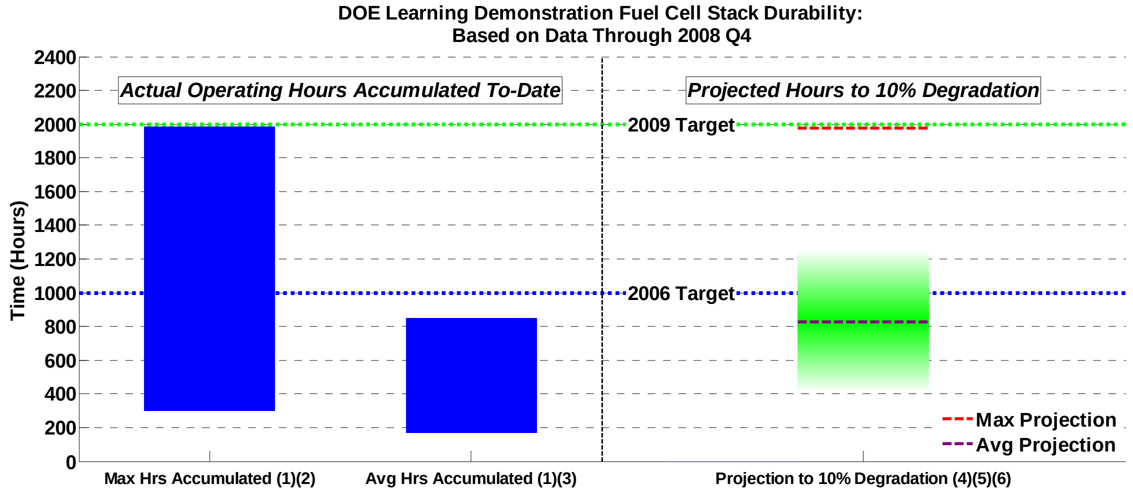
The specific power of first-generation fuel cell systems in this project ranged from around 200-300 W/kg, whereas second generation systems increased to 300-400 W/kg. This is a significant improvement and shows a steady climb on the path toward DOE's 2010 and 2015 target of 650 W/kg. It should be noted that NREL analyzed the fuel cell system power density (W/L), but it stayed relatively flat between generations. This may be because second-generation systems are all freeze capable and freeze tolerance may require more volume.

4.4 Fuel Cell Durability

One of this project's key metrics is fuel cell system durability. Fuel cell stacks will need roughly a 5,000 hour life to enter the market for light-duty vehicles. For this demonstration project, targets were set by DOE at 1,000 hours in 2006 for first-generation stacks and 2,000 hours in 2009 for second-generation stacks. Results were first published from this project by NREL in the fall of 2006. These results were relatively preliminary because most stacks at that time only had a few hundred hours of operation or fewer accumulated on-road. Since DOE's target for 2006 was 1,000 hours, NREL developed a methodology for projecting the gradual degradation of the voltage based on the data received to date to allow a comparison. This involved creating periodic fuel cell polarization curve fits from the on-road stack voltage and current data and calculating the voltage under high current [4]. This enabled us to track the gradual degradation of the stacks with time and create a linear fit through each team's data for all of their stacks. We then compared these results to the first-generation target of 1,000 hours for 2006.

In the past two and a half years, many more hours have been accumulated on the fuel cell stacks (first generation), and NREL has tabulated the actual number of hours. The range of fleet averages is ~200 to 850 hours, with the range of fleet maximums spanning ~300 to almost 2,000 hours (Figure 5). With the additional data we have received, we found that the accuracy of our projection of the 10% voltage degradation time could be improved by using a segmented-linear fit to account for the more rapid degradation that occurs within the first few hundred hours. Additionally, we made a change from doing a single fit of all stacks on one graph to doing fits of each individual stack and then weighting these individual projections to come up with a single number for each team. This new methodology was implemented in the fall of 2008 and refined for the spring 2009 results.

The projected time to 10% fuel cell stack voltage degradation from the four teams using the segmented-linear technique had an average of 828 hours with a high projection of 1,977 hours from



(1) Range bars created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.
(2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
(3) Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM's fleet.
(4) Projection using on-road data -- degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM's end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure.
(5) Using one nominal projection per OEM: "Max Projection" = highest nominal projection, "Avg Projection" = average nominal projection. The shaded green bar represents an engineering judgment of the uncertainty on the "Avg Projection" due to data and methodology limitations. Projections will change as additional data are accumulated.
(6) Projection method was modified beginning with 2008 Q2 data.

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Figure 5: First-generation stack operating hours and projected time to 10% voltage drop.

one team, surpassing the 1,000-hour DOE target for first-generation technology. Note that the 10% criterion, which is used for assessing progress toward DOE targets, may differ from the OEM's end-of-life criterion and does not address "catastrophic" failures such as membrane failure. The second-generation stacks introduced in this project in 2008 will be compared to the 2,000-hour target for 2009 in September.

4.5 Vehicle Maintenance Data

After four years of gathering operational data, we now have enough data (9,357 maintenance events for a total of 10,216 hours) to identify some trends. Figure 6 shows four pie charts. The top two show the maintenance for major parts of the vehicle system, including the fuel cell system, powertrain, battery, and vehicle (non-powertrain), with the left pie being the percentage of maintenance events attributed to these four parts of the vehicle and the right pie being the percentage of labor hours. We see that the fuel cell system is responsible for only 34% of the maintenance events, which take 49% of the time to repair. Non-powertrain maintenance is responsible for 57% of the maintenance events but only 24% of the time.

Looking at the bottom of this same figure, we see the detailed breakdown of maintenance for the fuel cell system (the green slices in the top two graphs). The surprising result is that the fuel cell stack is only the fifth most frequent maintenance trigger for parts of the fuel cell system, but it is responsible for 31% of the labor. Thermal management, the air system, controls, electronics, sensors, and the fuel system all triggered more maintenance events than the stack. This indicates that the fuel cell system supplier base needs to improve the durability and reliability of their parts of the system. Orders for higher quantities of parts as vehicle introduction increases should help drive simplified designs and improved quality.

4.6 Fuel Cell Stack Usage Statistics

4.6.1 Fuel Cell Stack Duty Cycle

Because this project has such a wealth of detailed stack operation data, we had several requests to provide more aggregate information publicly about the usage of the stacks. The first of these three results is the stack duty cycle (Figure 7). We took every second of operation from all stacks (first and second generation) and binned them in 5% increments as a function of the maximum fuel cell stack voltage. 100% stack voltage, therefore is roughly open-circuit and 50% is under heavy load. We superimposed on top of that the amount of time that the stack was also at low current (blue bars). We found that the stack is at open-circuit about 15% of the time and is at low current about 40% of the time. The stack is at <70% of maximum voltage only about 17% of the time.

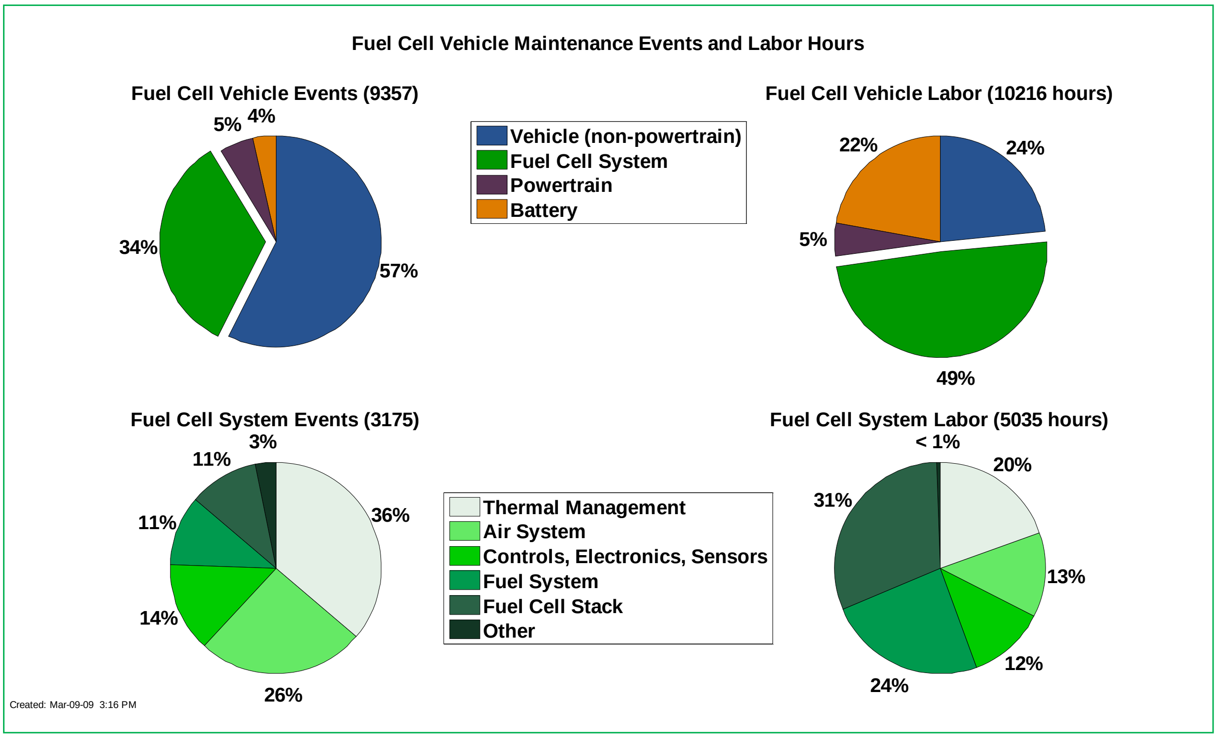
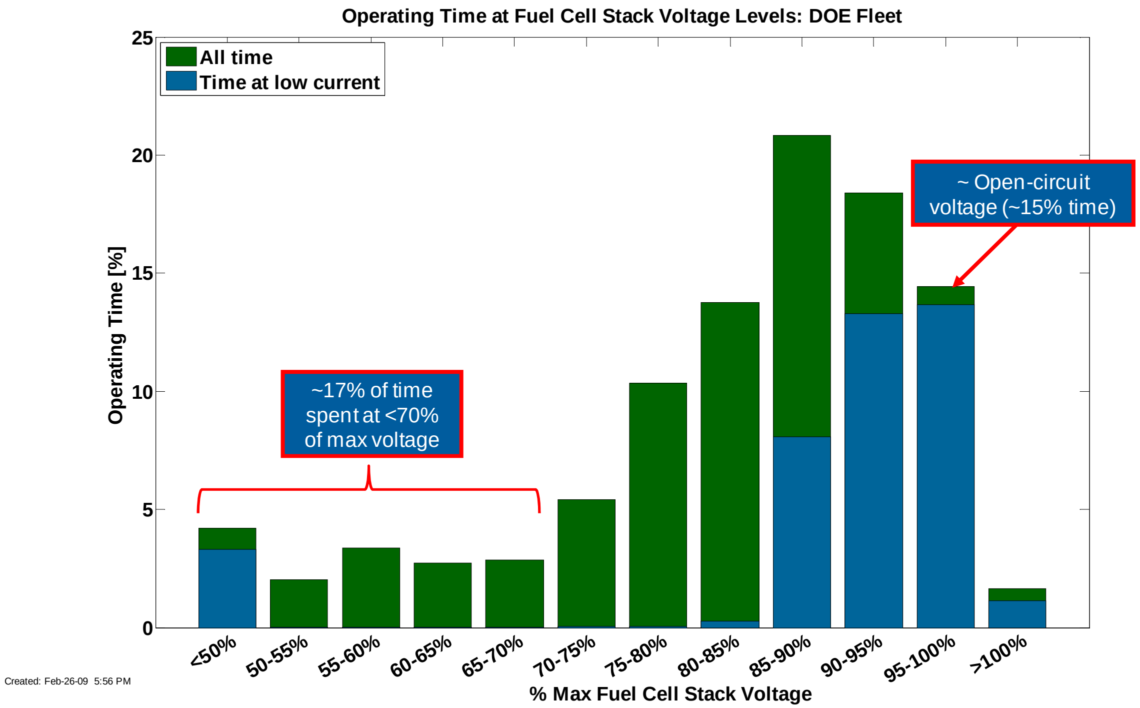


Figure 6: Fuel cell vehicle maintenance events and labor hours.

4.6.2 Fuel Cell Stack Trips per Hour

The next two CDPs show the number of stack trips per hour. Since degradation mechanisms are different during start-up, shutdown, and normal operation, knowing how many trips per hour is important for fuel cell developers in establishing appropriate test protocols for durability testing. Figure 8 shows a histogram of fuel cell stack trips per hour, broken up into 1-trip/hour bins. From this graph it is clear that ~4 trips/hour is a representative average number from our fleet, and the data are normally distributed about that mean. Figure 9 shows the same metric (trips/hour) as a function of stack operating hours.


Operating Time at Fuel Cell Stack Voltage Levels: DOE Fleet

~ Open-circuit voltage (~15% time)

~17% of time spent at <70% of max voltage

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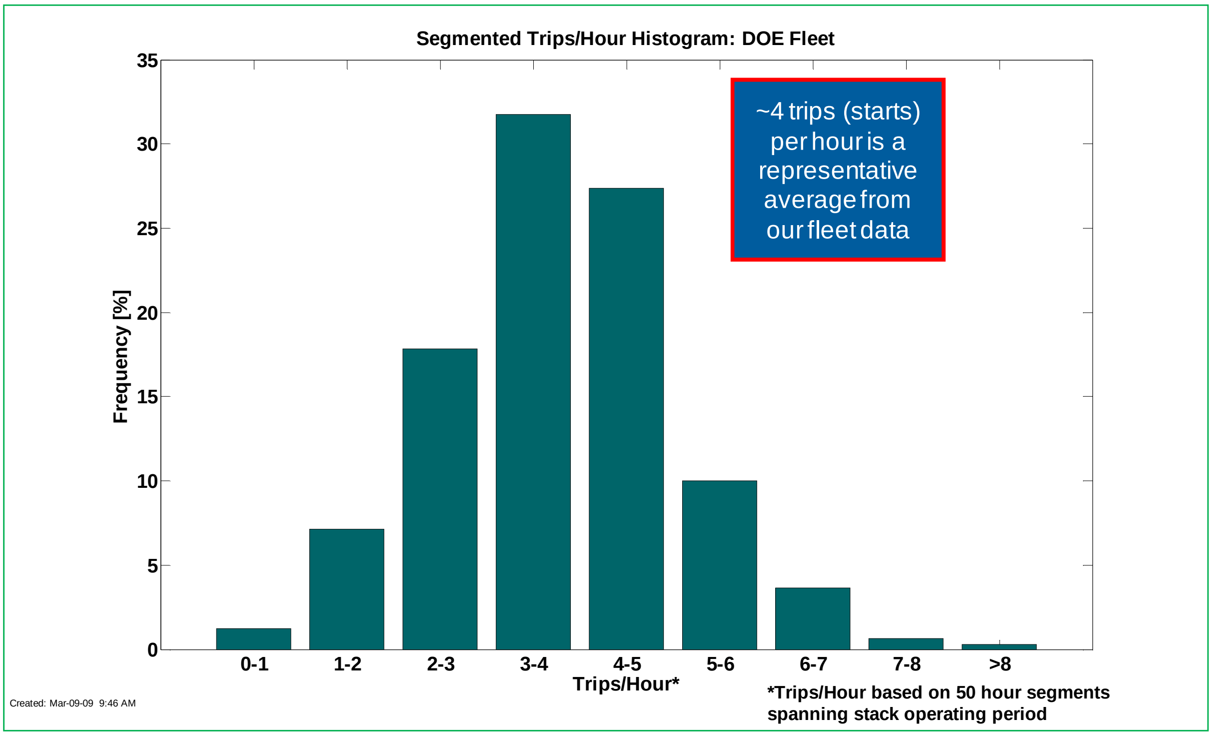
Figure 7: Fuel cell stack duty cycle; time at various voltage levels.


Segmented Trips/Hour Histogram: DOE Fleet

~4 trips (starts) per hour is a representative average from our fleet data

*Trips/Hour based on 50 hour segments spanning stack operating period

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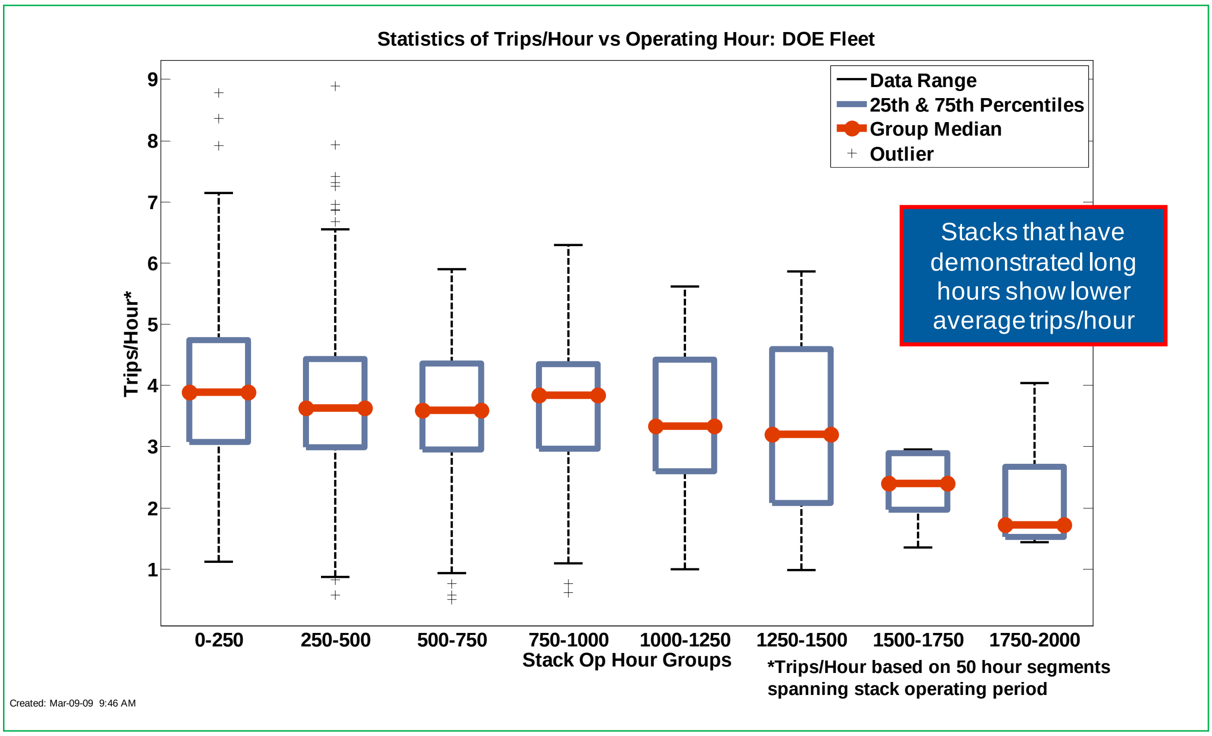
Figure 8: Fuel cell stack trips/hour histogram.



Stacks that have demonstrated long hours show lower average trips/hour

*Trips/Hour based on 50 hour segments spanning stack operating period

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Figure 9: Fuel cell stack average trips/hour as a function of stack operating hour.

We learn from this that the stacks that have demonstrated long hours also show a lower average trips/hour. We will have to wait until more data are accumulated to determine if having a lower number of trips/hour has a causal relationship to durability, as this graph might imply.

5 Infrastructure Results

5.1 Refueling Rate Investigation

Hydrogen vehicle refueling needs to be as similar as possible to conventional vehicle refueling to allow an easier commercial market introduction. Over 16,000 refueling events have been analyzed to date, and the refueling amount, time, and rate have been quantified. The average time to refuel was 3.3 minutes with 87% of the refueling events taking less than five minutes. The average amount per fill was 2.18 kg, reflecting both the limited storage capacity of these vehicles (~4 kg max) and peoples' comfort with letting the fuel gauge get close to empty. DOE's near-term target refueling rate is 1 kg/minute, and these Learning Demonstration results indicate an average of 0.78 kg/min, with 24% of the refueling events exceeding 1 kg/minute (Figure 10). Therefore, we can conclude that high-pressure gas storage is approaching adequate refueling times and rates for consumers; however, the challenge is still in packaging enough high-pressure hydrogen onboard to provide adequate range, or finding alternate advanced hydrogen storage materials that can replace the need for high-pressure tanks.

The refueling histogram just discussed included all types of refueling events, including communication, non-communication, 350 bar, and 700 bar pressures. Communication fills allow the refueling station to "talk" to the vehicle and monitor the tank's temperature and pressure to avoid overheating. There has been much interest from industry and from the codes and standards community about the potential for communication fills to occur at a higher rate and with a more complete fill. Figure 11 shows two curves: the red curve is a spline fit to the histogram for non-communication fills while the blue curve represents the communication fills. The center part of the graph shows a similar rate of fill for the communication and non-communication fills; however the communication fills are capable of having a higher fill rate (up to around 1.7 kg/min). There is also a group of vehicle/station combinations still doing non-communication fills at the slower rate of ~0.2 kg/min on the left portion of the graph, shaded in red. This rate of fill was established many years ago in California to provide a conservative and safe approach for refueling vehicles before much real-world experience had been gained.

When the data is analyzed by year, we find that this slower refueling rate was heavily used in 2006 but less dominant in 2007 and 2008. With these differences in distribution in mind, the average fill rate for all communication fills is 0.88 kg/min vs. 0.66 kg/min for non-communication fills, with 32% and 15%, respectively, exceeding DOE's 1 kg/min target.

Finally, slicing the same data by fill pressure level (350 vs. 700 bar) we find that the average rate of fills for 350 bar is 0.81 kg/min while it is only 0.59 kg/min for 700-bar fills (Figure 12). As more permanent 700-bar filling stations come online and the experience with this pressure grows, we expect to see the 700-bar fill rates increase to meet or exceed the 350-bar fill rates.

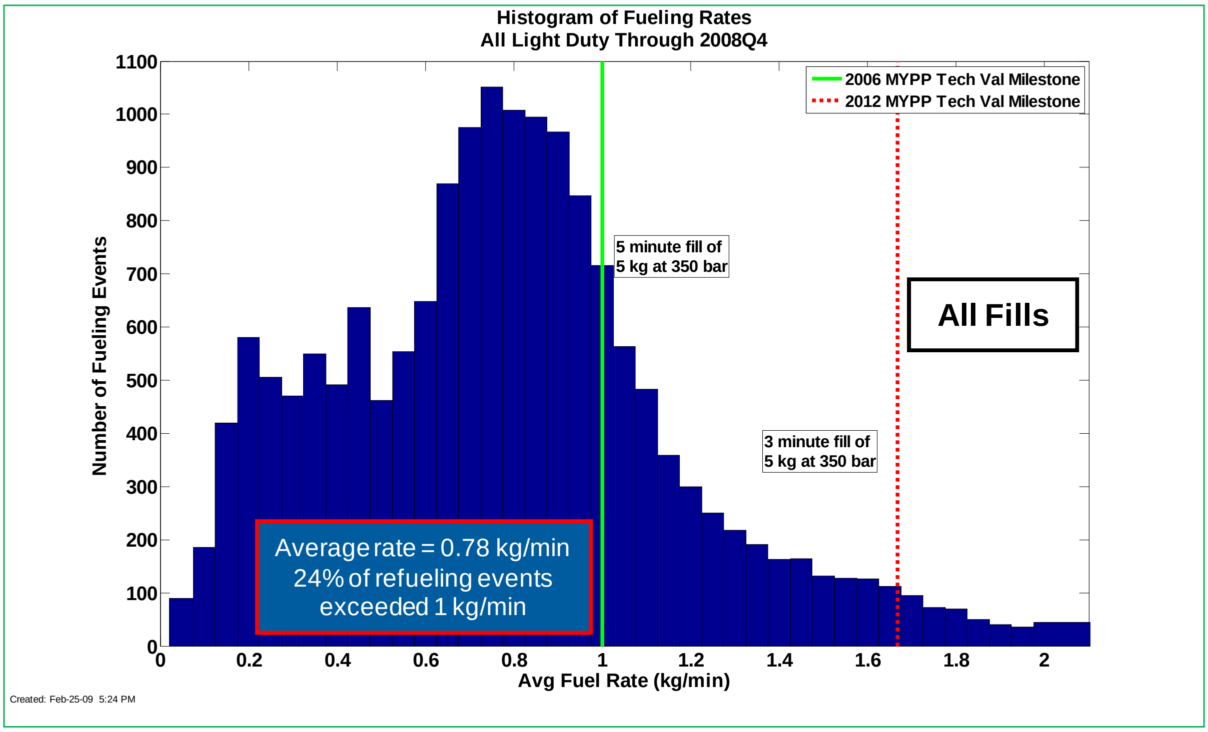
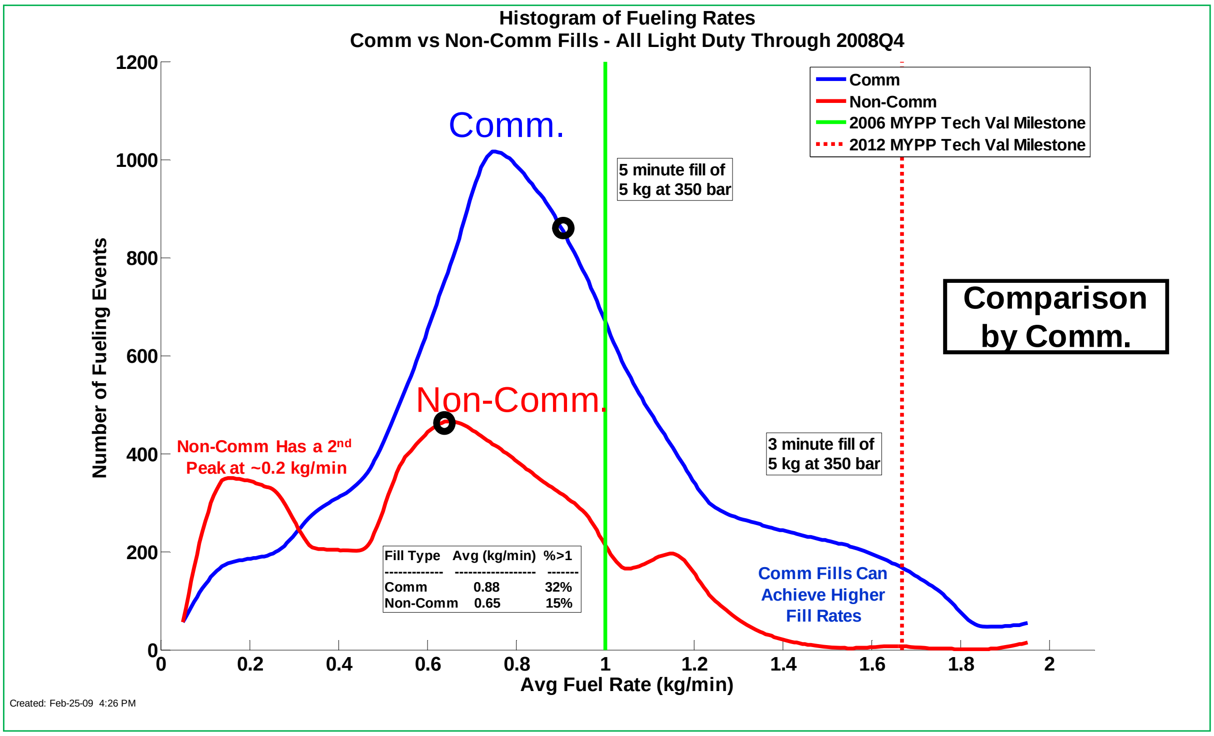
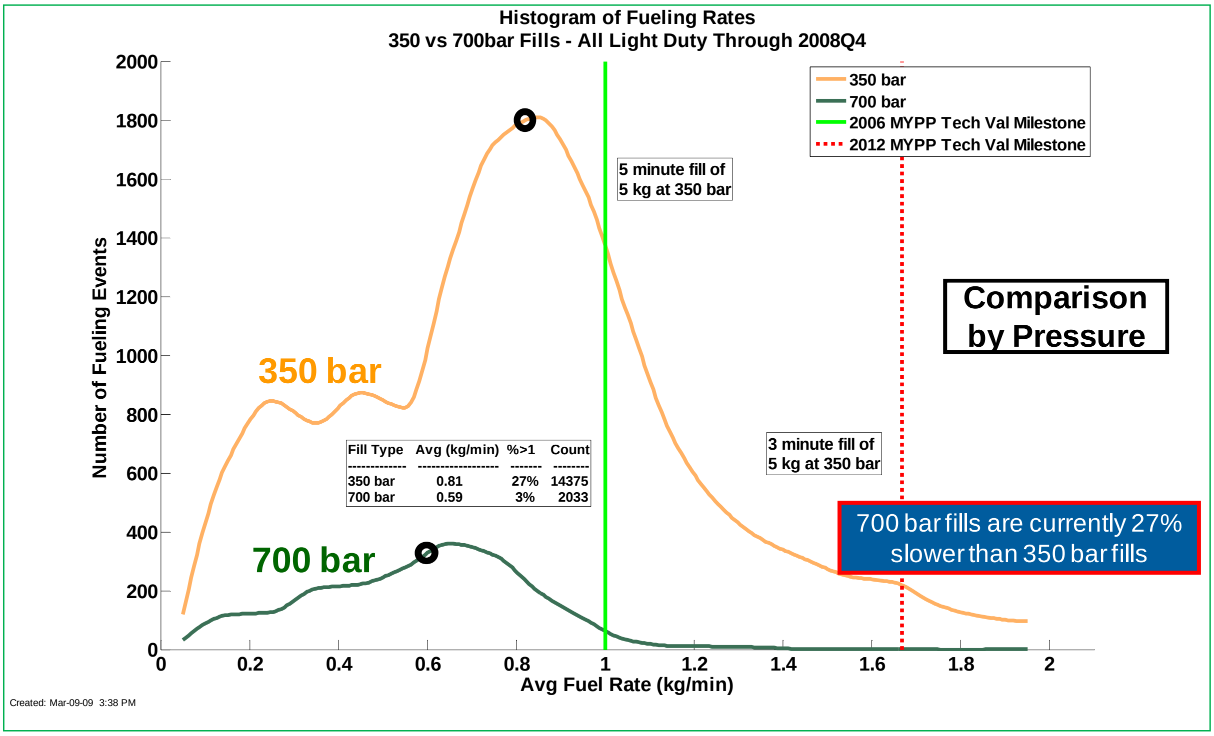


Figure 10: Vehicle refueling rates for all fills.



Fill Type	Avg (kg/min)	%>1
Comm	0.88	32%
Non-Comm	0.65	15%

Figure 11: Communication hydrogen fills achieve 35% higher average rate than non-communication.



Fill Type	Avg (kg/min)	%>1	Count
350 bar	0.81	27%	14375
700 bar	0.59	3%	2033

Figure 12: Histogram of fueling rates for 350 and 700 bar pressure fueling events.

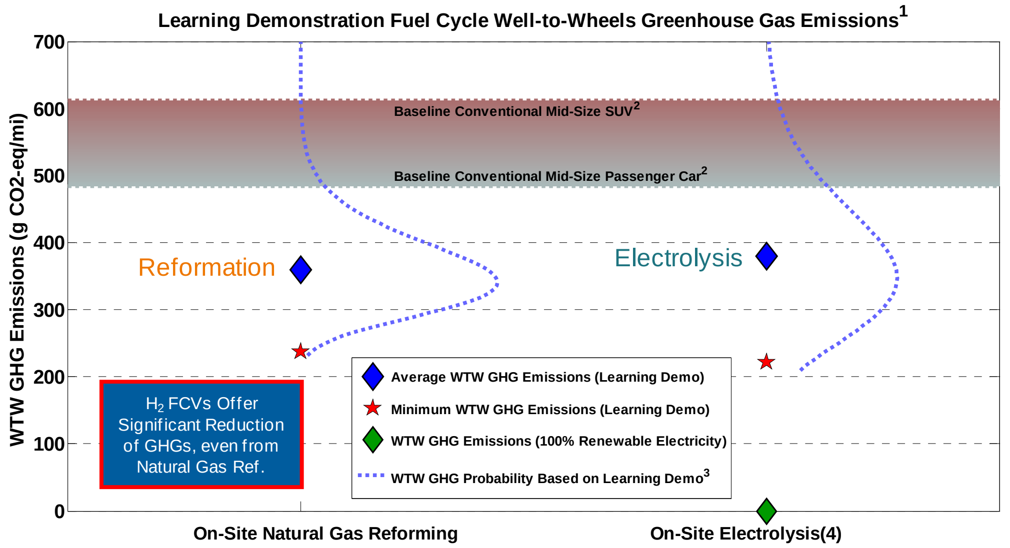
5.2 Well-to-Wheels Greenhouse Gas Emissions

The well-to-wheels greenhouse gas emissions were calculated for Learning Demonstration vehicles by using the actual quarterly on-site production efficiency numbers from natural gas reforming and electrolysis, the window-sticker fuel economy results, and running the DOE GREET model, version 1.8b. Figure 13 shows that when using hydrogen produced on-site via either natural gas reformation or water electrolysis, Learning Demonstration hydrogen FCVs offer significant reductions of greenhouse gas emissions relative to conventional gasoline vehicles.

Conventional gasoline mid-sized passenger vehicles emit 484 g CO_2-eq/mile (grams CO_2 equivalent per mile) on a well-to-wheels (WTW) basis and conventional mid-size sport utility vehicles emit 612 g CO_2-eq/mi. Average WTW greenhouse gas emissions for the Learning Demonstration fleet operating on hydrogen produced from on-site natural gas reformation were 356 g CO_2-eq/mi and the lowest emissions for on-site natural gas reformation were 237 g CO_2-eq/mi. For the Learning Demonstration fleet operating on hydrogen produced from on-site water electrolysis, average WTW GHG emissions were 380 g CO_2-eq/mi, with the lowest emissions estimated to be 222 g CO_2-eq/mi for the month with the best electrolysis production conversion efficiency. Emissions from fuel cell vehicles operating on renewable hydrogen are zero, providing a significant opportunity for FCVs to become zero-emissions vehicles as renewable energy sources are increasingly tapped as the source for automotive fuels.

6 Conclusions and Summary

NREL has now analyzed data from over four years of the six-year project with 140 vehicles having been deployed, 20 project refueling stations in use, and no fundamental safety issues identified. We’ve analyzed data from over 346,000 individual vehicle trips covering 1,900,000 miles traveled and over 90,000 kg hydrogen produced or dispensed. With additional hours of operation accumulated on the fuel cell stacks, the four-team average projection to 10% voltage degradation is 828 hours, and some stacks have demonstrated almost 2,000 hours (typically beyond 10% voltage degradation). The driving range milestone of 250 miles for 2009 has been met by second-generation vehicles using 700-bar compressed hydrogen storage. New fuel cell usage statistics such as the time at various voltages and the distribution of trips/hour have been generated to assist fuel cell



1. Well-to-Wheels greenhouse gas emissions based on DOE's GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all teams (as used in CDP #6); conversion efficiency values are the production efficiency data used in CDP #13.
2. Baseline conventional passenger car and light duty truck GHG emissions are determined by GREET 1.8b, based on the EPA window-sticker fuel economy of a conventional gasoline mid-size passenger car and mid-size SUV, respectively. The Learning Demonstration fleet includes both passenger cars and SUVs.
3. The Well-to-Wheels GHG probability distribution represents the range and likelihood of GHG emissions resulting from the hydrogen FCV fleet based on window-sticker fuel economy data and monthly conversion efficiency data from the Learning Demonstration.
4. On-site electrolysis GHG emissions are based on the average mix of electricity production used by the Learning Demonstration production sites, which includes both grid-based electricity and renewable on-site solar electricity. GHG emissions associated with on-site production of hydrogen from electrolysis are highly dependent on electricity source. GHG emissions from a 100% renewable electricity mix would be zero, as shown. If electricity were supplied from the U.S. average grid mix, average GHG emissions would be 1241 g/mile.

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Figure 13: Learning Demonstration fuel cycle well-to-wheels greenhouse gas emissions.

developers and those creating durability test protocols. With over 16,000 vehicle refueling events, we have been able to slice the data by communication vs. non-communication, by year, and by 350 vs. 700 bar to allow an objective comparison.

Finally, we've published a total of 60 CDPs to date and made them directly accessible to the public through our Hydrogen Technology Validation Web site (http://www.nrel.gov/hydrogen/proj_learning_demo.html). In the future, we will semi-annually (spring/fall) compare technical progress to program objectives and targets and provide results to the public by participating in technical conferences and writing reports. Specific results anticipated in the fall of 2009 are: fuel cell freeze tolerance and start-up energy, hydrogen production cost, and second generation fuel cell system efficiency. As an important part of the project, we will continue to identify opportunities to feed project findings back into HFCIT Program research and development activities to maintain the project as a true "learning demonstration."

References

[1] K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, "Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Spring 2009" Golden, CO: National Renewable Energy Laboratory, March 2009.

[2] K. Wipke, S. Sprik, J. Kurtz, J. Garbak, "Fuel Cell Vehicle Infrastructure Learning Demonstration: Status and Results," *ECS Transactions: Proton Exchange Membrane Fuel Cells 8*, September 2008.

[3] K. Wipke, S. Sprik, J. Kurtz, J. Garbak, "Field Experience with Fuel Cell Vehicles," *Handbook of Fuel Cells – Fundamentals, Technology and Applications, Volume 6, chapter 60: Advances in Electrocatalysis, Materials, Diagnostics and Durability*, John Wiley & Sons, Ltd. ISBN: 978-0-470-72311-1, 2009.

[4] C. Welch, K. Wipke, S. Gronich, J. Garbak, "Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Data Analysis Overview," National Hydrogen Association Conference, Washington, DC (March 2005).

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