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# Final Results from U.S. FCEV Learning Demonstration

## Preprint

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# Final Results from U.S. FCEV Learning Demonstration

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**Abstract**

The "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," also known as the National Fuel Cell Electric Vehicle Learning Demonstration, is a U.S. Department of Energy (DOE) project started in 2004 and concluded in late 2011. The purpose of this project was to conduct an integrated field validation that simultaneously examined the performance of fuel cell vehicles and the supporting hydrogen fueling infrastructure. The DOE's National Renewable Energy Laboratory (NREL) received and analyzed all of the raw technical data collected by the industry partners through their participation in the project over its seven-year duration. This paper reviews highlights from the project and draws conclusions about the demonstrated status of the fuel cell vehicle and hydrogen fueling infrastructure technology. Through September 2011, 183 fuel cell electric vehicles were deployed, 25 project fueling stations were placed in use, and no fundamental safety issues were identified. We have analyzed data from more than 500,000 individual vehicle trips covering 3.5 million miles traveled and more than 150,000 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. Ninety-nine of these CDPs have been generated for public use and posted on NREL's technology validation website. The results indicate that fuel cell vehicle technology continues to make rapid progress toward commercial readiness and that the fueling infrastructure technology is ready to provide a consumer-friendly fast fill and long range experience consistent with expectations of gasoline vehicle customers.

*Keywords: hydrogen, fuel cell, demonstration, ZEV (zero emission vehicle)*

## 1 Introduction

This paper discusses key analysis results based on data from early 2005 through September 2011 from the U.S. Department of Energy's (DOE's) Controlled Hydrogen Fleet and Infrastructure Validation and Demonstration Project, also referred to as the National Fuel Cell Electric Vehicle (FCEV) Learning Demonstration. The industry partners provided their final project data to NREL in October 2011 and we have now performed analysis across the entire seven-year period. During this time, 183 fuel cell electric vehicles were deployed, 25 project fueling stations were placed in use, and no fundamental safety issues were identified. We have analyzed data from more than 500,000 individual vehicle trips covering 3.5 million miles traveled and more than 150,000 kg hydrogen produced or dispensed. Key objectives of the project were to evaluate fuel cell durability, vehicle driving range, and on-site hydrogen production cost. This evaluation was performed through validating the use of FCEVs and hydrogen fueling infrastructure under real-world conditions using multiple sites, various climates, and a variety of hydrogen sources. DOE provided industry $170M in project funding, which was more than matched with $189M from industry, for a total of $359M over the seven years. NREL's analysis was supported by DOE with $6.6M since project inception in 2003. Figure 1 shows photographs of the first- and second-generation vehicles along with the structure of the industry teams providing data to NREL.


Figure 1: Learning Demonstration teaming arrangement and photos of the different vehicle generations. (Photo credit: Keith Wipke, NREL)

The project started with four automotive original equipment manufacturers (OEMs) and energy partner teams. Since that time DOE's California Hydrogen Infrastructure Project, executed by Air Products, began providing data. Additional hydrogen fueling infrastructure was also installed in California under state and local funding, and those projects provided data to NREL as well. Two of the four original OEM and energy partner teams concluded their project on schedule and provided their last data at the end of 2009 (based on the original five-year planned project duration), while two of the vehicle OEMs and Air Products continued their projects and provided data to NREL for another two years. After the first two project teams concluded their projects, subsequent analytical results needed to be structured differently to protect the sensitive data of the remaining two automotive companies providing data and because the first two teams were no longer available for review and concurrence of new results based on their data. The previous EVS-25 paper published on this project [1] covered the highlights of the first five years, when all project partners were still included in the project, so this paper will focus on the latest results and differences noted from the results of the first five years. Note that additional comprehensive progress reports that go into detail on each individual technical result were published by NREL in July 2007 [2], November 2007 [3], April 2008 [4], and September 2010 [5]. Additionally, a final comprehensive report is scheduled to be published in April 2012.

## 1.1 Objectives and Technical Targets

NREL's primary objective for this project is to validate hydrogen FCEVs and infrastructure in a real-world setting and identify the current status and evolution of the technology over the project duration. We strive to provide the DOE and industry with maximum value from the data produced by this "learning demonstration." We also seek to objectively understand the progress toward targets and market needs and provide that information to the DOE Fuel Cell Technologies Program and industry research and development (R&D) activities. This information will allow the program to move more quickly toward cost-effective, reliable hydrogen FCEVs and the supporting fueling infrastructure. A major outcome from this project is the publishing of results for key stakeholder use and investment decisions.

This project was designed to validate three high-level DOE technical targets for hydrogen FCEVs and infrastructure:

- 250-mile driving range
- 2,000-hour fuel cell durability
- $3/gallon gasoline equivalent (gge) hydrogen production cost (based on volume production).

## 1.2 Technical Approach

NREL's approach to accomplishing the project's objectives is structured around a highly collaborative relationship with each of the industry teams: Chevron/Hyundai-Kia, Daimler/BP, Ford/BP, GM/Shell, and Air Products. We received raw technical data on both the hydrogen vehicles and the fueling infrastructure that allowed us to perform unique and valuable analyses across all teams. To protect the commercial value of these data for each company, we established the Hydrogen Secure Data Center (HSDC) at NREL to house the data and perform our analysis. To ensure value was fed back to the hydrogen community and key stakeholders, we published composite data products (CDPs) twice a year and presented at technical conferences. These CDPs reported on the progress of the technology and the project, focusing on the most significant results. Additional CDPs were developed throughout the project to highlight trends and notable results. We also provided our detailed analytical results to each individual company based on their data to maximize the industry benefit from NREL's analytical work and obtain feedback on our methodologies. These individual company results were not made available to the public.

In order to evaluate such a large and growing data set, NREL developed an in-house tool called the Fleet Analysis Toolkit (NRELFAT), which helped organize and automate the various analyses being performed on both the vehicles and the infrastructure. The tool has been expanded to apply the analysis functions not only to FCEVs but also to fuel cell buses, fuel cell forklifts, laboratory fuel cells, backup fuel cells, stationary fuel cells, and plug-in hybrid vehicles. The overall functionality of the NRELFAT has been covered in previous publications, so it will not be discussed in detail here. This sophisticated in-house tool allowed us to rapidly respond to the DOE's and the U.S. Department of Defense's needs for evaluation of early market fuel cell applications.

## 1.3 Vehicle Deployments

Industry teams were selected by DOE for this project in April 2004. NREL received the first data in September 2004 after DOE had signed cooperative agreements with the industry partners. The teams continued to send data to NREL on a monthly or quarterly basis, resulting in more than 500,000 individual trips and 122 GB of second-by-second on-road data from the vehicles.

The project was scheduled to be completed in September 2009, and two of the teams, Ford/BP and Chevron/Hyundai-Kia, successfully completed their projects as planned in late 2009, while Daimler and GM elected to add scope and extend their projects two years with a new completion date of September 2011. Fifty-one vehicles were in

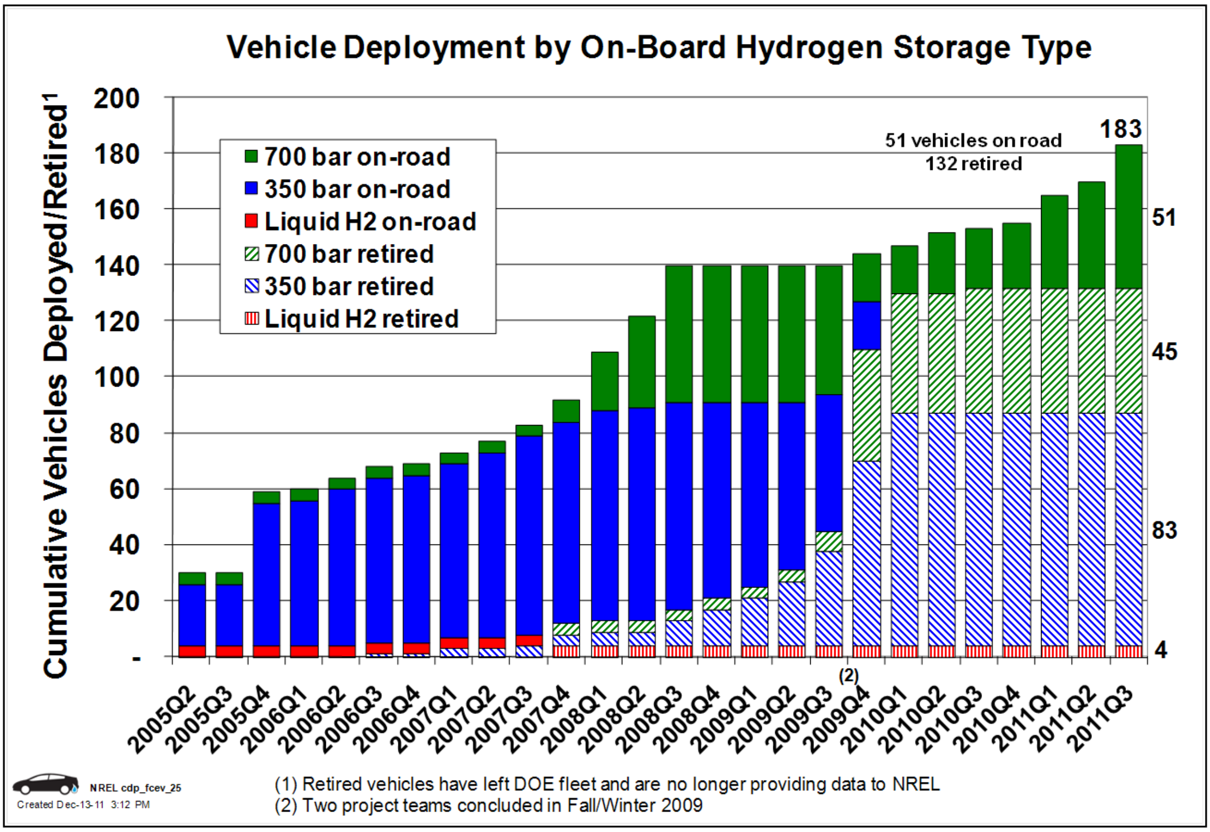


Figure 2: Population of vehicles throughout Learning Demonstration

operation by the end of the final two years of this project, reporting performance improvements from the latest technology.

This transition from four teams to two teams can be seen in some of the CDPs that show the number and status of the FCEVs and fueling stations. As shown in Fig. 2 (CDP25), a gradually increasing number of vehicles were retired through 2008 (approximately 20 vehicles), with a much larger number retired by the fourth quarter of 2009, when two teams completed their projects. Note that all of the first-generation vehicles utilizing 350-bar pressurized hydrogen storage or liquid hydrogen were retired from this project by that time, and only FCEVs with 700-bar storage were operated during the final two years of this project.

A summary of the major improvements between the first- and second-generation fuel cell vehicles were:

- Improved freeze capability
- Mild improvement in overall system efficiency and fuel economy.
- Improved stack technology and durability
- Improved driving range

## 1.4 Fueling Station Deployments

The cumulative number of fueling stations deployed through this project is 25. Of those 25, 12 were decommissioned, 6 continued operation outside of the project, and 7 continued providing data to NREL within the project. Stations demonstrated five major hydrogen infrastructure technologies (see Fig. 3 (CDP32)):

1) On-site hydrogen production through natural gas reformation
2) On-site hydrogen production through water electrolysis
3) Delivered liquid hydrogen
4) Delivered compressed hydrogen through tube-trailers
5) Delivered compressed hydrogen through a fixed pipeline.

Eight stations used delivered compressed hydrogen, and seven used on-site electrolysis. More than half of the electrolysis stations have been retired, whereas only one of the eight delivered compressed gas stations has been retired. While many of the project stations may come to the end of their useful demonstration life in the next few years, many new or upgraded stations are being opened in California as a result of the combined efforts of the California Air Resources

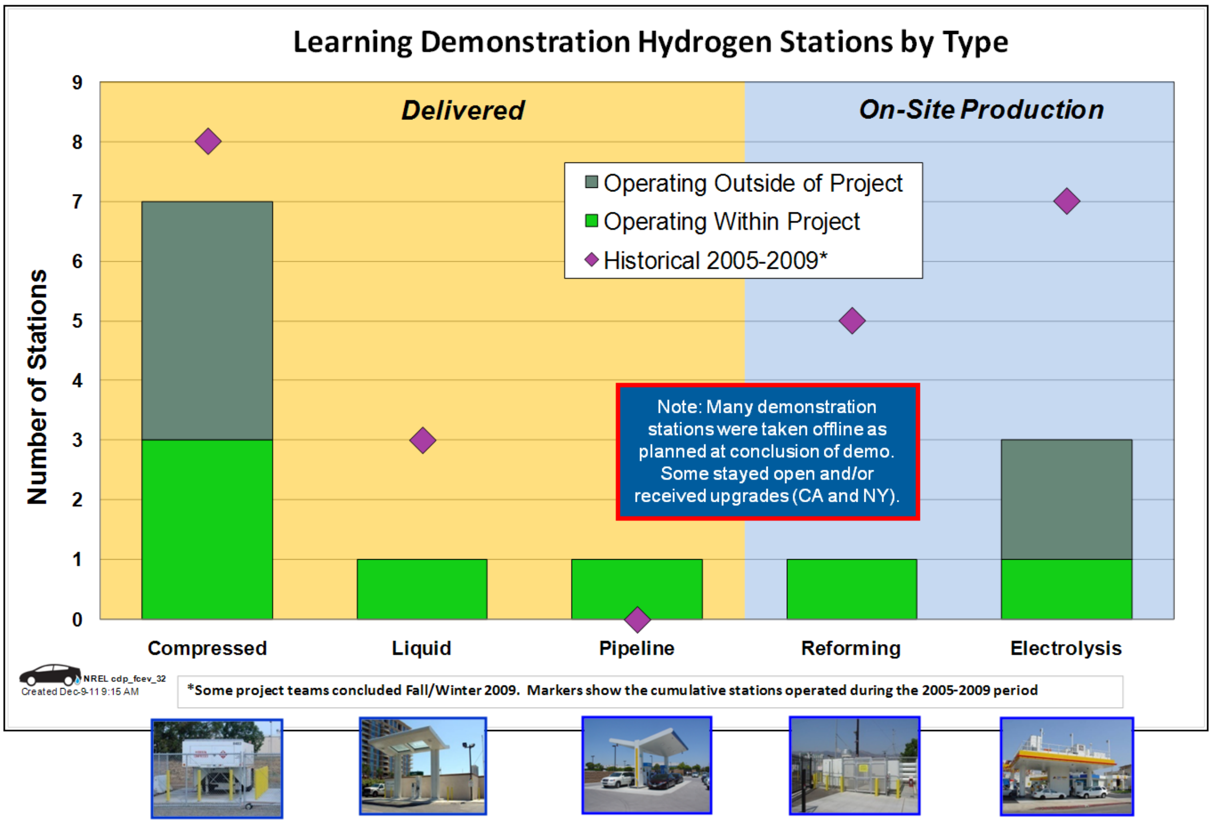


Figure 3: Multiple types of hydrogen fueling stations were deployed in the Learning Demonstration (Photo credit: Keith Wipke, NREL)

Board, the California Energy Commission (CEC), and the South Coast Air Quality Management District. These new stations are helping provide a bridge from the early demonstration stations (from this project and other demonstrations) to a point in the future when the number of FCEVs is large enough to create a market pull for private sector investment in hydrogen infrastructure.

In order to obtain a variety of data, the project included geographically diverse locations for demonstration of the vehicles and infrastructure. Initially, five regions of the country were involved, including the San Francisco Bay area, the Los Angeles area, the Detroit area, Orlando, and a corridor from Washington, DC, to New York. As two of the teams completed their portions of the project, all of the project stations in Florida were closed. As of January 2012, DOE's Alternative Fuels & Advanced Vehicles Data Center station locator [6], which receives regular station status updates from this project, shows that there are a total of 54 operational hydrogen fueling stations in the United States with 15 future stations (mostly in California) coming online in the next year or two. Additionally, the CEC will be providing up to $18.7M for new or upgraded stations in California [7] to prepare for upcoming vehicle launches planned by the OEMs in the 2014-2017 timeframe.

# 2 Key Project Results Compared to Three Primary 2009 Targets

As previously mentioned [1], the EVS-25 paper detailed the results from the first five years (through 2009) on fuel cell stack durability, vehicle driving range, and hydrogen fueling cost at the station. Table 2 shows a summary of these results compared to the 2009 targets.

As the table shows, the best individual team performance results exceeded the two technical targets for fuel cell stack durability and vehicle driving range. An additional experiment was performed outside of this project [8] in conjunction with Savannah River National Laboratory that verified that a fuel cell vehicle could be capable of up to a 430-mile driving range without refueling.

Table 1: Comparison of Results Compared to Key Technical Targets

| Metric | 2009 Target | 2009 Project Results |
|---|---|---|
| **Fuel Cell Stack Durability**[1] | 2,000 hours | 2,521 hours |
| **Vehicle Driving Range**[2] | 250 miles | 196–254 miles |
| **Hydrogen Cost at Station** (early market) | $3/gge | On-site natural gas reformation: $7.70–$10.30/kg On-site electrolysis: $10.00–$12.90/kg |

To evaluate the third target for hydrogen cost at the station, cost estimates from the Learning Demonstration energy company partners were used as inputs to an H2A analysis to project the hydrogen cost for 1,500 kg/day early market fueling stations. H2A is DOE's suite of hydrogen analysis tools, with the H2A Production model focused on calculating the costs of producing hydrogen. Results indicated that on-site natural gas reformation could lead to a price range of roughly $8–$10/kg and on-site electrolysis could lead to a range of $10–$13/kg hydrogen cost. Note that 1 kg $H_2$ is approximately equal to the energy contained in a gallon of gasoline, or gallon gasoline equivalent (gge). While these project results do not achieve the $3/gge cost target, two external independent review panels commissioned by DOE concluded that distributed natural gas reformation could lead to a price range of $2.75–$3.50/kg [9] and distributed electrolysis could lead to a price range of $4.90–$5.70/kg [10]. Therefore, this objective was met outside of the Learning Demonstration project by distributed natural gas reforming.

While additional data was gathered for two more years in 2010–2011 with only two automotive OEMs involved, we focused on analyzing and publishing results in a different style in which we either 1) based the results only on the participants providing data in the final two years, or 2) overlaid the final two years of results on top of the first five-year results. This was necessary due to the fact that we were required to get review and concurrence from our project partners and could only do so with partners who were still active in

[1] maximum team projected hours to 10% voltage degradation from second-generation vehicles
[2] based on EPA-adjusted dynamometer fuel economy results and usable on-board hydrogen fuel

the project. The next section highlights the results from the final two years of the project in this manner.

# 3 Highlights of Results from Final Two Years of Project

In the final years of the project we received data from two automotive OEMs: Daimler and GM. At the end of this project we were gathering on-road data from 51 vehicles. We also received data from hydrogen fueling stations being used to support these vehicles, along with stations supporting many other vehicles in the California region by Air Products. This resulted in infrastructure data being provided to NREL from seven stations during the final two years of the project. The next subsections will focus on results from participants in the final two years of the project on the topics of:

- On-road driving range
- Fuel cell stack durability
- Infrastructure utilization
- Infrastructure reliability
- Hydrogen fueling rates.

## 3.1 On-Road Driving Range (Distance Between Fuelings)

During the first five years of the project, we evaluated the actual driving range observed between vehicle fuelings for both first- and second-generation vehicles and compared them in CDP #80. With two additional years of data, some minor improvements in fuel economy of the latest vehicles, and better hydrogen station coverage in California, we wanted to evaluate whether the observed driving range was improving. So we graphed the first- and second-generation distribution from the first five years in two different shades of gray, and then overlaid on top of them the latest results from post-2009Q4 data. See Fig. 4 for these driving range results.

The results show that the median distance between fueling events was 56 miles for first-generation vehicles (light grey), 81 miles for second-generation vehicles (dark grey), and 98 miles for post-2009Q4 vehicles (yellow). This reflects a 45% improvement between first- and second-generation vehicles and a 75% improvement between first-generation vehicles and the latest advanced technology vehicles. The combination of improved fuel economy and greater driver comfort in using more of the hydrogen in the tank due to fueling availability and reliability resulted in 21% longer driving between fuelings between the latest vehicles and the second-generation vehicles. It should be noted that these same vehicles were capable of 200–250 miles if driven to empty under controlled driving conditions.

As the industry moves toward commercial vehicle

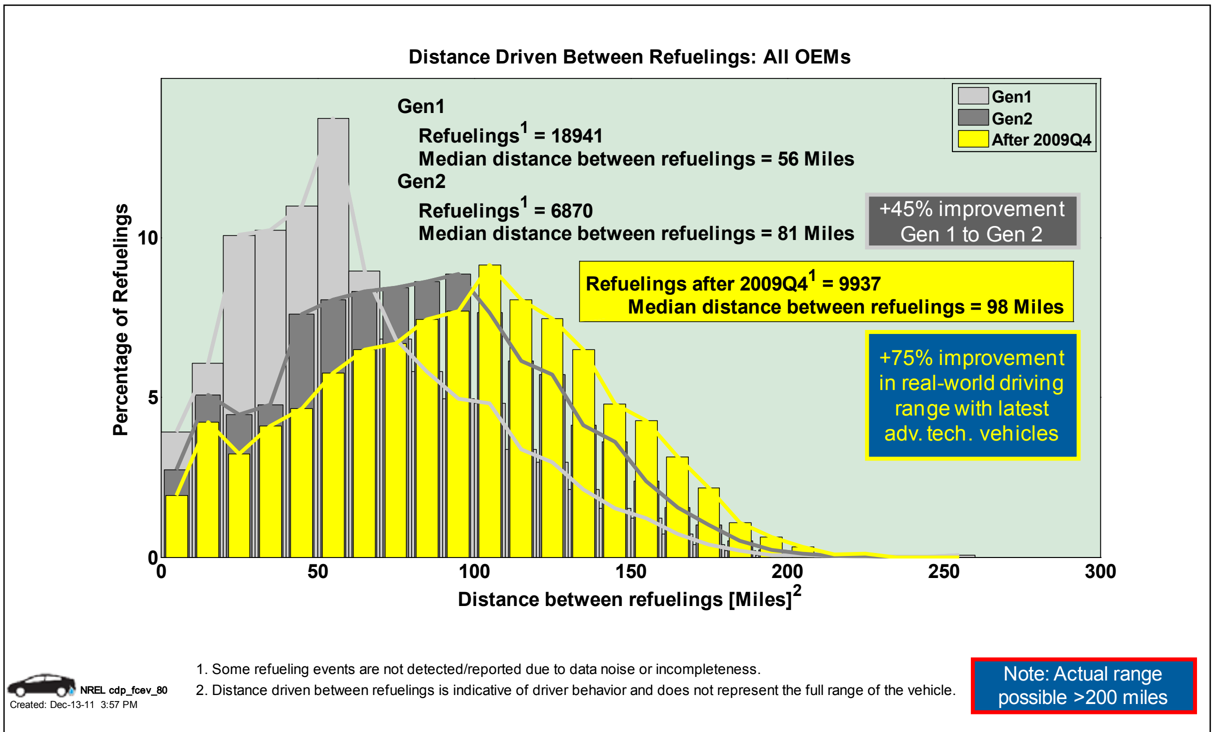


Figure 4: Demonstrated on-road driving range, determined through distance driven between fuelings

products and improved fueling station coverage in certain regions of the country, we should see the practical driving range of FCEVs approach that of conventional gasoline vehicles (around 250–300 miles).

## 3.2 Fuel Cell Stack Durability

Evaluating fuel cell stack durability with the partners involved in the final two years of the project was a challenge due to the limited time to gather sufficient data, as determining durability inherently requires data over a long period. In quantifying the operation of the vehicles from this period (see CDP 86 at [11]), we found that:

- 25% of the fuel cell stacks had accumulated >937 hours
- Some stacks had operated more than 1,400 hours, but roughly half were still below 600 hours
- The median time accumulated was 620 hours

We performed analysis on the maximum power observed in the field from each stack to examine how that degraded with time. As can be seen in Fig. 5, there is a knee in the curve at around 200 hours after which the degradation significantly decreases its slope. We see a similar result in the voltage of the stack under load with aging, through an analysis method that we documented toward the beginning of this project [12]. This method performs polarization curve fits for roughly every hour and then tracks the long-term voltage drop under high load from these polarization curve fits.

Using this voltage analysis technique and all of the data (starting at beginning of life), we project a fleetwide average of 1,748 hours to 10% voltage drop (see Fig. 6). While this is lower than the ~2,500 hours obtained from the second-generation vehicles, the primary reason is the limited amount of data accumulated, which requires us to artificially put a limit in our projections of two times the highest hours demonstrated within a fleet to limit the extrapolation. This shows up in the figure as a large clustering of stack projections above 2,700 hours. Unfortunately, now that this project has concluded we will not receive more data on these stacks to know what their ultimate durability will be without our 2X limit being in place. Additional information about the progress of fuel cell stack durability will need to come from outside of this project.

To explore the impact of the first 200 hours, we also analyzed the data with our voltage fits starting after the first 200 hours, and the projection to 10% voltage drop increased by 500 hours. Even more stacks then become limited by the 2X projection constraint. This indicates that the voltage projection results are relatively sensitive to the

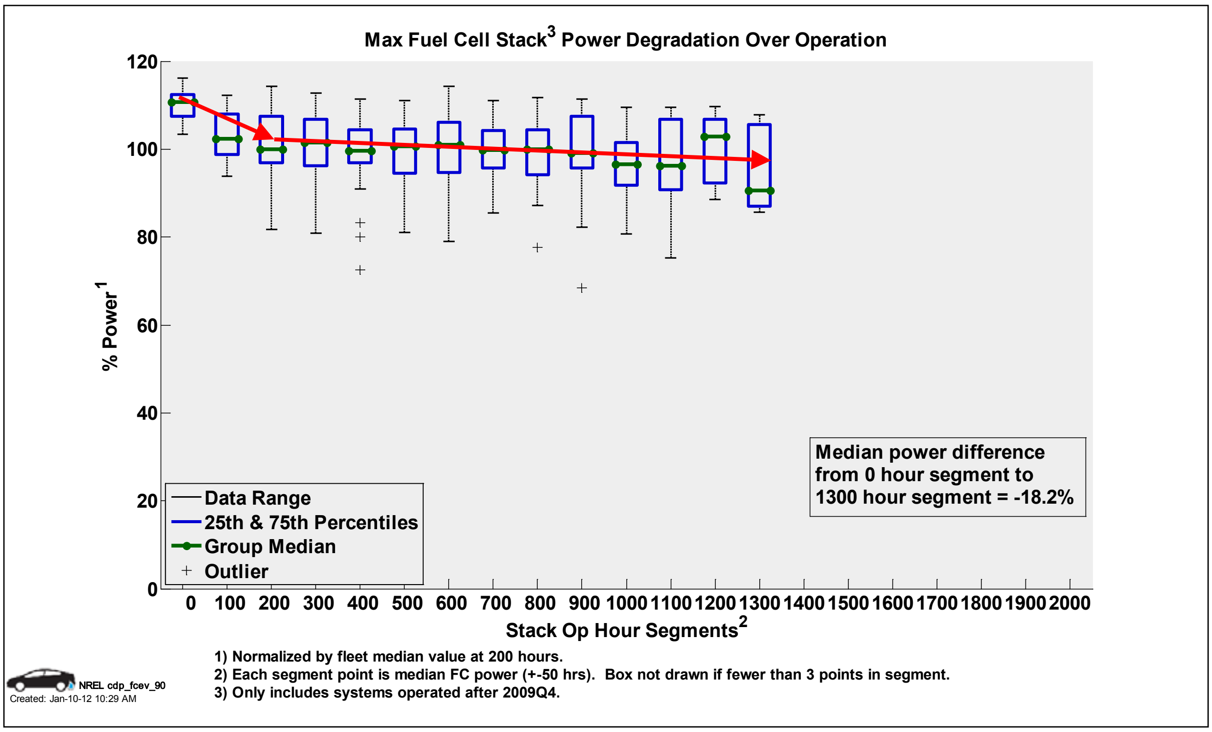


Figure 5: Maximum FC power degrades with time, most sharply in the first 200 hours

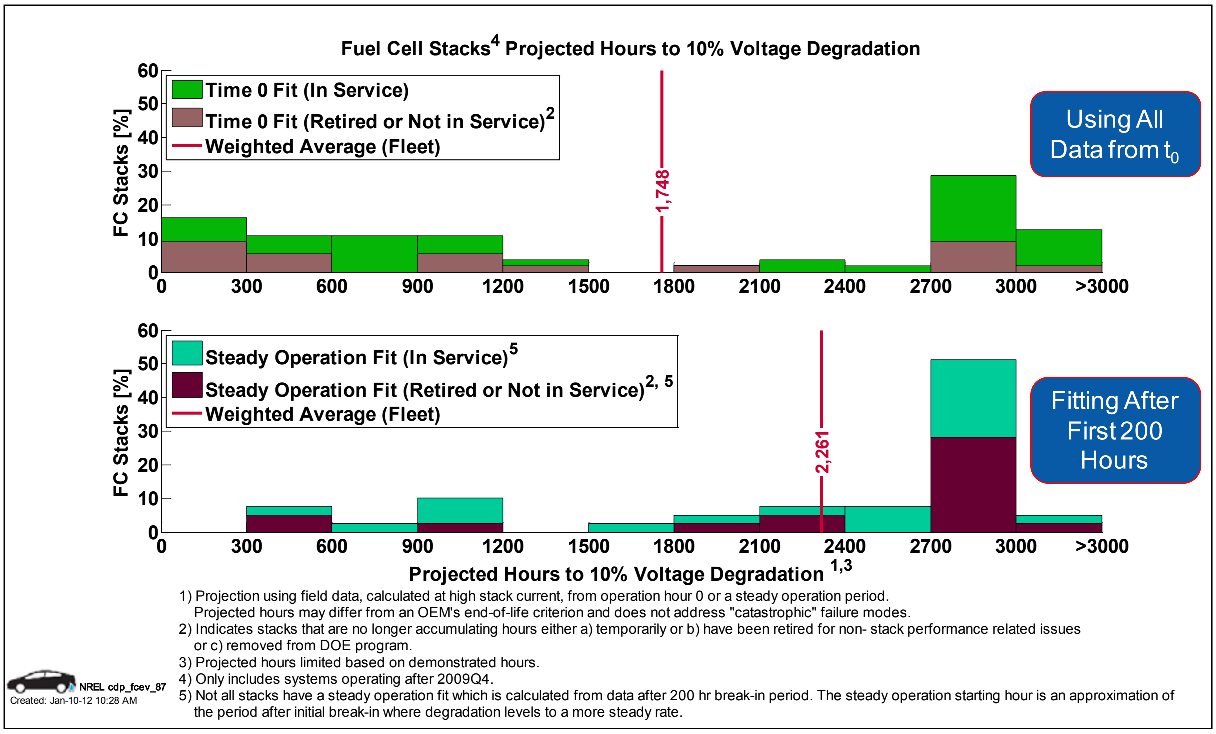


Figure 6: Projected time to 10% voltage degradation; two different fits

impact of the early degradation observed in the field, which was also the case for the first- and second-generation vehicles from the first five years.

Based on the observed performance from this project, durability has significantly improved from first generation (~2003–2005) technology to the latest generation (~2006–2009). To validate a sustained rate of progress on durability, it would be beneficial to gather new data on ~2010–2012 technology that would be representative of what is expected to be launched into the marketplace in the 2015 timeframe.

## 3.3 Infrastructure Utilization

Recent discussions within the hydrogen community indicate that there will be two major thrusts of hydrogen infrastructure build-out. The first will focus on geographic coverage to ensure that early adopters will have convenient fueling within a reasonable distance to where they live or work. The second stage of the deployment will focus on capacity and allowing the quantity of vehicles supported by the infrastructure to rise rapidly as the OEMs accelerate their production of the vehicles.

During the “coverage” stage, the stations will necessarily have excess capacity and appear to be underutilized. This is the stage in which this demonstration project operated in, as seen in Fig. 7, which shows the maximum daily utilization, maximum quarterly utilization, and average daily utilization for each of the seven stations. The results show that one station is heavily used, with an average daily utilization of 58.9% and a maximum quarterly utilization of around 90%, while many of the stations have an average daily utilization that is between 15% and 30%. The highest average daily usage from the busiest Learning Demonstration station is 27 kg/day. As the hydrogen infrastructure moves from the coverage stage to the capacity stage, many of these demonstration stations will quickly become saturated and will need to be upgraded or replaced to allow for increased vehicle usage and capacity.

## 3.4 Infrastructure Reliability

Hydrogen infrastructure maintenance was previously reported from the first five years of the project (2,491 maintenance events), and results indicated that after system control and safety (22% of the maintenance events) the hydrogen compressor was the biggest single component to cause issues at the station (18% of events). This was followed by the natural gas reformer and the electrolyzer with 13% of the maintenance events each.

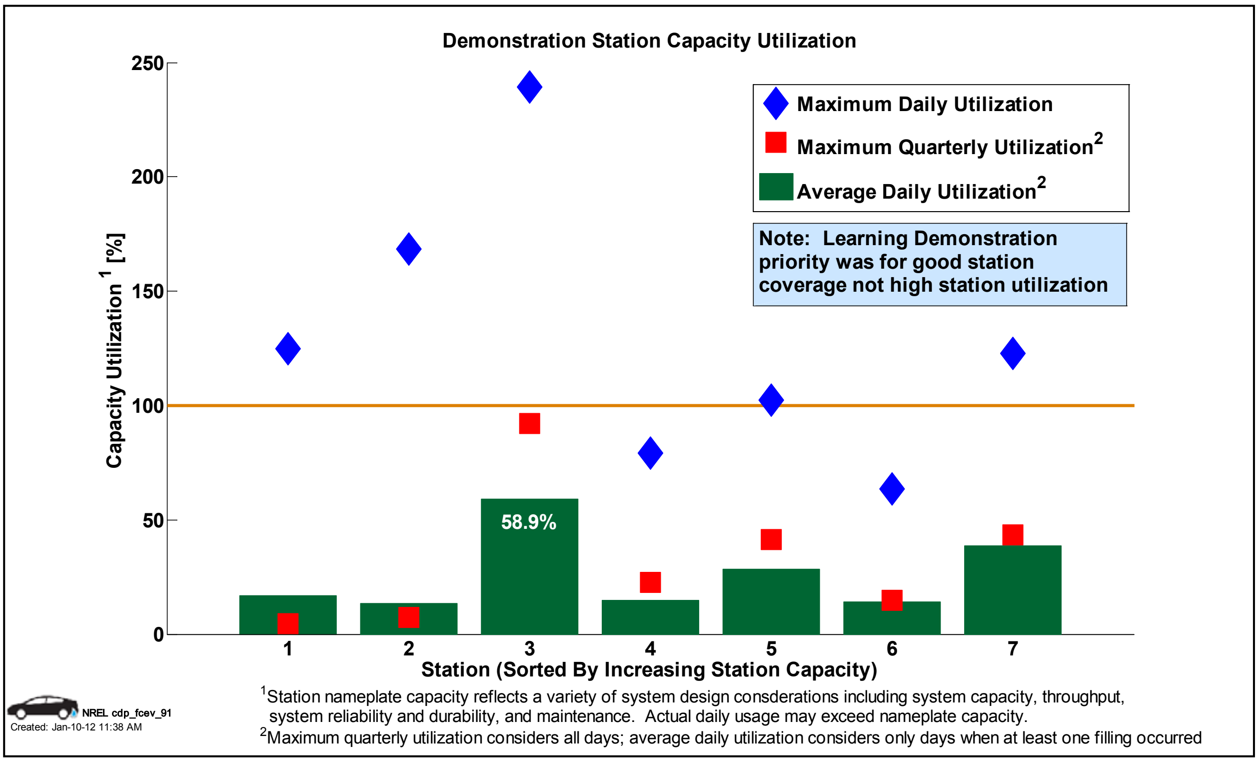


Figure 7: Hydrogen station utilization during "coverage" phase of infrastructure roll-out

For stations that operated during the last two years of the project (1,095 events), we changed our categorization of maintenance events slightly to better reflect the nature of the underlying issues. We found that electrical issues and software issues each made up 21% of the events and hydrogen compressors were responsible for 12% of the events. So the top infrastructure maintenance items were still system related and not necessarily hydrogen specific. The single hydrogen-specific component that caused the most frequent issues was still the hydrogen compressor. As a larger market emerges for hydrogen compressors designed specifically for fueling stations, demand should drive these products toward more reliable and consistent performance.

We also performed statistical analysis of the infrastructure maintenance data to evaluate the reliability growth using the Crow-AMSAA method. We found in the last 20% of the maintenance events the instantaneous mean-time between failure (MTBF) improved (increased) for five of the seven sites. Looking at the entire life of these seven stations, reliability is continuing to improve at most sites. For reference, the details of these results [11] can be seen in CDPs 63, 94, and 97.

## 3.5 Hydrogen Fueling Rates

Having a fast fueling time of 3–5 minutes for a full hydrogen fill allows fuel cell vehicles to provide a customer fueling experience comparable to that of conventional gasoline vehicles. The Learning Demonstration has been tracking hydrogen data from each fueling event for seven years, including the hydrogen amount dispensed, the fueling time, and the subsequent fueling rate in kg/min (analogous to gge/min). The intermediate target is to fill 5 kg in 5 min (1 kg/min) and the longer term target is to fill 5 kg in 3 min (1.67 kg/min).

From the first five years of the project we saw a gradual increase in the fueling rate each year, with an average of 0.77 kg/min gathered from more than 25,000 fueling events (see gray bars in Fig. 8). Of these fueling events, 23% exceeded the 1 kg/min target. In the last two years, we saw a 25% increase in the hydrogen amount per fill but a 37% increase in the average fueling time, resulting in an overall decrease in the average fueling rate of 16%, to 0.65 kg/min. This was primarily caused by some of the high-throughput 350 bar stations being decommissioned in 2009 as well as a shift to 700 bar fuelings, for which the protocols and hardware are still being adjusted and improved.

We found that the 350 bar fueling rates dropped from 0.82 kg/min to 0.70 kg/min due to some of

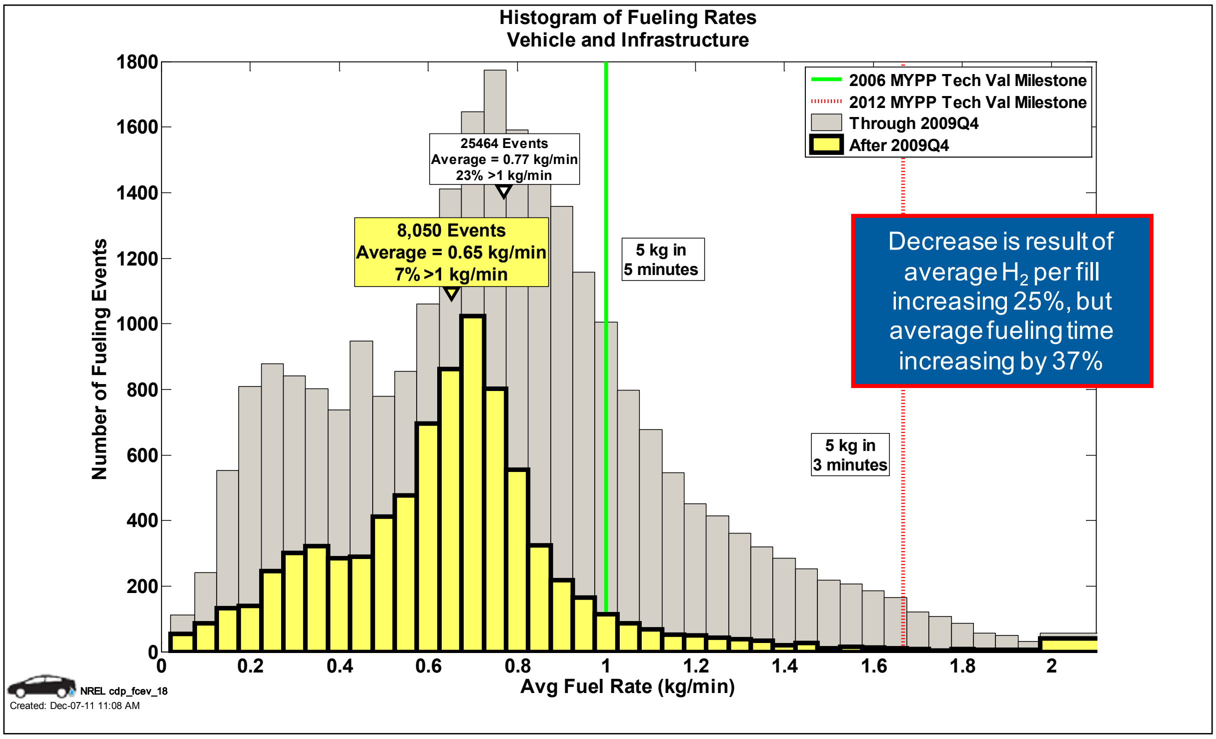


Figure 8: Changes in refueling rate trends – average refueling rate decreased 16% due to some high throughput stations leaving project

the stations being taken offline, while the 700 bar fueling rates held relatively constant at around 0.63 kg/min. We also saw a flip in the trends for fueling rates with communication (when the station talks to the vehicle to determine the tank temperature and state) vs. non-communication. The communication fill rates dropped from 0.86 kg/min to 0.58 kg/min while the non-communication rates went from 0.66 kg/min to 0.81 kg/min. Graphs of these results are available in CDPs 14 and 29, respectively (not included here, but available online at [11]). It is expected that the fueling protocols and hardware will settle down in the next year or two and that fueling rates will approach or exceed 1 kg/min.

# 4 Conclusions

The Learning Demonstration project was the largest single fuel cell vehicle and hydrogen infrastructure demonstration in the world to date, and the first time such comprehensive data were collected by an independent third party and consolidated and analyzed for public dissemination. NREL has published 99 CDPs to communicate the technical results to a broad audience of stakeholders. Through seven years of real-world validation the project deployed 183 vehicles travelling 3.5 million miles through 500,000 trips, resulting in 154,000 hours of second-by-second data delivered to NREL. The project also deployed 25 hydrogen fueling stations that produced or dispensed 151,000 kg of hydrogen through over 33,000 fueling events.

Both of DOE's key technical targets for 2009 were exceeded, demonstrating >250 mile range and >2,000 hour fuel cell stack durability. The third major objective of evaluating $3/gge hydrogen cost was met outside of this project through results from an independent panel of experts.

After two project participants concluded their participation as planned in 2009, an additional two years of data was gathered from two OEMs and seven fueling stations. From this new data we found that the real world distance driven between fueling events was increasing and has reached a median distance of 98 miles. Fuel cell stack durability continues to be tracked, but projections were artificially limited to twice the demonstrated hours to minimize excessive extrapolation.

Hydrogen compressors continue to be the component requiring the most maintenance at the stations, while it appears that station reliability is improving in most of the stations during the last 20% of their operation. Infrastructure utilization has improved in the last two years but is still in a mode focused on geographic coverage rather than capacity utilization. Hydrogen fueling rates have dropped slightly in the last two years as some of the higher throughput stations were decommissioned and some of the latest technology stations (700 bar) were gradually brought up to full speed.

For further detail on all of the results you can refer to the final report, which is available on the NREL website [11]. NREL will continue to receive hydrogen infrastructure data from California beyond this project, and we are in discussions with stakeholders about how to best continue to assess FCEV progress in the coming years.

## Acknowledgments

NREL would like to thank the staff from the automotive and energy companies for their collaboration with NREL on advancing the state-of-the-art methods for assessing performance of hydrogen fuel cell vehicles and associated fueling infrastructure. NREL would also like to acknowledge the support from the U.S. Department of Energy's Fuel Cell Technologies Program that has enabled NREL to participate in this exciting project.

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