# National Fuel Cell Electric Vehicle Learning Demonstration Final Report

K. Wipke, S. Sprik, J. Kurtz, T. Ramsden,
C. Ainscough, and G. Saur

**NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.**

**Technical Report**
NREL/TP-5600-54860
July 2012

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Prepared under Task No. HT12.8110

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# Executive Summary

This report 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. This report serves as one of many mechanisms to help transfer knowledge and lessons learned within various parts of DOE's Fuel Cell Technologies Program, as well as externally to other stakeholders. It is the fifth and final such report in a series, with previous reports being published in July 2007 [1], November 2007 [2], April 2008 [3], and September 2010 [4]. Other pathways for communicating results are through technical conferences and through our website, which contains all of our results, presentations, and publications (http://www.nrel.gov/hydrogen/proj_learning_demo.html).

The Learning Demonstration project started in 2004 with DOE competitively selecting four automotive original equipment manufacturer (OEM) and energy partner teams. It was critical for NREL to establish the Hydrogen Secure Data Center (HSDC) to handle the proprietary data from these companies and enable the publication of aggregate results without identifying the companies' individual data contributions. This type of detailed sensitive hydrogen and fuel cell technology data had never been shared and reported outside of the companies before, and the HSDC launched a new paradigm for NREL in how to work with industry partners and their proprietary data. Since the launch of this project DOE's California Hydrogen Infrastructure Project, executed by Air Products and Chemicals, Inc., provided additional data on its fueling stations for inclusion in our analysis.

Two of the four original OEM and energy partner teams concluded their projects on schedule (based on the original five-year planned project duration) and provided their last data at the end of 2009, while two of the vehicle OEMs and Air Products extended 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. Technical staff members from the two teams that concluded their projects were no longer available for review and concurrence of new results based on their legacy data. Publication of the last comprehensive report in September 2010 occurred just after the transition in the makeup of the industry participants who initiated the project in 2004.

This report is the first comprehensive report to include all new or updated results (40 composite data products (CDPs)) published in the last two years. This report recaps the highlights from the first five years and summarizes new results from the final two years of the project. Where possible, we compare performance trends between the first five years and the final two years. The industry partners provided their final project data to NREL in October 2011, and we 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 analyzed data from more than 500,000 individual vehicle trips covering 3.6 million miles traveled and more than 152,000 kg hydrogen produced or dispensed. The three primary objectives of the project were to evaluate fuel cell durability, vehicle driving range, and on-site hydrogen production cost and compare to DOE's targets. The three high-level DOE technical targets for hydrogen FCEVs and infrastructure were:

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

Progress toward these three objectives is summarized in this Executive Summary, with all 99 CDP results covered in detail in the body of the report.

**Fuel Cell Stack Durability:** The maximum number of hours a first-generation fuel cell stack (2003–2005 stack technology) accumulated without repair is 2,375, which is the longest stack durability from a light-duty FCEV in normal use published to date that we are aware of. On average, the rate of the initial power degradation is higher in the first 200 hours and becomes much lower after that, similar to the fuel cell voltage degradation. We also found that stack operation of around 1,000 hours is required to reliably determine the rate of the more gradual secondary degradation. Finally, significant drops in power were observed at 1,900–2,000 hours, providing a solid upper bound on first-generation stack durability. The maximum and average projected times until 10% voltage degradation for first-generation systems were 1,807 hours (best of the four teams) and 821 hours (average of all teams).

For second-generation fuel cell stacks (2005–2007 stack technology), the range of maximum hours accumulated by the four teams was approximately 800 to more than 1,200 hours, and the range of average hours accumulated by the four teams was approximately 300 to 1,100 hours. Relative to projected durability, the Spring 2010 results indicate that the highest single-team average projected time to 10% voltage degradation for second-generation systems was 2,521 hours, with a multi-team average projection of 1,062 hours. Therefore, DOE's 2,000-hour target for durability has been validated.

Over the past two years, additional fuel cell durability data were acquired from updated GM and Daimler vehicles (2007–2009 stack technology) during their extended projects. Because there are only two teams, it is not possible to provide both the maximum and the average without revealing the individual results of both teams, but we can report that the average projected time to 10% voltage degradation of the two teams is 1,748 hours, a significant increase over first-generation and second-generation results, as shown in Table ES-1.

**Table ES-1: Summary of Average Projected Time to 10% Voltage Degradation from the Three Distinct Sets of Vehicles**

| Fuel Cell Generation | First-Generation Fuel Cell Systems | Second-Generation Fuel Cell Systems | Fuel Cell Systems Operated after 2009 Q4 (two OEMs) |
|---|---|---|---|
| Average of all teams' fleet projections to 10% voltage degradation | 821 hours | 1,062 hours | 1,748 hours |

**Vehicle Driving Range:** In FY 2008, the driving range of the project's FCEVs was evaluated based on fuel economy from dynamometer testing (EPA adjusted) and on-board hydrogen storage amounts and compared to the 250-mile target. The resulting second-generation vehicle driving range from the four teams was 196–254 miles, which met DOE's 250-mile range target. In June 2009, an on-road driving range evaluation was performed in collaboration with Toyota and Savannah River National Laboratory. The results indicated a 431-mile on-road range was possible in southern California using Toyota's FCHV-adv fuel cell vehicle [5]. More recently, the significant on-road data that have been obtained from second- and first-generation vehicles allowed a comparison of the real-world driving ranges of all the vehicles in the project. The data show that there has been a 45% improvement in the median distance between fueling events of second-generation vehicles (81 miles) as compared to first-generation vehicles (56 miles), based on actual distances driven between more than 25,000 fueling events. Over the last two years, we saw a continuation of this trend, with a median distance between fuelings of 98 miles, which is a 75% improvement over the first-generation vehicles. Obviously the vehicles are capable of two to three times greater range than this, but the median distance travelled between fuelings is one way to measure the improvement in the vehicles' capability, driver comfort with station location and availability, and how they are actually being driven.

**On-Site Hydrogen Production Cost:** Cost estimates from the Learning Demonstration energy company partners were used as inputs to an H2A analysis [6] 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 from version 2.1 of the H2A Production model indicated that on-site natural gas reformation could lead to a cost range of roughly $8–$10/kg and on-site electrolysis could lead to a hydrogen cost of $10–$13/kg. Note that 1 kg hydrogen 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 cost range of $2.75–$3.50/kg [7] and distributed electrolysis could lead to $4.90–$5.70/kg [8]. Therefore, this objective was met outside of the Learning Demonstration project using distributed natural gas reforming.

**Summary of Results:** We have summarized the previously discussed key performance numbers, along with other metrics of interest such as fuel economy and fuel cell efficiency, and compared them to DOE targets in Table ES-2. The table shows that this project has exceeded the expectations established in 2003 by DOE, with all of the key targets being achieved except for on-site hydrogen production cost, which would have been difficult to demonstrate through this project because the hydrogen stations were not designed, constructed, and utilized as full scale, commercial stations. All 99 composite data products (CDPs) published to date are included in this report as well as directly accessible from our Hydrogen Technology Validation website (http://www.nrel.gov/hydrogen/proj_learning_demo.html).

**Table ES-2: Learning Demonstration Key Performance Metrics Summary**

| Vehicle Performance Metrics | Gen 1 Vehicle | Gen 2 Vehicle | 2009 Target | After 2009Q4 |
|---|---|---|---|---|
| ***Fuel Cell Stack Durability*** | | | **2,000 hours** | |
| Max Team Projected Hours to 10% Voltage Degradation | **1,807 hours** | **2,521 hours** | | -- |
| Average Fuel Cell Durability Projection | 821 hours | 1,062 hours | | 1,748 hours |
| Max Hours of Operation by a Single FC Stack to Date* | 2,375 hours | 1,261 hours | | 1,582 hours |
| ***Driving Range*** | | | **250 miles** | |
| Adjusted Dyno (Window Sticker) Range | **103-190 miles** | **196-254 miles** | | -- |
| Median On-Road Distance Between Fuelings | 56 miles | 81 miles | | 98 miles |
| *Fuel Economy (Window Sticker)* | 42 – 57 mi/kg | 43 – 58 mi/kg | no target | -- |
| *Fuel Cell Efficiency at ¼ Power* | 51 – 58% | 53 – 59% | 60% | -- |
| *Fuel Cell Efficiency at Full Power* | 30 – 54% | 42 – 53% | 50% | -- |

| Infrastructure Performance Metrics | | | 2009 Target | After 2009Q4 |
|---|---|---|---|---|
| ***$H_2$ Cost at Station (early market)*** | On-site natural gas reformation **\$7.70 – \$10.30/kg** | On-site Electrolysis **\$10.00 – \$12.90/kg** | **\$3/gge** | -- |
| *Average $H_2$ Fueling Rate* | 0.77 kg/min | | 1.0 kg/min | 0.65 kg/min |

**$H_2$ Cost:** Outside of this project, DOE independent panels concluded that for 500 replicate stations/year:
Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg** (2006)
Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70** (2009)

*Note that time available to demonstrate fuel cell systems from Gen 2 vehicles and post-2009Q4 vehicles was limited.

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# 1 Project Background and Current Status

## 1.1 Introduction

This report 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. This report serves as one of many mechanisms to help transfer knowledge and lessons learned within various parts of DOE's Fuel Cell Technologies Program, as well as externally to other stakeholders. It is the fifth and final such report in a series, with previous reports being published in July 2007 [1], November 2007 [2], April 2008 [3], and September 2010 [4]. Other mechanisms have included briefings to FreedomCAR and Fuels technical teams, detailed data and methodology discussions with our industry partners, presentations at technical conferences, presentations at DOE's Annual Merit Review, presentation via a live webinar, and participation in groups such as the California Hydrogen Business Council, the California Fuel Cell Partnership, and various U.S. Fuel Cell Council working groups. All of the results are also posted on the National Renewable Energy Laboratory's (NREL's) website (http://www.nrel.gov/hydrogen/proj_learning_demo.html).

The Learning Demonstration project started in 2004 with four automotive original equipment manufacturers (OEMs) and energy partner teams. Since that time DOE's California Hydrogen Infrastructure Project, executed by Air Products and Chemicals, Inc., also provided data on its fueling stations for inclusion in our analysis. See Figure 1 for photos of the first- and second-generation vehicles and the structure of the industry teams that provided data to NREL. Fuel cell vehicle results will be discussed in section 2.1. Figure 2 shows the five different types of hydrogen fueling stations evaluated in this project, which will be discussed in section 2.2.

Two of the four original OEM and energy partner teams concluded their projects on schedule (based on the original five-year planned project duration) and provided their last data at the end of 2009, while GM, Daimler, and Air Products extended 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. Technical staff members from the two teams that concluded their projects were no longer available for review and concurrence of new results based on their legacy data. Publication of the last comprehensive report in September 2010 occurred just after the transition in the makeup of the industry participants who initiated the project in 2004, so this report is the first comprehensive report to include all new or updated results (40) published in the last two years. This report will recap the highlights from the first five years as well as summarize new results from the final two years of the project. When possible, we compare performance trends between the first five years and the final two years.

The industry partners provided their final project data to NREL in October 2011 and we have 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. NREL has analyzed data from more than 500,000 individual vehicle trips covering 3.6 million miles traveled and 152,000 kg hydrogen produced or dispensed. The three primary objectives of the project were to evaluate fuel cell durability, vehicle driving range, and on-site hydrogen production cost. The executive summary shows progress toward these objectives, while the body of this report covers all of the results in detail.


**Figure 1: Photographs of the industry partners who provided vehicle and infrastructure data to NREL for this project (Photo credit: Keith Wipke)**

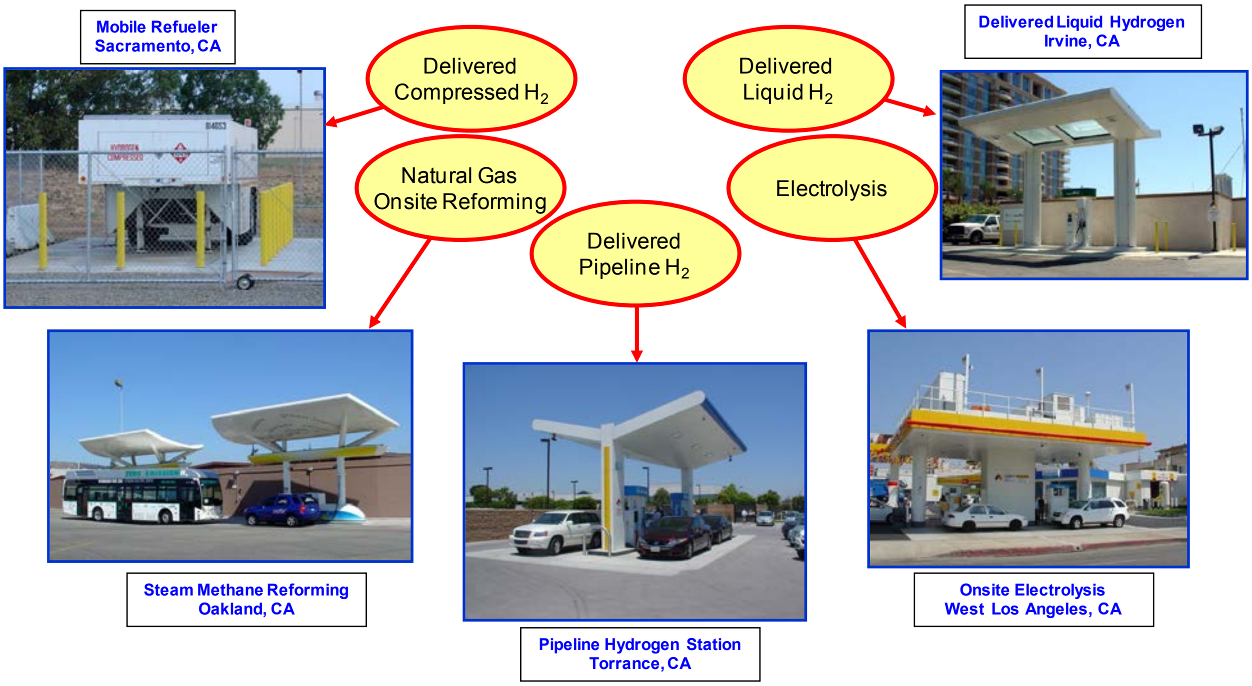


**Figure 2: Five examples of hydrogen production and fueling facilities (Photo credit: Keith Wipke)**

## 1.2 Objectives and Technical Targets

NREL's primary objective for this project was 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 was the publishing of results for benchmarking technology status and for use by key stakeholders to help inform their 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).

## 1.3 Approach

NREL's approach to accomplishing the project's objectives was 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 each individual company with detailed analytical results 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. See Figure 3 for a diagram of this work flow and Figure 4 for a graph showing the steady rate at which data was received and analyzed within the HSDC.

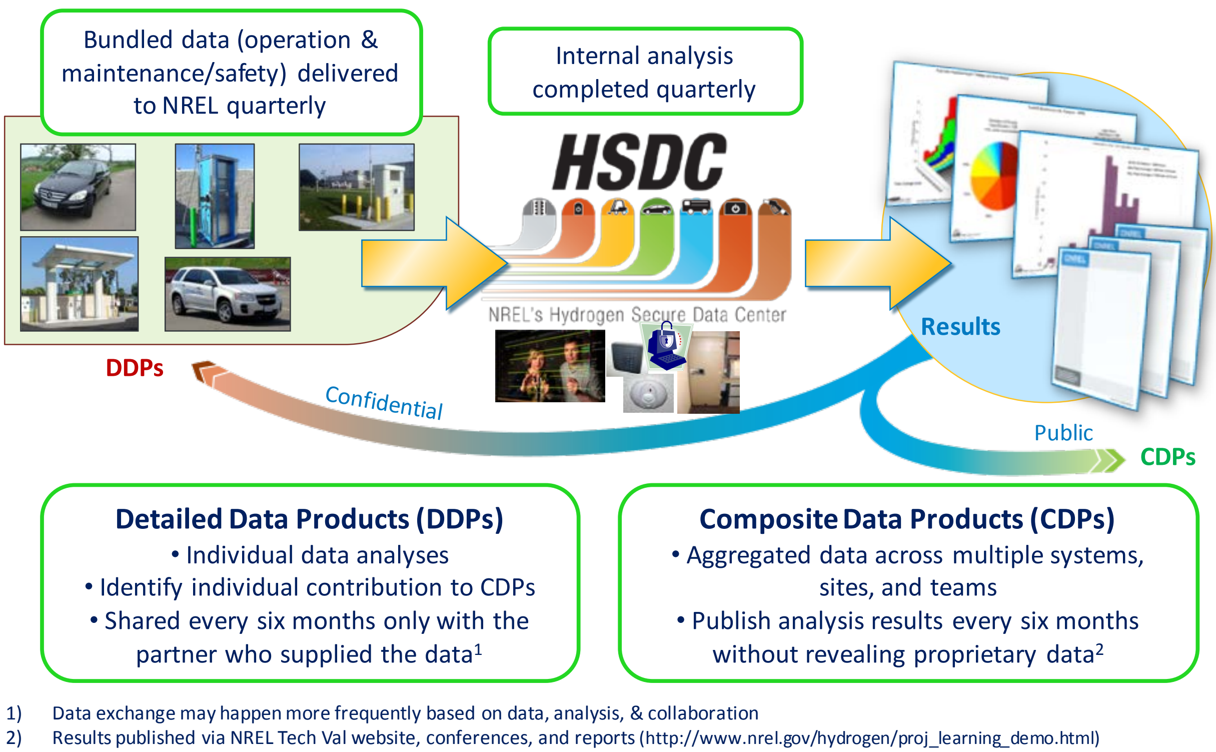


**Figure 3: Data flow through NREL's HSDC, resulting in both Detailed Data Products and Composite Data Products**

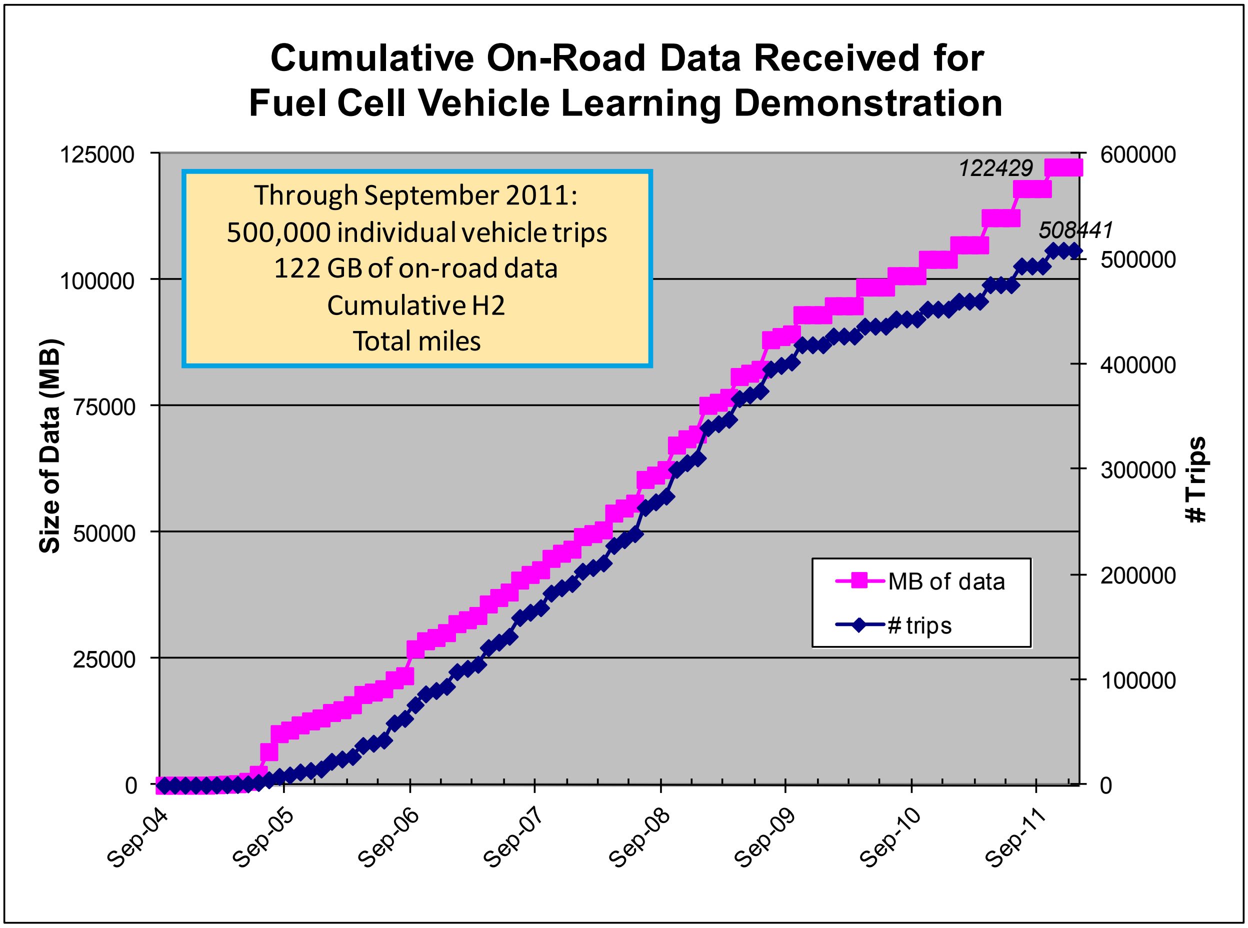


**Figure 4: Quantity of on-road vehicle data received and analyzed within the HSDC**

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 functionality of the NRELFAT has been covered in previous publications, so it will not be discussed in detail here. Figure 5 shows a screen capture of the first screen from the graphical user interface of the NRELFAT tool. 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 [9].

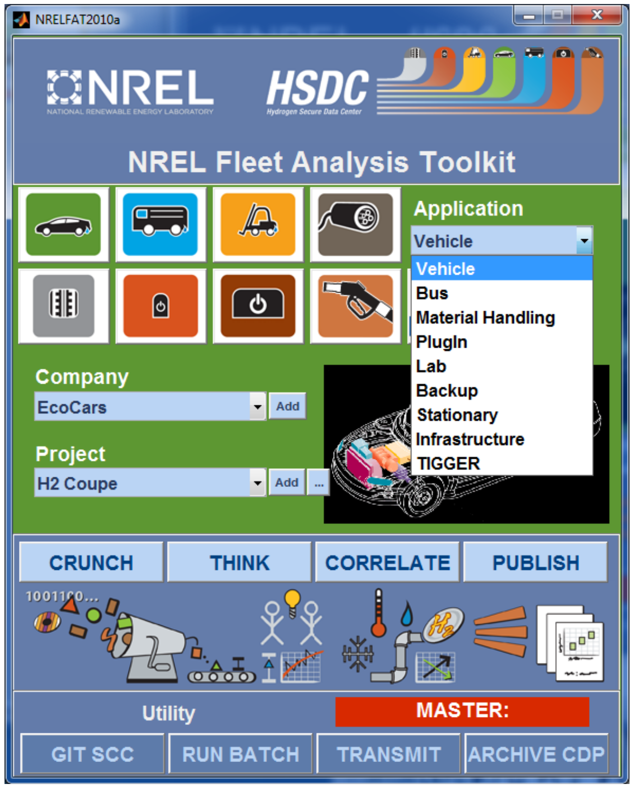


**Figure 5: Introductory screen of NREL's Fleet Analysis Toolkit**

## 1.4 Status

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 122 GB of second-by-second on-road vehicle data from more than 500,000 individual trips.

The project was scheduled to be completed in September 2009. 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 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 hydrogen fueling stations. As shown in Figure 6 (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 technical improvements between the first- and second-generation fuel cell vehicles were:

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

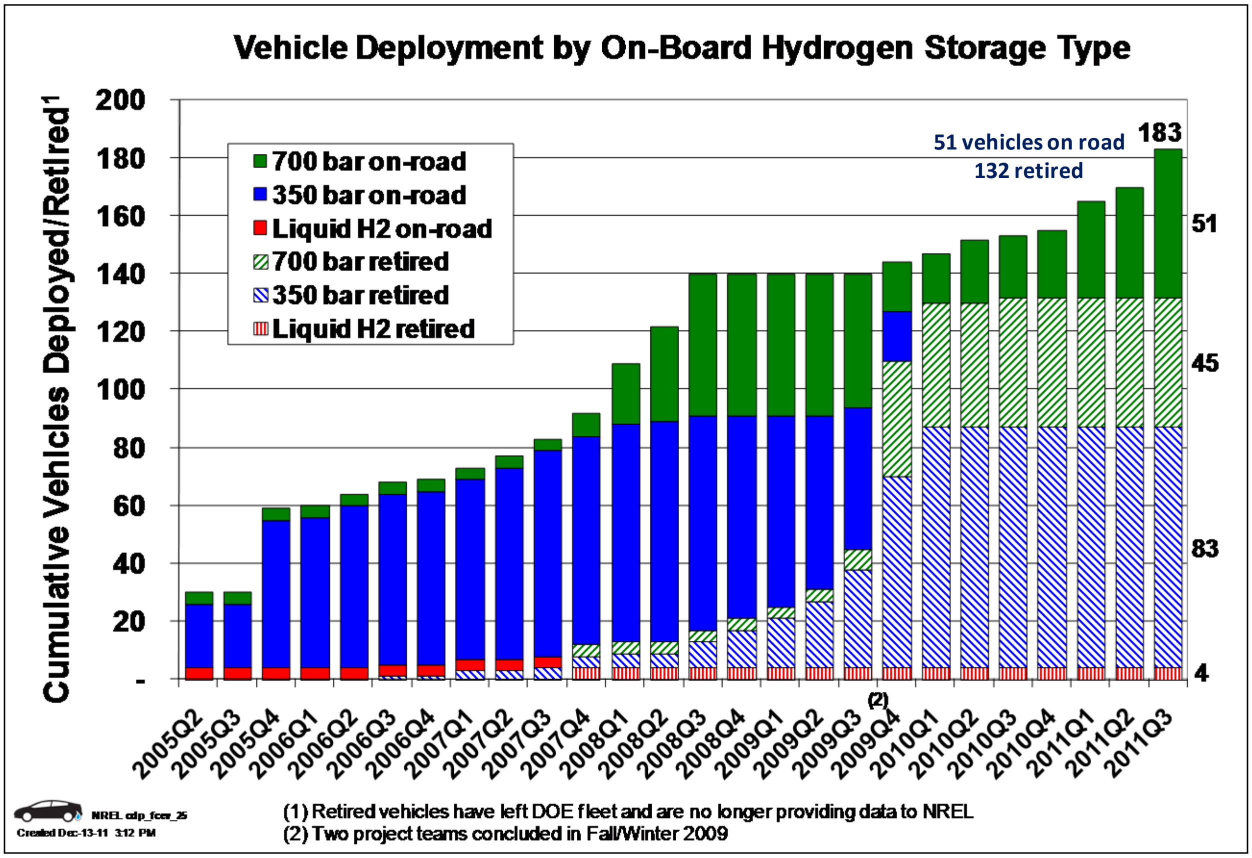


**Figure 6: Cumulative number of vehicles deployed, by hydrogen storage type and status (CDP25)**

Figure 7 (CDP31) shows the cumulative number of stations deployed with a total of 25. As of September 30, 2011, 12 stations were decommissioned, 6 continued operation outside of the project, and 7 were providing data to NREL within the project. Stations demonstrated five major hydrogen infrastructure technologies (see Figure 8 (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 and natural gas reforming 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, new or upgraded stations are being opened in California as a result of the combined efforts of the California Air Resources 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 next few years when the number of FCEVs is large enough to create a market pull for private sector investment in hydrogen infrastructure.

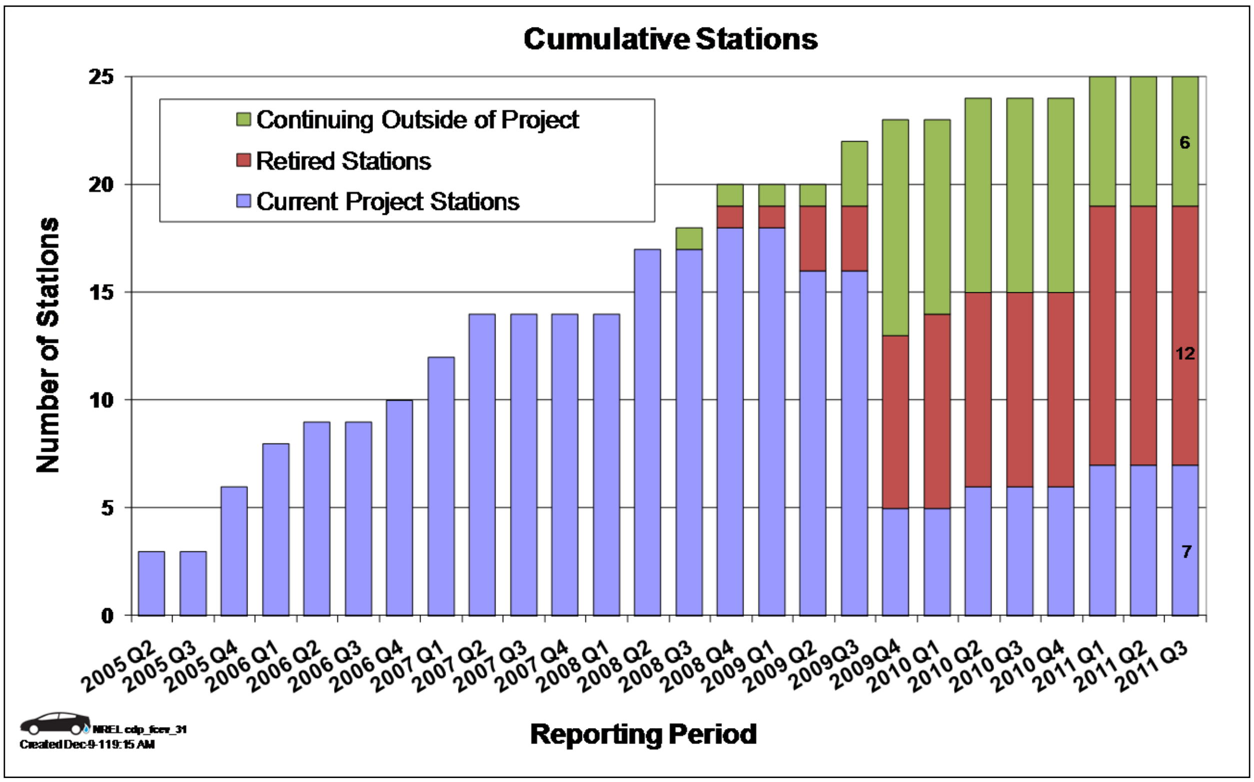


Figure 7: Cumulative project stations commissioned with current status (CDP31)

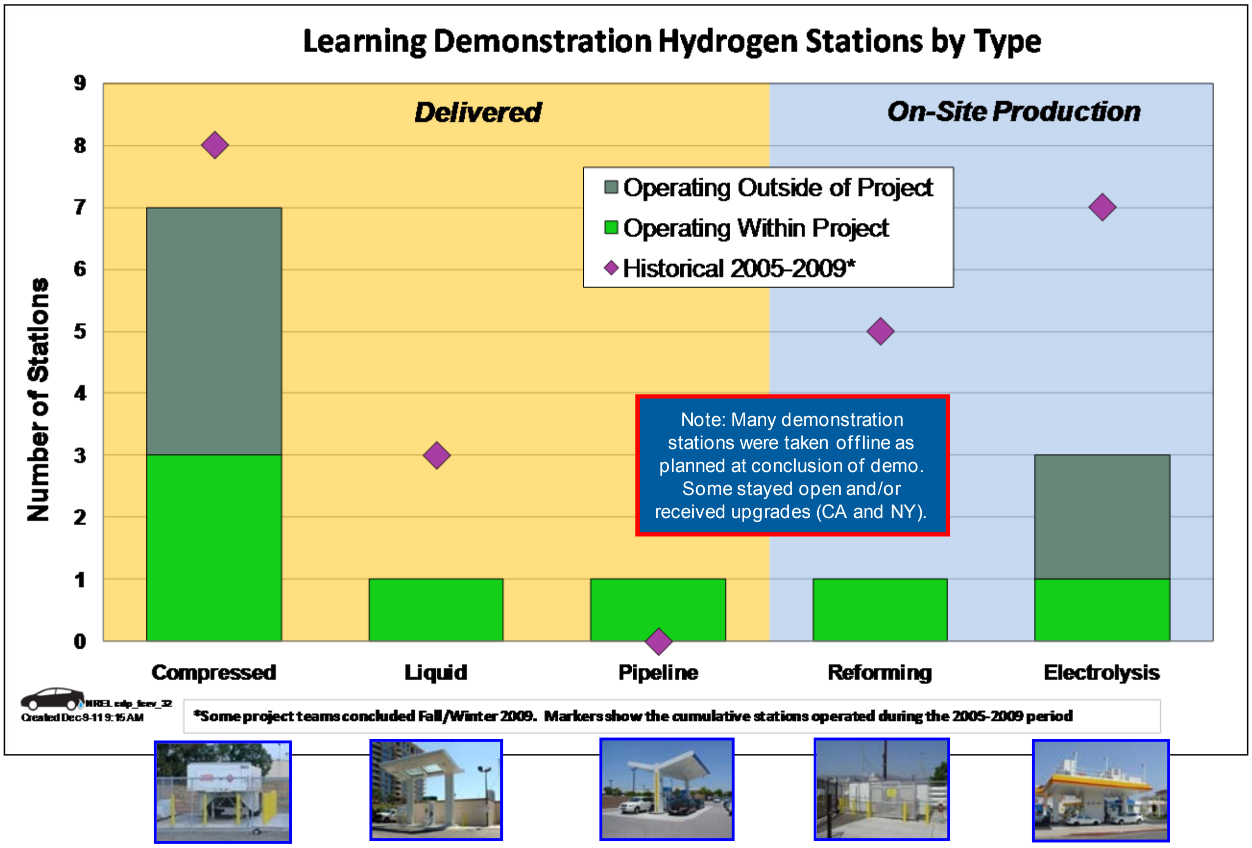


**Figure 8: Multiple types of hydrogen fueling stations were deployed in the Learning Demonstration (CDP32)**

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. When 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 and Advanced Vehicles Data Center station locator [10], 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 (see Figure 9). Additionally, the CEC will be providing up to $18.7 million for new or upgraded stations in California [11] to prepare for upcoming vehicle launches planned by the OEMs in the 2014–2017 timeframe.

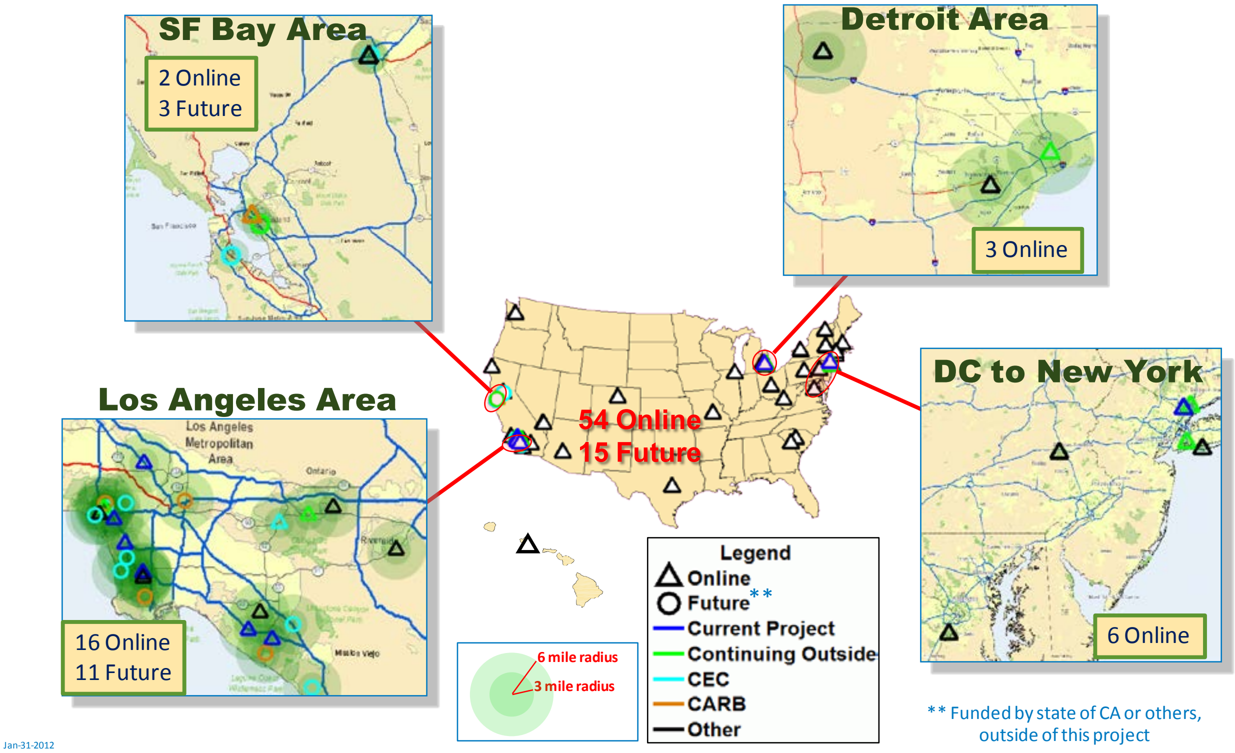


**Figure 9: Locations of current and future hydrogen stations in the United States as of January 2012**

## 2 Results

The results discussed in this report came from analyzing seven years of vehicle and infrastructure data (through September 2011). A total of 99 CDPs were published and presented publicly over this period (see Figure 10 for thumbnails of the complete set of CDPs). Because there were so many technical results from the project, they could not all be discussed during 15–20 minute conference presentations. Therefore, in January 2007 NREL launched a Web page at http://www.nrel.gov/hydrogen/cdp_topic.html to provide the public with direct access to the results (see Figure 11 for a screen capture of this Web page). The Web page makes current and archived CDPs available to the public. Highlights from the most recent CDPs will be presented as Winter 2011 results at the EVS-26 conference and at the 2012 DOE Hydrogen and Fuel Cells Program Annual Merit Review. NREL is also in the process of taking select results and making them interactive (we call them iCDPs) through new Web development tools. In order to focus on high-level results, conclusions, and trends, this report will discuss each of the results briefly. The results are organized and grouped by technical topic. The last section of this report (section 6) includes all of the CDPs in the order they are referenced to keep the flow of the discussion.

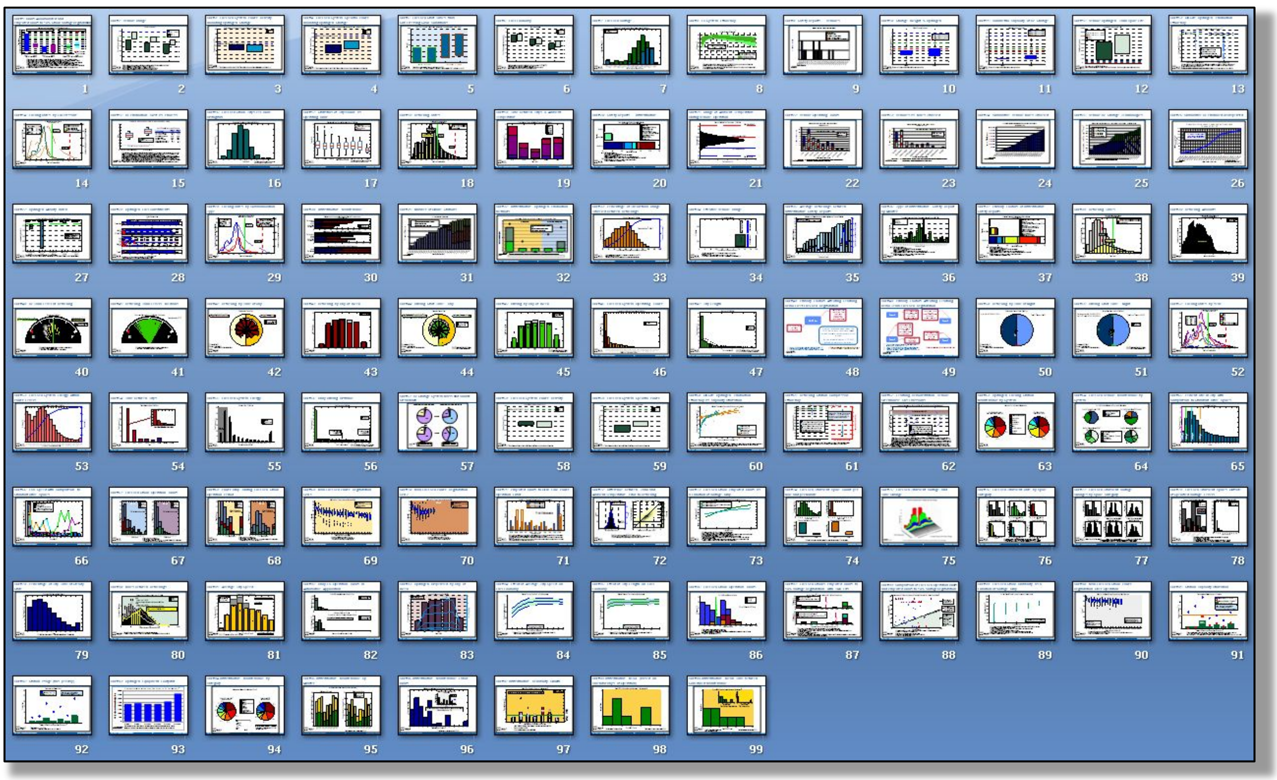

**Figure 10: Thumbnail images of the complete set of 99 CDPs published and updated during the project**

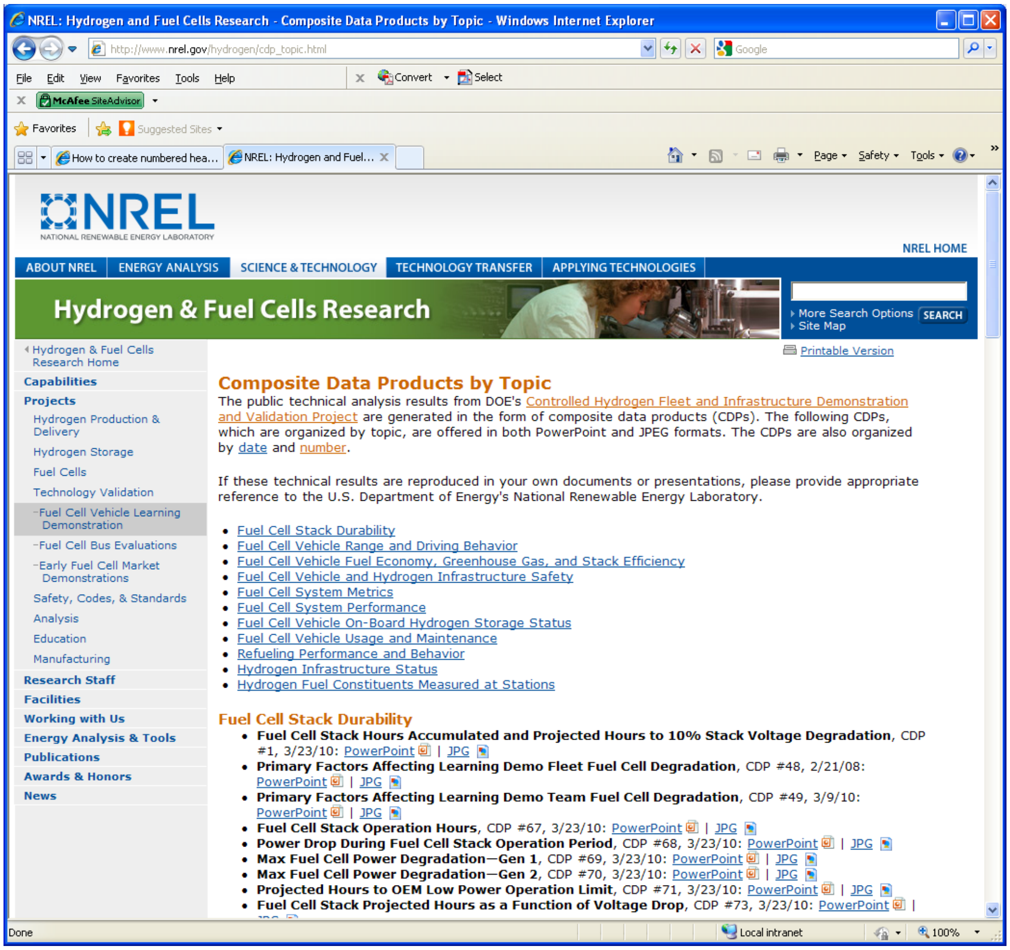


**Figure 11: Screen capture of the composite data product page from NREL's Technology Validation website**

## 2.1 Vehicle Results

### *2.1.1 Fuel Cell System Efficiency*

Researchers from the car companies measured fuel cell system efficiency from select vehicles on a vehicle chassis dynamometer at several steady-state points of operation. NREL worked with the companies to ensure that appropriate fuel cell balance-of-plant electrical loads were included in the measurements. This ensured that the results were comparable to the target and based on the entire system rather than just the fuel cell stack. DOE's technical target for net fuel cell system efficiency at quarter-power is 60%. Baseline data from the four Learning Demonstration teams in 2006 showed a range of net system efficiency from 51% to 58% for first-generation (Gen 1) systems, which was very close to the target. As second-generation (Gen 2) vehicles were introduced, the companies also performed baseline dynamometer testing that revealed an efficiency of 53% to 59% at quarter-power, within one percentage point of the target. In 2009 we expanded this CDP to include a comparison of the efficiency at full power, for which DOE's target was 50% net system efficiency (Figure 13, CDP08). The data show first-generation systems as having 30% to 54% efficiency at full power while second-generation systems have 42% to 53% efficiency, exceeding the 50% target. Additionally, we included the ranges of Gen 1 and Gen 2 efficiency data from the four teams as two shaded green sections, showing that Gen 2 data are more closely clustered (and in general, higher) than Gen 1 data.

### *2.1.2 Fuel Cell Operating Points*

Because a fuel cell system's peak efficiency for transportation applications is normally at low power levels (typically 10% to 25%), we evaluated the fuel cell system operation from a number of different perspectives to better understand whether the unique performance characteristics of the fuel cell system were being maximized. A significant amount of time is being spent at low fuel cell system power (Figure 14, CDP46). In fact, the teams' average amount of time spent at <5% of peak power was over 50%. We subdivided these bars into the time with zero speed to show that almost all of the time with zero speed is at less than 10% fuel cell system power. However, for overall vehicle fuel efficiency, the critical metrics are the amount of energy spent at various power levels and the efficiency at those power levels. We found that much of the fuel cell energy (almost 50%) is expended at fuel cell power levels between 20% and 50% of peak power (Figure 15, CDP53). This matches up very well with the peak fuel cell system efficiency points (at approximately 25% power) previously discussed. Only about 25% of the energy is expended at power levels less than 15% of peak power, indicating that low-power efficiency is not as important as the percentage of time spent there would imply. The high amount of time spent at low power levels may be because of the demonstration nature of this project and not typical in traditional vehicles.

### *2.1.3 Duty-Cycle Evaluation*

In order to understand why so much time was spent at low power, we analyzed the lengths of all trips and compared the results to national statistics (Figure 16, CDP47). With more than 40% of the Learning Demonstration trips being less than one mile, it is clear that the amount of time spent at low fuel cell power is due in part to a large number of short trips for which the vehicle is not likely accelerated to higher speeds. This differs from the national driving statistics (overlaid with pink diamonds on this same graph), which show that only about 10% of the national average trips are less than one mile. If a large number of starts per hour is one of the major degradation factors, as has been reported at the laboratory scale, then this large number of short driving trips could be prematurely shortening the life of the Learning Demonstration fuel cells.

Further investigation would be necessary before that linkage could be made based on analysis of the real-world data.

We have received many questions about how the vehicles were driven; therefore, we created two CDPs that compare the Learning Demonstration driving with well-known dynamometer drive cycles. Figure 17 (CDP66) compares the distribution of operating time to that of four dynamometer drive schedules used for EPA and Japanese emissions certification. We can see that the large amount of time spent at 0–5 mph matches most closely to the Japanese 10-15 mode drive schedule (40% of time spent in this speed bin). The Learning Demonstration distribution has a very low percentage of time at the higher speeds contained in the HWFET (highway driving) and US06 (aggressive acceleration/deceleration) driving schedules. This is not surprising, given that many of the vehicles were deployed in congested traffic regions such as New York and Los Angeles. The gray portion of the 0–5 mph bar shows the zero-speed idle time, which makes up about 28% of all Learning Demonstration vehicles' driving time. Figure 18 (CDP 65) compares the distribution of the trip idle time percentages within each trip to the same four drive cycles. The Learning Demonstration most closely matches the percentage idle of the UDDS (urban driving) cycle with about 12% of the trips matching that idle time of about 19%.

While understanding the vehicle usage relative to standard drive cycles is useful to establish a common state of reference, it doesn't relate the vehicle usage to everyday typical drivers and how they use vehicles. For that we turned to the National Highway Transportation Survey [12] and the average trip speed (Figure 19, CDP81). We graphed the average trip speed histogram of all of the Learning Demonstration trips in 5 mph increments, and then added the NHTS data (pink diamonds). There are some strange histogram artifacts contained in the NHTS source data that make the points jump around in the 15–30 mph ranges. If we smoothed the NHTS data points in those ranges it would be similar to the data from the last two years of the Learning Demonstration, shown in the orange bars. The average trip speeds from the first five years (gray bars) are not as close to the NHTS data, with a bias toward more lower-speed driving.

### 2.1.4 The Impact of Short Trips

There has been much public attention on the potential for plug-in electric vehicles (PEVs) to improve the United States' oil-dependency situation. The Learning Demonstration vehicle data were evaluated to see how these early FCEVs were being driven (mostly in fleet operation) and what impact these duty cycles would have on plug-in vehicles and potential future plug-in versions of these FCEVs. We first looked at the amount of energy consumed by all Learning Demonstration vehicle trips (Figure 20, CDP55) and found that about 35% of the trips required less than 0.5 kWh of energy to be produced by the fuel cell system (red "FC" bar in the figure). This indicates that a battery would not require much storage energy to handle several plug-in FCEV trips for the Learning Demonstration vehicles as long as the battery could also provide the peak power required and survive the larger swings in state-of-charge. However, this is not the entire story, and if the assumption is that PEVs will primarily be recharged slowly during off-peak/night times, then these data need to be analyzed with both the daily miles traveled (Figure 21, CDP56) and the amount of time between trips (Figure 22, CDP54) in mind.

What we find is that an effective 20-mile electric range would allow electrification of about one-half of the Learning Demonstration fleet's daily miles traveled. However, this would satisfy only about one-quarter of the national daily average miles traveled. An effective 40-mile electric range would allow electrification of more than two-thirds of the Learning Demonstration vehicle miles and just over half of the national daily miles traveled. While many US drivers average less than 40 miles per day, longer trips are common and a vehicle capable of both short and long trips are the expected norm. Extended-range electric vehicles allow the benefit of the early electrified miles without sacrificing the utility for all trips. While the large number of Learning Demonstration vehicle "hot-starts" could be beneficial for FCEV fuel efficiency (about 60% of trips occur within one hour of the previous trip), this also indicates that there may be limited opportunities for daytime opportunity charging (of the 60% of the trips that are separated by less than one hour, more than half of those are separated by less than 10 minutes). Having an engine (internal combustion engine (ICE) or fuel cell) on-board maximizes the number of miles that can be driven electrically through using a smaller battery pack that is frequently fully discharged. This is because the battery does not have to be recharged during the day in order to avoid running out of charge before returning home in the evening. The bottom line is that a thorough analysis of actual target-market duty cycles and charging opportunities must occur for the benefits of PEVs to be understood, preferably through using actual PEV fleets and recharging behavior. Such an evaluation has been initiated by DOE's Vehicle Technologies Program and NREL has also initiated such analysis and studies for an OEM with large demonstration data sets.

### *2.1.5 Vehicle Fuel Economy*

Vehicle fuel economy was measured using city and highway drive-cycle tests (Figure 23, CDP06, left two bars, each bar representing the range of four points, one from each OEM) on a chassis dynamometer using draft SAE J2572. These raw test results were then adjusted according to U.S. Environmental Protection Agency (EPA) methods to create the "window-sticker" fuel economy that consumers see when purchasing the vehicles (0.78 x Hwy, 0.9 x City), with the ranges displayed in the center two bars. This resulted in an adjusted fuel-economy range of 42–57 miles/kg hydrogen for the four teams for first-generation vehicles and 43–58 miles/kg hydrogen for second-generation vehicles. As with all vehicles sold today, including gasoline hybrids, actual on-road fuel economy is slightly lower than this rated fuel economy (right two bars). The on-road fuel economy spans the range of 31–45 miles/kg hydrogen for Gen 1 and 36–52 miles/kg hydrogen for Gen 2. This last comparison shows an important finding, which is that Gen 2 vehicles have made significant system and technology improvements to allow higher fuel economy (relative to Gen 1) to be obtained even when driven under all different kinds of conditions. This result was not updated again after publication in 2010.

The EPA has adjusted its testing and reporting methodology, beginning with model-year 2008 vehicles, to try to make the window-sticker fuel economy better reflect on-road driving performance. This project used the EPA adjustment that was in place when the vehicles were introduced to avoid performing retests or applying the new standard corrections that have not yet been validated for application to hydrogen FCEVs.

In addition to the overall average on-road fuel economy analysis, we also evaluated on-road fuel economy for each trip over the last two years and then examined the overall fuel economy of the entire fleet as a function of average trip speed and trip length. As shown in Figure 24 (CDP84), and as expected, the average trip speed has a significant impact on on-road fuel economy. The fuel economy is almost two times better at a 30–55 mph average trip speed than it is at very low speeds (~5 mph). We also see the fuel economy starts to drop at average trip speeds greater than 50 mph. This graph is a plot of the average of the fleet medians (solid curve) along with the range of individual trips covering the 25$^{th}$ to 75$^{th}$ percentile data in order to filter out everything outside of the middle 50%. While we also examined the effect of trip length on fuel economy (Figure 25, CDP85), we saw almost no effect on fuel economy except at short trip lengths of less than 10 miles.

### *2.1.6 Vehicle Driving Range*

Vehicle driving range was calculated using the fuel economy results discussed above and multiplying them by the usable hydrogen stored onboard each vehicle (Figure 26, CDP02). Using the EPA-adjusted fuel economy resulted in a first-generation vehicle range from just over 100 miles up to 190 miles from the four teams. The second-generation vehicles subsequently pushed this range higher, to 196–254 miles using 700-bar storage, and met the DOE 250-mile range objective established for this project. In June 2009, an on-road driving range evaluation was performed in collaboration with Toyota and Savannah River National Laboratory. The results indicated a 431-mile on-road range was possible in southern California using Toyota's FCHV-adv FCEV [5]. See Table 1 for the results from that experiment.

**Table 1: Test Results from 1-day Range Test of Two Toyota FCHV-adv Fuel Cell Vehicles in Southern California in 2009**

| | Average trip distance (miles) | $H_2$ consumed (kg) | Remaining usable $H_2$ (kg) | Calculated remaining range (miles) | (miles) | (miles) |
|---|---|---|---|---|---|---|
| Vehicle #1 | 331.50 | 4.8255 | 1.4854 | 102.04 | 433.55 | 431 |
| Vehicle #2 | 331.45 | 4.8751 | 1.4328 | 97.41 | 428.87 | |

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 the previously published CDP80. 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 distributions from the first five years in two different shades of gray and then overlaid the latest results from post-2009Q4 data in yellow. See the recently updated Figure 27 (CDP80) for these driving range results.

The results show that the median distance between fueling events was 56 miles for first-generation vehicles (light gray), 81 miles for second-generation vehicles (dark gray), and 98 miles for post-2009Q4 vehicles (yellow). This reflects a 45% increase between first- and second-generation vehicles and a 75% increase 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 fuel availability and reliability resulted in 21% longer driving distance between fuelings for the latest vehicles compared to the second-generation vehicles. It should be noted that these same vehicles were capable of 200–250 miles between fuelings if driven to empty under controlled driving conditions.

As the industry moves toward commercial vehicle 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).

Two other CDPs relating to range were also generated and previously reported. Figure 28 (CDP33) shows a histogram of the distance vehicles actually traveled between fuelings as a percentage of each vehicle's dynamometer range. This shows that the majority of the vehicles (75%) travel less than 50% of the dynamometer range between fuelings. This is due to several factors, but the dominant ones are limited hydrogen infrastructure, fear of running out of fuel, and actual on-road fuel economy being lower than the dynamometer fuel economy, as has already been discussed. Figure 29 (CDP34) shows the on-road range of the four teams (green bars) as a percentage of their dynamometer range. The spread of this on-road range has decreased significantly for Gen 2 (light green) compared to Gen 1 (dark green), showing the vehicle's robustness to differences in driving styles relative to vehicle fuel economy and subsequent range even more clearly than in the fuel economy CDP.

### *2.1.7 On-Board Hydrogen Energy Storage System Status*

Storage data were reported to NREL using a hydrogen storage system spreadsheet. This spreadsheet includes the breakdown of the mass and volume of the hydrogen itself, the pressure vessel, and the balance-of-plant. The balance-of-plant category includes:

- Controls and measurement (hydrogen storage-specific electronics)
- Fuel delivery to power plant (plumbing)
- Hazard mitigation components (hydrogen sensors, pressure release devices (PRDs)), venting)
- Fueling equipment (filters, nozzle receptacle, piping, communications, grounding)
- Mounting brackets, auxiliary equipment (thermal management, etc.).

Figure 30 (CDP10) shows the difference in the ranges of mass (as a percentage of the total storage system mass) stored in the teams' 350-bar and 700-bar systems. We can see the potential for the percentage of system mass to increase in the second-generation (700-bar) systems, but the second-generation systems also typically have the benefit of economies of scale because they have a larger total mass of hydrogen stored to meet customer range expectations.

Figure 31 (CDP11) shows the same type of 350-bar vs. 700-bar comparison but for the volumetric capacity (how much hydrogen can be stored per storage system volume). This is where the advantage of going to a higher pressure really shines, showing a significant increase in the mass of hydrogen stored per liter, making the packaging of the system in a vehicle more attractive.

Finally, the percentage breakdown by each of these categories was averaged across the four teams and displayed in pie charts to examine the differences between 350-bar and 700-bar storage for the mass and volumetric characteristics (Figure 32, CDP57). The comparison shows that while the average hydrogen weight percentages are similar for 350 and 700 bar (within 1%), and the pressure vessel and balance-of-plant for 700 bar take up a larger percentage of the system volume, the 700-bar systems ultimately allow for a more compact package and extended range. Figure 33 (CDP12) shows the tank cycle life for both generations of vehicles and shows some improvement in tank cycle life, still far exceeding DOE's cycling goals set for advanced materials-based technologies.

### 2.1.8 Fuel Cell System Power Density and Specific Power

DOE's target for fuel cell system power density in 2010 and 2015 is 650 W/L and for fuel cell system specific power is 650 W/kg. System-level data were gathered from the fuel cell teams and aggregated into ranges for first- and second-generation systems separately. First-generation fuel cell systems had a specific power range of 183–323 W/kg, while second-generation systems improved to the range of 306–406 W/kg (Figure 34, CDP59). On the other hand, fuel cell system power density (Figure 35, CDP58) stayed the same or dropped slightly (staying in the range of 300–400 W/L), perhaps because the second-generation systems had more balance-of-plant in order to support the required freeze tolerance. Some of the fuel cell systems also had increased power output, and may have been optimized for efficiency and durability rather than power density.

Because of the attention that plug-in hybrid vehicles were getting in 2009, we were asked to generate fuel cell system power density and specific power results that also included the hydrogen storage and then compare those results to the FreedomCAR targets. For fuel cell system specific power, we found that while Gen 2 showed significant progress over Gen 1 (Figure 36, CDP04), the 178–261 W/kg was still shy of the 325 W/kg FreedomCAR research goal when the hydrogen storage system was included. The fuel cell system power density (Figure 37, CDP03), with hydrogen storage included, came extremely close (for both Gen 1 and Gen 2) to satisfying the 2010 and 2015 FreedomCAR research goal of 220 W/L (Gen 1 was 152–214 W/L, and Gen 2 was 127–213 W/L). This indicates that fuel cell systems are a relatively compact means of storing both energy and power relative to batteries.

### 2.1.9 Fuel Cell Durability (from first 5 years)

Fuel cell stacks will need roughly a 5,000-hour life to meet light-duty vehicle customer expectations and compete with conventional technologies. For this demonstration project, targets were set by DOE at 1,000 hours in 2006 and 2,000 hours in 2009. Results were first published in Fall 2006. These results were relatively preliminary because most stacks at that time only had a few hundred hours or less of accumulated on-road operation. Because DOE's target for 2006 was 1,000 hours and the vehicles had operated a small fraction of that time frame, NREL developed a methodology for projecting the gradual degradation of the voltage based on the data received to date. This involved creating periodic fuel cell polarization curve fits from the on-road stack voltage and current data and calculating the voltage at high current. This enabled us to track the gradual degradation of the stacks with time and do a linear fit through each team's data. We then compared these results to the first-generation target of 1,000 hours for 2006.

Many improvements have been made in NREL's fuel cell durability analysis methodology over the seven-year period, including using a two-segment linear fit and a weighting algorithm to come up with a more representative, robust, and automatic fleet average. The durability analysis was applied to every fuel cell stack with on-road operation data. A fleet average included all fuel cell stacks of a common design and technology generation. We found that the individual fuel cell degradation rates could vary within a technology generation and common design. The maximum number of hours a first-generation stack accumulated without repair is 2,375, which is the longest stack durability from a light-duty FCEV in normal use published to date that we are aware of (see left blue bar in Figure 38, CDP01). As shown in Figure 39 (CDP69), on average the rate of initial power degradation is higher in the first 200 hours and becomes lower after that. We also found that around 1,000 hours of data on each stack were required to reliably determine the secondary degradation rate. Finally, with significant drops in power observed at 1,900–2,000 hours, it appears as though this is a solid upper bound on first-generation stack durability (characterizing 2003–2005 technology). The projected time until 10% voltage drop for first-generation stacks was 1,807 hours (best of the four teams) and 821 hours (average of all teams).

For second-generation fuel cell stacks (2005–2007 technology), the range of maximum hours accumulated by each team was approximately 800 to more than 1,200 hours (Figure 38, CDP01), and the range of average hours accumulated by each team was approximately 300 to 1,100 hours. Relative to projected durability, the Spring 2010 results indicated that the highest single-team average projected time to 10% voltage degradation for second-generation systems was 2,521 hours, with a multi-team average projection of 1,062 hours. Therefore, the 2,000-hour target for durability has been validated. Figure 40 (CDP70) shows that not as much data had been gathered on second-generation stacks at the time that CDP was published in Spring 2010, and so the 10% durability projections were less certain for Gen 2 stacks than for Gen 1 stacks.

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. There are many systems that can successfully operate beyond 10% voltage degradation, and so we projected the voltage degradation to 30% to show the sensitivity to this value. As you can see in Figure 41 (CDP73), the diamond values on the left are the same as the average projections from Figure 38 (CDP01). The projected hours then increase as the voltage drop is allowed to increase. To avoid unconstrained extrapolation in our durability projections, especially on stacks with low hours demonstrated and low degradation rates, we placed a limit of two times the highest hours demonstrated within a company's fleet. The Gen 2 curve does not rise as fast as the Gen 1 curve because of this limit on the extrapolation. Gen 2 had a smaller quantity of data and so there were more active limitations on the extrapolations. For Gen 1, which has more operation time and fewer extrapolations, increasing the percentage from 10% to 30% roughly doubles the projected time to that voltage drop, although the stacks may not operate as required at the higher voltage degradation levels.

In addition to analyzing voltage drop, we examined the stack power drop because that is what is ultimately converted into propulsion through the electric motor and what the driver experiences. Figure 42 (CDP68) shows histograms for Gen 1 and Gen 2 percentage power drop for each stack, and the stacks' status. One thing you can see for Gen 1 is that many stacks had a power drop of more than 40% before being retired, and some of those stacks continued to be operational. The Gen 2 stacks that have been retired exhibited a high power drop (greater than 40%), and a lot of the Gen 2 stacks range between 10% and 20% power drop. Since we calculated each stack's power drop, we were asked to examine the time to OEM-acceptable power drops; each OEM provided an acceptable percentage for its vehicles. Figure 43 (CDP71) shows these results, with an additional distinction of separating out the projections that were made from stacks with less than 200 hours from those with more than 200 hours. In general, many of the low projections are based on stacks with low operating hours for both Gen 1 and Gen 2. Comparing these results to the 2009 2,000-hour target, 27% of Gen 1 stacks exceeded that projection and 17% of Gen 2 stacks exceeded it. As previously mentioned, more data would be required to fully assess the durability of the second-generation systems, as can be seen in the stack-hour histogram shown in Figure 44 (CDP67), which also shows that only two Gen 2 stacks had been removed for low performance. The blue bars indicate the stacks that are no longer accumulating hours but were not removed due to low performance. Most of these stacks stopped accumulating data either because the project team concluded at the end of 2009 or because the host vehicles were retired for a variety of reasons.

### *2.1.10 Fuel Cell Durability (from final 2 years)*

Over the past two years, additional fuel cell durability data were acquired from improved GM and Daimler vehicles (2007–2009 technology) during their extended projects. 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 Figure 45, CDP 86), 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 Figure 46 (CDP90), there is a knee in the curve at around 200 hours (which follows the same trend as data from the first five years of the analysis), after which the degradation rate significantly decreases. 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 [13]. 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 (Figure 47, CDP87). While this is lower than the maximum ~2,500 hours projected from the second-generation vehicles, the primary reason is the limited amount of data accumulated. Projections from stacks with low operation hours tends to be lower because the initial degradation is a dominant factor in the projections. As previously mentioned, to avoid unconstrained extrapolation in our durability projections, especially on stacks with low hours demonstrated and low degradation rates, we placed a limit of two times the highest hours demonstrated within a company's fleet. 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 constraint being in place. To explore the impact of the first 200 hours, we also analyzed the data with our voltage fits starting after the first 200 hours (lower half of figure). The projection to 10% voltage drop increased by 500 hours and more stacks become limited by the 2X projection constraint. This indicates that the voltage projections are sensitive to the impact of the early degradation observed in the field (especially with low-operation-hour stacks), which was also the case for the first- and second-generation vehicles from the first five years.

Figure 48 (CDP88) shows a more detailed look at our recent durability projections, with a symbol for each fuel cell stack. It plots the projected hours as a function of the operation hours of that stack, including whether the stack was still in service, retired, or had its projection limited to twice the team's highest demonstrated hours. By looking at the red diamonds (retired stacks) we see that many of them operated past 10% voltage degradation before being retired. At the top of the graph, the brown triangles indicate the stacks that have been limited to 2X the max hours accumulated from their team. Many of these stacks had very limited hours of operation, which is why it was important to limit their projections from being unreasonable. Finally, as we did for Gen 1 and Gen 2 stacks, we can similarly explore the projected time to voltage drops up to 30% (Figure 49, CDP89). The projected durability rises from 1,748 hours up to more than 2,500 hours if the drop is allowed to change from 10% to 30%.

Because there are only two teams in this data set, we can't provide both the maximum and the average projected time to 10% voltage drop without revealing the individual results of both teams. But as discussed earlier, the average projected time to 10% voltage drop between the two teams is 1,748 hours, a significant increase over Gen 1 and Gen 2 results, as shown in Table 2.

**Table 2: Summary of Average Projected Time to 10% Voltage Degradation from the Three Distinct Sets of Vehicles**

| Fuel Cell Generation | First-Generation Fuel Cell Systems | Second-Generation Fuel Cell Systems | Fuel Cell Systems Operated after 2009Q4 (two OEMs) |
|---|---|---|---|
| Average of all teams' fleet projections to 10% voltage degradation | 821 hours | 1,062 hours | 1,748 hours |

Based on the observed performance from this project, durability has significantly improved from the first generation (~2003–2005) to the latest generation (~2007–2009) of the technology. To evaluate 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.

### *2.1.11 Factors Affecting Fuel Cell Durability*

In addition to evaluating the projected durability of the fuel cell stacks in this project, a significant amount of effort was expended in characterizing the factors that might be having a strong effect on the durability.

The first area of focus was on startup and shutdown of the fuel cell. While some vehicles may shut off the stack during idle or coast-down, all systems are shut off when the vehicle is turned off. In laboratory studies this has been shown to be one of the degradation mechanisms, and, given the large number of short trips discussed earlier, we wanted to quantify how frequently the startups and shutdowns occurred. Therefore, we quantified the number of trips (from vehicle key-on to key-off) per hour (Figure 50, CDP16) and found a relatively normal distribution around three to four trips per hour. These data were requested by researchers in order to calibrate their accelerated testing against what was being seen in the field. We also wanted to see whether the stacks that were demonstrating long life had more or fewer starts than those that had not yet achieved long life. Figure 51 (CDP17) shows the same trip per hour data as a function of stack operating hours (binned into 250-hour operating hour groups). These results show that the stacks that have accumulated up to 2,000 hours did have fewer trips per hour (about half) than those with than 1,500 hours or less, but this correlation alone does not establish a causal relationship between fewer trips per hour and long life.

We embarked upon a multivariate study in 2007 to determine the dominant factors that are affecting the rates of degradation. We started out by creating a database of all of the Learning Demonstration stacks and various performance attributes. Each individual stack was examined for the hours of data accumulated to date and the confidence in the fit of the degradation slope. We then manually removed about one-third of the stacks from the degradation factors analysis to try to have as clean a data set as possible for the analysis. The database included the following key factors for each stack:

- Average voltage degradation rate (key dependent variable)
- Ambient temperature
- Time at various voltages
- Time at various currents
- Number of cold and hot starts (based on time between trips)
- Idle time
- Trip length
- Average number of stack starts/hour.

After trying many techniques, we focused on partial least squares (PLS) regression analysis because it was the most direct way of measuring how much of the variance in voltage degradation could be explained by specific groups of factors. We first performed the PLS analysis on the stack data from all four teams to see if there were any overall trends that covered all of the technology involved (Figure 52, CDP48). The trends across all four teams were not strong, which we soon discovered was because the trends among the companies were often different.

Next we looked at each team's data individually and performed the same PLS analysis (Figure 53, CDP49). The connection between voltage degradation rate and the variables improved, and we were able to pull out groupings of factors that appeared to cause either higher or lower than average decay rates within each team. Note that the teams' PLS models have a high percentage of explained decay rate variance, but the models are not very robust and results are scattered. We found that while there were some common factors among several teams' results, there were also often contradictory trends between the teams (an example of this conflicting trend is for high voltage time and low current time for team four vs. team two). This work was done in close collaboration with each of our industry partners, who have also had challenges extracting dominant factors from the field data.

In discussions with fuel cell researchers, the voltage cycling of the stack was identified as something that would be worth our team investigating further. Prior to this analysis, only the amount of time spent at different voltages was evaluated (Figure 54, CDP07), and not the rate of change of the voltage or the number of times the voltage changed. Figure 12 (below) shows the overall approach we used to 1) define a voltage transient cycle, 2) find voltage transient cycles in the on-road stack data, and 3) categorize and collect voltage transient cycle details.

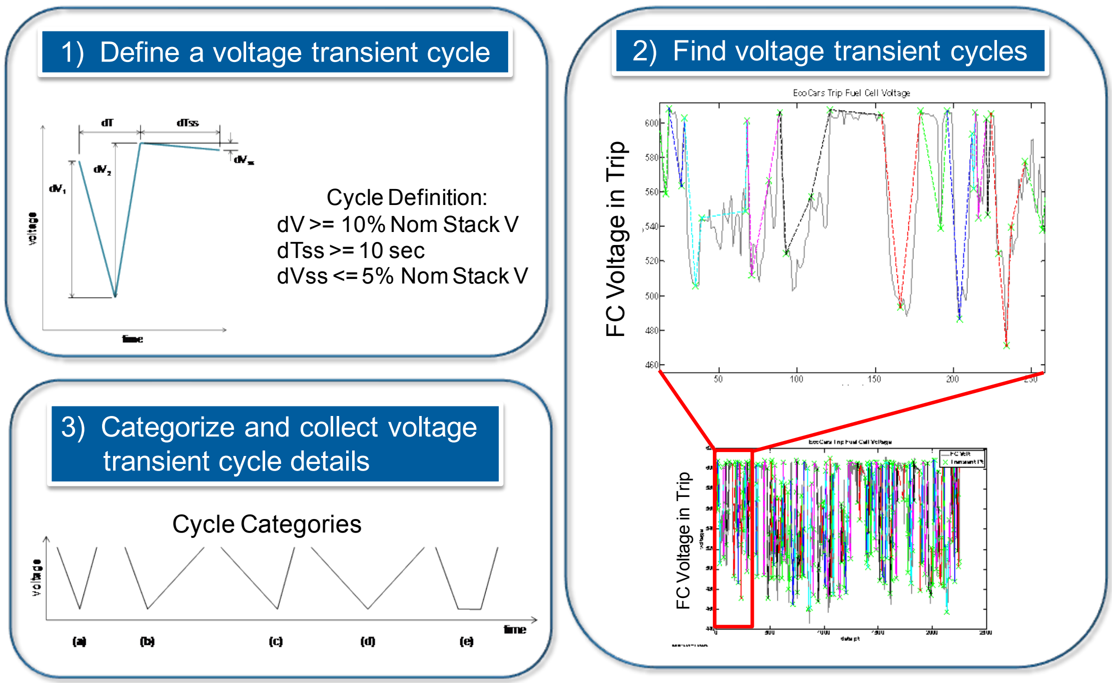


**Figure 12: Approach for characterizing voltage transient cycles**

Looking at the data graphically (Figure 55, CDP75), we see a relatively symmetric distribution of the magnitude of voltage change about 0, with most of the changes lasting less than 15 seconds. Once we characterized the voltage cycles, the first thing we noticed was that the number of cycles per trip mile (and per trip minute) was drastically reduced between Gen 1 and Gen 2 for at least one team by a factor of 4 (Figure 56, CDP74). We found that the dominant transient cycle category was the “SlowDown” category (Figure 57, CDP76), which was a slow voltage drop followed by a fast voltage rise. This could come from a gradual acceleration of the FCEV, followed by taking the foot off the accelerator pedal due to traffic at a stop sign or light. The frequency of each of these five cycle categories is now available to use as a new input to any future multivariate analyses. Figure 58 (CDP77) shows the same characterization but includes the relative magnitude change in voltage rather than the rate of voltage change. Using this same data analysis technique, we took the subset of “steady-state” transients, which had a drop in voltage followed by a period of relative steady-state voltage, and evaluated the amount of trip time the stacks spent in this condition of steady state (Figure 59, CDP79). The results showed that the most common bin was 10%–15% of time at steady state, but that some trips got up to as high as 50% of the time at steady state. Finally, we also examined the number of the voltage cycles that were outside of a threshold between 70% and 90% of maximum stack voltage (Figure 60, CDP78). We found that these more extreme voltage transients occurred on average less than twice per mile (accounting for about one-quarter of all voltage transients), with the drop below 70% maximum stack voltage occurring more times per mile than the rise above 90% maximum stack voltage.

### 2.1.12 Fuel Cell System Maintenance

We evaluated the fuel cell vehicle maintenance categorized by system (Figure 61, CDP64). We see that only one-third of the FCEV maintenance events were due to the fuel cell system, while one-half of the labor hours were attributed to repairing the fuel cell system. Breaking down the maintenance events related to the fuel cell system, we find that 39% of events were associated with the thermal management, 23% with the air system, 13% with controls/electronics/sensors, 12% with the fuel system, and only 10% with the fuel cell stack itself. This indicates that as the vehicles get closer to being a marketplace product, the balance-of-plant (BOP) needs some attention if the vehicles are to meet customer expectations for reliability. Note that we were unable to update this result in the last two years due to the sensitivity of this data with only two OEMs involved. DOE has recently announced that it will be funding Eaton to improve the state-of-the-art air management systems.

### 2.1.13 Time of Day Vehicles Are Driven

Some questions were asked early in the project about whether the Learning Demonstration vehicles are being driven like conventional vehicles or whether their usage is being too "controlled" to match typical driving behavior. To investigate this, we looked at the time of day people initiated their trips and which day of the week the trips were occurring on. Figure 62 (CDP44) shows a clock-face radial histogram of the time of day when people initiated their trips, with the green bars representing the last two years and the gray bars representing the previous five years. We have overlaid pink diamonds to show the national statistics based on the 2001 National Household Travel Survey (NHTS) data. What we find is that the Learning Demonstration vehicles were driven at very similar times of day during the last two years compared to the national statistics, with the exception of the late afternoon between 4 and 6 p.m. when the average person (nationally) is likely either picking up children from school, driving home from work, or running errands. Comparing the green bars and the gray bars to the pink diamonds shows that the Learning Demonstration vehicles were much more representative of average U.S. driving over the last two years than over the first five years. Because the first- and second-generation Learning Demonstration vehicles were primarily used for professional or fleet activities, it is not surprising that there would be such a difference. The percentage of trips taken between 6 a.m. and 6 p.m. corresponds relatively closely to the national statistics (85.3% and 75% vs. 81.5%). The nighttime driving behavior trend is also similar to the national statistics (Figure 63, CDP51), although slightly more evening trips are driven nationally (18.4%) than within the Learning Demonstration (14.7%).

### 2.1.14 Day of Week Vehicles Are Driven

We examined the days of the week that people drove the Learning Demonstration FCEVs and compared this with the national statistics. Figure 64 (CDP45) shows a bar for each day of the week, beginning with Sunday, and overlays a diamond symbol for the national statistics. We can easily see that nationally the trips are relatively uniform on weekdays, with a slight dip on the weekends, but that the Learning Demonstration vehicles are rarely driven on the weekends.

Additionally, Learning Demonstration vehicles have significantly more trips Tuesday through Thursday as compared to Monday and Friday, which does not reflect typical national behavior. While the day of the week does not matter to the car's performance, it might be an indication that some of the weekend types of trips (for example: long trips to mountains or lots of short trips to the hardware store) are not being captured in this Learning Demonstration data set because many of the vehicles were used in fleets and not predominantly for personal activities.

### *2.1.15 Vehicle Safety*

The Learning Demonstration has had a very strong safety record to date. Figure 65 (CDP09) shows the number and type of vehicle safety reports by quarter for seven years. Within the last two years, there have been no vehicle safety reports. In the two years prior to that there were only two vehicle safety reports, both involving minor hydrogen leaks detected during fueling. Earlier there were four traffic accidents in which there was no hydrogen released and only minor injuries due to the two-vehicle impact (not hydrogen related). During these traffic accidents the on-board mechanisms performed as intended. For the case identified as "tank scratch," the team determined that the tanks had been scratched during service of a nearby system and that the scratches could be easily repaired without affecting the safety of the tanks.

### *2.1.16 Vehicle Climate Compatibility*

Figure 66 (CDP21) shows the range of ambient temperature during the first five years of vehicle operation spanning –5.8°F to 140°F. Clearly, the vehicles are capable of operating in extreme temperature conditions. The data show that 28.2% of the trips were in temperatures hotter than 28°C and only 1.4% of the trips were in temperatures below 0°C. Special tests were performed in cold chambers to determine the ability of second-generation vehicles to start in sub-freezing temperatures. Figure 67 (CDP05) shows the fuel cell system start times in sub-freezing conditions, with the left two bars showing time to drive away, and the right two bars showing the time to maximum fuel cell power. It appears as though at least one team has a sufficiently short time to drive away (approximately 15 seconds) while one team requires some more improvements (at just less than 5 minutes). All of the teams could probably improve their time to maximum power, with the fastest team being about 1.5 minutes and the slowest being around 9 minutes.

We also analyzed the time between trips and classified them by the ambient temperature range (Figure 68, CDP19). This result shows a relatively equal spread of the extreme temperatures between the different soak times, indicating that vehicles need to be designed for any duration of soak at any temperature; however, these data could be used to understand the probability of the vehicle being left for various times between trips when optimizing the system for energy efficiency. For example, it is 3 times more likely that the vehicle will be driven again in less than 10 minutes than that it will be driven again in 30 to 60 minutes.

Another climate consideration relates to the temperature rise of the tank during fueling, with the constraint that the temperature of the tank should never exceed 85°C. We were approached by the SAE J2601 committee, which was drafting the standard for filling hydrogen vehicles. They had made some assumptions about what the tank temperature would be when it arrived at a station to receive fuel, and they wanted some real-life data from this project in order to calibrate their computer model inputs. Therefore, we created the two graphs in Figure 69 (CDP72) to provide them with publicly available data to use. The left graph shows that the mean temperature at which the tanks arrive for fueling is –3.8°C below ambient temperature, with a standard deviation of 6.1°C. The graph on the right shows a frequency surface plot of each of the tank/ambient temperature pairs.

### *2.1.17 Other Vehicle Metrics*

There are several other vehicle-related CDPs that will be briefly mentioned here as they do not logically fall into one of the other categories. Figure 70 (CDP22) shows the distribution of vehicle operating hours, showing a total of 154,000 hours with a median between 750 and 1,000 hours. The introduction of second-generation vehicles (with low hours initially) and then later the post 2009Q4 vehicles kept this median from rising too much. Similarly, with vehicle miles traveled (shown in Figure 71, CDP23), the peak number of vehicles occurs at 7,500 to 15,000 miles. Both of these graphs are color-coded to compare the vehicles that are still in operation (solid blue) to the vehicles that have been retired (hashed red) from the project. You can see that the vehicles still in operation are spread relatively uniformly across the histograms, with many of the high hour and high mileage vehicles being the ones that are still in operation.

Over the seven-year period, the Learning Demonstration fleet accumulated 3.6 million miles. Figure 72 (CDP24) shows that after the first few quarters, mileage accumulation has been relatively linear, with a slight decrease in slope at the end of 2009 as two teams completed their projects.

Finally, we plotted histograms of the daily fuel cell operation hours (Figure 73, CDP82). The primary purpose of creating this CDP was to create a baseline for a future cross-application CDP that will include material handling equipment (MHE) and buses on the same graph to highlight how each different application uses the fuel cell systems; however, it is also useful as a standalone result. The bottom axis identifies the trend of average hours of operation per day for a system. For the systems analyzed in the last two years, 18% averaged more than 30 minutes of operation per day, which indicates that most of the vehicles were not used for long daily travel. This is, however, twice the number of fuel cell systems exceeding 30 minutes/day when compared to the first five years. This average does not include days when the system did not operate at all. The top axis highlights the hours of operation in a day for all days when at least one system was operated. This chart follows the trend of daily miles traveled, with the majority of the days with 15 minutes, or less, of operation. This trend also confirms that the average hours of operation per day for a system is not significantly skewed due to a few high operation days.

## 2.2 Infrastructure Results

### *2.2.1 On-Site Production Efficiency from Natural Gas Reformation and Electrolysis*

Detailed data on all of the energy inputs required to produce hydrogen on-site were gathered and analyzed and compared to DOE's 2010 program target for natural gas reformation and 2012 program target for water electrolysis. The purpose of comparing our actual results to these future targets is to benchmark demonstrated progress toward the targets while technical research and development continues to improve the state-of-the-art. The results indicate that natural gas reformation efficiency was demonstrated close to the 2010 target of 72% through achieving a best quarterly efficiency of 67.7% and a best monthly efficiency of 69.8% (Figure 74 (CDP13) and Figure 75 (CDP60)). The best monthly and quarterly efficiency for water electrolysis was 61.9%, compared to the 2012 target of 69%. Note that targets for both of these technologies were for future years at the time they were evaluated and the results from 2005–2008 technology were not yet expected to have achieved 2010–2012 targets. Additionally, the targets were set for significantly larger stations (1,500 kg/day of hydrogen) and higher utilization (70% capacity factor) than we had in the Learning Demonstration. Figure 75 (CDP60) shows that, in general, the efficiency of the systems increases with capacity utilization, but there were only a few months during which some reformation stations were run at between 60% and 70% capacity utilization, and electrolysis stations never had average capacity utilization above 35%.

### *2.2.2 Greenhouse Gas Emissions*

Greenhouse gas emissions from the Learning Demonstration fleet have been assessed and compared to greenhouse gas emission estimates of conventional gasoline vehicles. The results indicate that when using hydrogen produced on-site via either natural gas reformation or water electrolysis, Learning Demonstration hydrogen FCEVs offer significant reductions of greenhouse gas emissions relative to conventional gasoline vehicles (Figure 76, CDP62). 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 SUVs emit 612 g $CO_2$-eq/mile on a WTW basis. WTW greenhouse gas emissions for the Learning Demonstration FCEV fleet, which includes both passenger cars and SUVs, were analyzed based on the window sticker fuel economy of the Learning Demonstration fleet and the actual distribution of hydrogen production conversion efficiencies from on-site hydrogen production. The average WTW greenhouse gas emissions estimate for the Learning Demonstration fleet operating on hydrogen produced from on-site natural gas reformation was 356 g $CO_2$-eq/mile, and the lowest WTW GHG emissions estimate for on-site natural gas reformation was 237 g $CO_2$-eq/mile. For the Learning Demonstration fleet operating on hydrogen produced from on-site water electrolysis (including some renewable sources of electricity), the average WTW GHG emissions estimate was 380 g $CO_2$-eq/mile, and the lowest emissions estimate was 222 g $CO_2$-eq/mile for the month with the best electrolysis production conversion efficiency.

### *2.2.3 Fueling Station Compressor Efficiency*

As part of our analysis of the fueling station subsystems, we gathered available data (which was limited) on compressor energy usage to evaluate compressor efficiency (Figure 77, CDP61). We found that the average station compressor efficiency (as defined by DOE's Multi-Year Program Plan) was just under 90%, a few points lower than DOE's targets for 2010 and 2015. The compression energy was on average 15.4 MJ/kg, with the best monthly data at 6.4 MJ/kg. In layman's terms, this means that on average 11.3% of the energy contained in the hydrogen fuel is required for the compression process.

### 2.2.4 On-Site Hydrogen Production Cost

Cost estimates from the Learning Demonstration energy company partners were used as input to an H2A analysis to project the hydrogen cost for 1,500 kg/day early market fueling stations. Results indicate that on-site natural gas reformation could lead to a hydrogen cost of $8–$10/kg and on-site electrolysis could lead to a hydrogen cost of $10–$13/kg (Figure 78, CDP15). While these 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 $2.75–$3.50/kg hydrogen [4] and distributed electrolysis could lead to $4.90–$5.70/kg hydrogen [5]. Therefore, this objective was satisfied outside of the Learning Demonstration project.

### 2.2.5 Hydrogen Quality

Hydrogen quality was determined by measuring the impurities and calculating the hydrogen fuel quality index as a percentage. SAE J2719 has established a 99.99% hydrogen fuel quality index target. The hydrogen fuel quality index from all of the stations sampled ranged from 99.73% to 99.999%, as shown in Figure 79 (CDP27). The values on the lower end were due to some high detection limits on inert gases and likely do not really represent hydrogen fuel quality that low. We also separated the results by year and by production technology. With five years of data now analyzed, we can see that the hydrogen quality index of 99.97% has been achieved in all the quality samples for the last three years analyzed and does not seem to be an issue.

### 2.2.6 Hydrogen Impurities

More important than the absolute hydrogen fuel quality index is the actual level of impurities by constituent. Impurities evaluated include particulates, inert gases ($N_2$ + $H_2$ + Ar), $NH_3$, CO, $CO_2$, $O_2$, total HC, $H_2O$, and total S, and the results are summarized in Figure 80 (CDP28). Each of these constituents was broken out separately and shown as a function of year. There are 18 of these results (Figure 81 to Figure 98 (all subsets of CDP28)), so we will not discuss each one individually except to say that the detection limits continue to improve (get lower) through better gas analysis techniques, and there do not appear to be any major issues with any of the impurities. Impurity data from this project has been used by the hydrogen quality community on numerous occasions to answer the question of what hydrogen quality is possible and what are the actual impurities found in hydrogen fuel made by various techniques.

### 2.2.7 Hydrogen Infrastructure Maintenance

An evaluation of all of the maintenance required on fueling station equipment in the first five years of the project found that roughly one-half of all labor hours were unscheduled, accounting for 60% of the maintenance events (Figure 99, CDP30). With the large volume of infrastructure maintenance items over the past five years, we have not seen much shift in the split of planned and unplanned maintenance events. Similar to the FCEV maintenance, we also classified the parts of the fueling station systems that caused the maintenance events (Figure 100, CDP63). The left pie shows the number of events (2,491 events) separated by subsystem while the right pie shows the number of labor hours (11,430 hours). Results indicate 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. The main conclusion from this result is that system control and safety required both the most labor hours to fix and the most frequent maintenance. The rest of the major maintenance time was spread relatively evenly between the compressor, reformer, electrolyzer, and dispenser.

### *2.2.8 Hydrogen Infrastructure Reliability*

A key metric of any technology's success is its reliability because people resist adopting new technologies that require significantly more maintenance than incumbent technologies. For stations operating in the final two years of the project, we changed our categorization scheme to allow a finer parsing of the underlying issues. For instance, the category "system control and safety" (Figure 100, CDP63) used for the first five years was broken into four distinct categories: electrical, software, control electronics, and safety (Figure 101, CDP94). Note that the "safety" category in the maintenance analysis refers to maintenance events on safety-related equipment such as calibrating combustible gas detectors and checking fire extinguishers.

It is clear from the resulting analysis that system integration issues such as electrical and software, at 21% each of unscheduled maintenance events, remain the top reliability challenges facing hydrogen infrastructure (Figure 101, CDP94). These two categories combined represent 45% of the unplanned maintenance labor hours among stations operating in the last two years of the project. However, these challenges are not hydrogen-specific and could exist at any installation of industrial equipment.

Among hydrogen-specific equipment issues, hydrogen compressors remain the largest single cause of unplanned maintenance by both event count (12%) and repair labor hours (14%). More than 900 maintenance hours were logged on this single component of the stations in use during the last two years of the project.

Adding to the importance of this finding are two exacerbating factors: compressor criticality to station operation, and the highly specialized nature of compressor repair parts. While some of the software and electrical issues discussed previously did not immediately adversely affect station performance, a non-functioning hydrogen compressor certainly will through incomplete fills, slow fills, or station unavailability. Unlike many electrical and software components, hydrogen compressor technology is far from ubiquitous, necessitating keeping a constant inventory of rare spare parts nearby the station to ensure fast repair times. This places an additional financial burden on hydrogen infrastructure.

The experience with hydrogen compressors is not unique to light-duty vehicle fueling infrastructure. NREL has published CDPs for the material handling equipment (MHE) market [9], which show hydrogen compressors are the leading cause of unscheduled maintenance labor hours with 28% of the total (MHE CDP 18). In addition, they are responsible for 28% of safety near-miss events (MHE CDP 46) and 25% of hydrogen leaks (MHE CDP 51).

All of these issues combine to result in a mean time between failure (MTBF) of 25 days at most for the seven stations active at the end of the project. Three sites had cumulative MTBF of between 5 and 10 days (Figure 102, CDP98). In general, scheduled maintenance occurred at most every 50 days, with the majority of the sites reporting a mean time between scheduled maintenance (MTBSM) of 20 days or less (Figure 103, CDP 99). Scheduled maintenance is further broken down into regular preventative maintenance and equipment upgrades (figure insets). Preventative maintenance dominates the MTBSM numbers, with upgrades being reported at most sites every 250 days or less. One site did not report any upgrades and one site reported very few, resulting in a high mean time between upgrades (MTBU), which can be considered an outlier. Calendar time was the aging parameter that we used to evaluate station reliability.

Figure 104 (CDP 95) shows the number of maintenance events (scheduled, unscheduled, and operator induced) and the associated labor hours per thousand vehicle fills over time. On average over the last eight quarters reported, there were 58 maintenance events (of all types) per one thousand fills and 179 maintenance labor hours per thousand fills. Note that the maintenance events did not necessarily result in a station outage.

Combined with the fact that the mean service call length was nearly five hours (Figure 105, CDP96), the reliability data make a strong case for requiring a dedicated, local service presence for each station, or for a group of stations located together, in order to deal with unscheduled station downtime. This is clearly a long way from the maturity of gasoline stations today, which use much simpler and more reliable equipment.

On a positive note, reliability growth is generally trending toward better reliability. A Crow-AMSAA analysis of the data showed that for the last 20% of events, instantaneous MTBF increased (improved) for five of the seven sites still in operation at the project's end (Figure 106, CDP97). Considering the overall lifetime of these seven sites, reliability is growing or stable at all but two, and one of these showed remarkable improvement in instantaneous MTBF.

In order for hydrogen to achieve significant market penetration, the reliability of stations must improve relative to the incumbent technology (gasoline). Although serious challenges remain, the trend in reliability growth is pointing to a maturing of the technology and resolution of some critical issues.

### *2.2.9 Hydrogen Infrastructure Safety*

With respect to the hydrogen fueling infrastructure, there have been just a handful of events classified as incidents, according to DOE's Hydrogen Safety Panel definition. On most of the safety CDPs we have included the DOE definitions of incident and near-miss that are being used for this project to remove any questions about what they mean. Most of the safety incidents reported were due to equipment malfunction with one event having a minor hydrogen release that did not lead to ignition and another one involving a major hydrogen release and a fire. Details of this event are available from DOE's Hydrogen Safety Panel. At a less severe level (see Figure 107, CDP20), there were about 50 events categorized as near-misses and around 275 non-events (more than 100 were alarms-only and about 70 were "system trouble, not alarm"). All but a handful of the near-misses involved a minor release of hydrogen with no ignition.

Figure 108 (CDP37) shows that no single primary factor led to the majority of infrastructure safety reports, but the top three most frequent primary factors for the non-events were 1) calibrations, settings, and software controls; 2) maintenance required; and 3) not yet determined (in other words insufficient information was provided for us to determine how to categorize some of the events).

Figure 109 (CDP35) shows a graph of the number of stations deployed (light blue bars) and the average number of fuelings between safety reports for each quarter (dark blue curve). This normalized number of fuelings per safety report had improved for the first two years (higher is better), but then bounced around 50 as new stations came online. It then increased again and stayed above 100 for the last year that all four teams were reporting. Figure 110 (CDP36) shows a mild correlation between new stations coming online and a higher number of safety reports.

### 2.2.10 Vehicle 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 was 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). More than 33,000 fueling events have been analyzed, and the fueling amount, time, and rate have been quantified. For many of the fueling CDPs we separated the first five years of data (marked by gray bars in the background, labeled “Through 2009Q4”) from the last two years of data (yellow bars in foreground, labeled “After 2009Q4”) so that we can observe the overall trends.

In the first five years the average amount per fill was 2.13 kg (see Figure 111, CDP39), reflecting both the limited storage capacity of these vehicles (approximately 4 kg maximum) and people’s comfort level with letting the fuel gauge get close to empty, which will be shown in a separate analysis. In the last two years we saw the average fill amount increase by 24% to 2.64 kg, in part because some of the smaller-hydrogen-capacity vehicles had been retired.

The average time to fuel in the first five years was 3.26 minutes with 86% of the fueling events taking less than 5 minutes (Figure 112, CDP 38), whereas the last two years had an average fill time of 4.49 minutes with 69% of the fills occurring in less than 5 minutes. This represents a 38% increase in the fill time, which is partially accounted for by higher filling amounts.

As shown in Figure 113 (CDP52), we saw a gradual increase in the average fueling rate from the first year of the project through 2009 (dashed curves), and a decrease over the last two years (solid curves). Over the first five years the average fueling rate was 0.77 kg/min, gathered from more than 25,000 fueling events (gray bars in Figure 114, CDP18), and after 2009Q4 it was 0.65 kg/min, resulting in an overall decrease in the average fueling rate of 16%. 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. This will be discussed in the next two sections.

### 2.2.11 Communication vs. Non-Communication Fueling Rates

The previous fueling histograms included all types of fueling events. There has been interest from industry and the codes and standards community about the potential for communication fills to occur at a higher rate and with a more complete fill. A communication fill means that the vehicle communicates data about the state of its hydrogen storage tank(s), such as tank temperature, pressure, and max pressure rating, to the fueling station. Figure 115 (CDP29) shows four curves: the red curves are a spline fit to the histogram for non-communication fills while the blue curves represent the communication fills. The data have been further subdivided by the same pre- and post-2009Q4 periods previously used. In the first five years, communication fills were capable of having a higher fill rate (up to around 1.8 kg/min) as compared to the non-communications fills (blue vs. red dashed curves). However, we recently saw a flip in the trends with the communication fill rates dropping from an average of 0.86 kg/min to 0.58 kg/min while the non-communication rates went up from 0.66 kg/min to 0.81 kg/min. These averages are marked as circles in the graph as well as tabulated in the inset box. We believe that the primary reason for this shift is due not so much to communication vs. non-communication but to these fills being performed at two different pressures, as discussed in the next section. Several OEMs have been experimenting with different techniques to achieve fast and complete fills using non-communication techniques, enabled by some of the more advanced fuel station hardware, and these trends will be explored more fully in a subsequent fueling station analysis project in FY12 and beyond.

### *2.2.12 Fueling Rate by Storage System (350 bar vs. 700 bar)*

We performed another partitioning of the fueling rate data by the hydrogen storage system employed by each vehicle. Figure 116 (CDP14) shows the fueling rates for 350-bar fills and compares them to the fueling rates for 700-bar fills, with the data subdivided into the two time periods. In the first five years there were significantly more 350-bar fills (19,659) than 700-bar fills (5,590); the 700-bar fuelings mainly began with the second-generation vehicles halfway through the project. In the last two years, that finding is reversed with about double the number of 700-bar fills compared to 350-bar fills. The two orange curves show that the 350-bar fueling rates dropped from 0.82 kg/min to 0.70 kg/min when some of the higher throughput 350-bar stations were taken offline in 2009.

By comparison, the 700-bar fueling rates held relatively constant at around 0.63–0.64 kg/min. 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. These lower fill rates for 700-bar fills do not appear to be a limitation of the technology, as very high fill rates at 700 bar have been demonstrated in Germany and Canada, but rather a reflection of the current technology that has been deployed in this first wave of 700-bar stations. Many of the first 700-bar stations were installed to provide temporary fueling capability and coverage for vehicles and were not intended as permanent, full-scale stations. It also reflects that optimum fueling protocols for these faster fills that can be used by all OEMs are still being refined. Station data received in the coming years from the new 700-bar stations in California should demonstrate the full capability of 700-bar fueling, and NREL will continue to track the fueling rate.

### *2.2.13 Level in Fuel Tank When People Refuel*

As previously mentioned, with limited hydrogen fueling infrastructure and limited on-board hydrogen storage, some drivers do not like to let the tank get close to empty to minimize the risk of running out of fuel. To investigate this further, NREL used the submitted data in a unique way, which was to analyze what the fuel level in the tank was just prior to each fueling event. In some cases these data came from on-board data based on the pressure in the tank, and in other cases they came from refueling logs where each fill was assumed to end at the “full” level, allowing a subtraction of the amount fueled to determine the initial tank level.

Figure 117 (CDP40) shows the results of this analysis, with a histogram placed radially on an image of a fuel gauge to make interpreting the graph as intuitive as possible. In the first five years, the level at which people most commonly fuel the Learning Demonstration vehicles is at just over one-quarter full; this segment covers 14% of the fuelings. While some drivers were letting the tank get even lower than that, few let it get close to being empty. Additionally, we placed a dark gray needle on the chart to indicate the median tank level at fill (half above, half below), which is a little above three-eighths of a tank (42% of full). In the last two years the level at which the vehicles were most commonly fueled was just under a half-tank, with the median pre-fill level rising to 50% from 42%. While the causes of this shift are not known definitively, it could be because some of the recent vehicles have been placed much closer to a convenient filling station than before so the drivers are able to top up to a full tank more easily and frequently. Increased on-board hydrogen storage for the vehicles in the last two years of the project may also be a cause for the shift. Figure 118 (CDP41) shows the collection of medians for each of the vehicles driven in just the first five years (this wasn't updated in the last two years because it wasn't deemed critical to do so) to show that there is a large spread in the fuel tank level when drivers fuel their vehicles, with several vehicles being fueled more than half of the time with greater than a half-full tank, but with the majority being fueled between one-quarter and one-half full, on average. In the future, we would like to compare these data results to data from conventional liquid-fueled vehicles, if they exist, to see if people are fueling their FCEVs differently than their conventional vehicles. Ultimately the decision by a driver as to when to fuel their vehicle is a very personal decision that includes a number of different factors in addition to fuel availability and vehicle driving range.

### *2.2.14 Time of Day When People Fuel Their FCEVs*

We examined the time of day people fueled their vehicles in order to understand the usage patterns at the hydrogen fueling stations and to better allow operators of new stations to understand the potential future demand by time of day. For traditional liquid fuels, with big tanker truck deliveries periodically, the time of day people fuel does not normally matter. Instead, the station operator must simply ensure that the next tanker comes before he runs out of fuel and that the truck is not blocking access to dispensers during peak fueling times. For today's hydrogen fuel stations, with very limited on-site storage capacity and some sites producing hydrogen throughout the day, it is important to know the time of day that people fuel in order to closely match the supply with the demand.

Figure 119 (CDP42) shows a radial histogram (emulating a clock face) of the time of day Learning Demonstration vehicles were fueled between 6 a.m. and 6 p.m., with Figure 120 (CDP50) showing the time of fuelings between 6 p.m. and 6 a.m. (Note that CDP50 was not updated for the last two years since it included only around 10% of the data.) We found that 90% of the fills during the first five years (gray bars) took place between 6 a.m. and 6 p.m., with 10% being done at night. This daytime fueling decreased slightly to 88% over the last two years. The distribution is relatively uniform but the peak fueling time over the last two years is between 3 and 4 p.m., with 10% of the fueling events occurring then. The conclusion from this analysis is that if you have a uniform distribution of when people fuel during the day, a station that has on-site production can either be sized to meet that demand during the day and then essentially shut off at night, or it can be sized (smaller) for the average over a 24-hour period, have a larger on-site hydrogen storage buffer, and run continuously. We next looked at what day of the week people were fueling (Figure 121, CDP 43) and found that the Learning Demonstration vehicles were almost exclusively fueled Monday through Friday, with very few vehicles fueled on the weekend. Over the last two years there was an increase in weekend fuelings but they were still far below the number done during the week. This is consistent with the days of the week that people are driving the vehicles most and when the hydrogen stations that have attendants are open. Newer hydrogen stations, in general, are required to have 24/7 open access, which will allow for more evening and weekend fuelings to occur.

### 2.2.15 Fueling Station 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 by the stations to ensure that early adopters will have convenient fueling within a reasonable distance from where they live or work. The second stage of the deployment will focus on fueling capacity expansion 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. Figure 122 (CDP83) is a variation on CDP43 but covers data from stations in the last two years of the project. The left axis shows the percentage of hydrogen dispensed by day, rather than showing the percentage of fills in a day. On the right axis it also shows the average hydrogen dispensed by day for each station with a separate vertical axis scaling. The highest average daily usage from the busiest Learning Demonstration station is 27 kg/day.

To further understand how much these stations are being used as a function of their design conditions, Figure 123 (CDP91) shows the maximum daily utilization, maximum quarterly utilization, and average daily utilization for each of the seven stations. The maximum daily utilization can be greater than 100% because of various design choices that may have been made for customer convenience, such as rate of back-to-back fills. The station may have been stressed above this design point by high customer demand or even specific OEM experimentation with their vehicles at the station. 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%.

Because many key stakeholders in state and local government think in terms of vehicle fills, not kilograms of hydrogen, we also created an easily digestible graph of the number of fills per day (both average and maximum). These results (Figure 124, CDP92) indicate that most of the stations are serving six or fewer vehicles per day on average, with several stations serving between 10 and 23 cars on their busiest days.

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 capacity and vehicle usage.

### 2.2.16 Hydrogen Infrastructure Footprint and Production Amounts

In order to answer questions about the footprint of a hydrogen station, we had the stations operating over the last two years provide us with data on the station area dedicated to hydrogen equipment (Figure 125, CDP93). The stations ranged in capacity from 25 to 100 kg/day and were arranged from smallest (on left) to largest (on right). The footprint does not include the dispenser area, which is typically on the order of about 10 square feet per dispenser. The results indicate that most of the stations were between 2,200 and 2,600 square feet, with one station at about 3,600 square feet. We will continue to track the hydrogen footprint as station designs evolve, and we will likely want to normalize future footprints by the daily hydrogen production/dispensing capacity to see if there are any useful correlations for economic modeling purposes.

The cumulative amount of hydrogen produced or dispensed has been tracked by quarter in Figure 126 (CDP26). Note that the amount of hydrogen produced was not the same as the amount dispensed because the project included a power park where the unused hydrogen could be converted back into grid electricity during peak utility load periods in the afternoon (due to higher air-conditioning loads) using on-site fuel cells. The graph shows an increasing rate of hydrogen use until 2009 Q3 when two of the teams concluded their project, after which the rate of hydrogen dispensed within the project slowed significantly.

# 3 Conclusions and Future Directions

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. This project addressed the critical need for technology validation to bridge the gap between R&D and commercial readiness of the vehicle and station technologies. 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 3.6 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 152,000 kg of hydrogen through more than 33,000 fueling events.

The technical results from this project have exceeded the DOE expectations established in 2003. Two of DOE's key interim technical targets for 2009 were achieved – demonstrating >250 mile range and >2,000 hour fuel cell stack durability. The third target of $3/gge on-site hydrogen production cost was met outside of this project through results from an independent review panel of experts. After two project participants concluded their participation as planned in 2009, an additional two years of data were gathered from two OEMs and seven fueling stations. From this new data we found that the real-world distance driven between fueling events increased to a median distance of 98 miles. We continued to track fuel cell stack durability, but projections had to be limited to twice the demonstrated hours to minimize excessive extrapolation.

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 because some higher throughput stations were decommissioned and some of the latest technology stations (700 bar) were gradually being brought up to full speed.

The Learning Demonstration fulfilled a key objective of providing lessons learned to guide and inform research and development activities within DOE. One example of this is with durability and reliability of the hydrogen fueling stations. Recent trends show most stations (5 out of 7) exhibit an overall increase in reliability. However, among hydrogen-specific equipment, compressors continue to be the component requiring the most maintenance. This is one example that has been fed back to the data providers and to DOE's R&D program as a recommendation for future development work. Much more detailed analysis results were also provided to the developers to facilitate technology improvements. Our website will continue to be the primary repository for NREL's hydrogen fuel cell vehicle and infrastructure analysis results, as well as results from technology validation of other hydrogen components and systems [14]. NREL will continue to receive hydrogen infrastructure data from California beyond this project, and will be analyzing and publishing CDPs from future hydrogen vehicle and infrastructure projects supported by DOE.

From all of the project results that NREL has generated, it is our conclusion that FCEVs have advanced rapidly in the last seven years. As the automotive OEMs and other researchers worldwide continue to focus on the remaining challenges of balancing durability, cost, and high-throughput manufacturability, we are optimistic that improvements will result in a manageable incremental cost for fuel cell technology. We therefore expect continued progress to lead to several vehicle manufacturers introducing thousands of vehicles to the market in the 2014–2016 timeframe, at which time the hydrogen community will have its first true test of whether the technology will be embraced by the public.

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# 5 Publications and Presentations

All publications and presentations prepared under the National Fuel Cell Electric Vehicle Learning Demonstration project are listed below and can be downloaded from the following website: http://www.nrel.gov/hydrogen/proj_learning_demo.html.


**2012**

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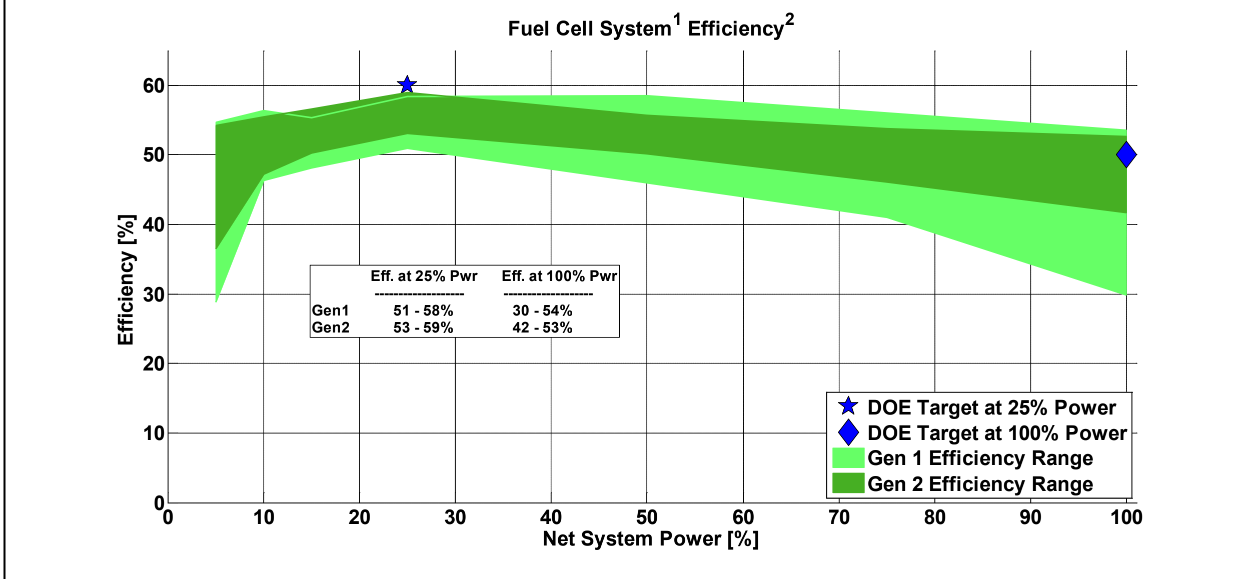
# 6 Composite Data Products Referenced in Report Body




[1] Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.
[2] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).
[3] Individual test data linearly interpolated at 5,10,15,25,50,75,and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

**Figure 13: Fuel cell system efficiency (CDP08)**

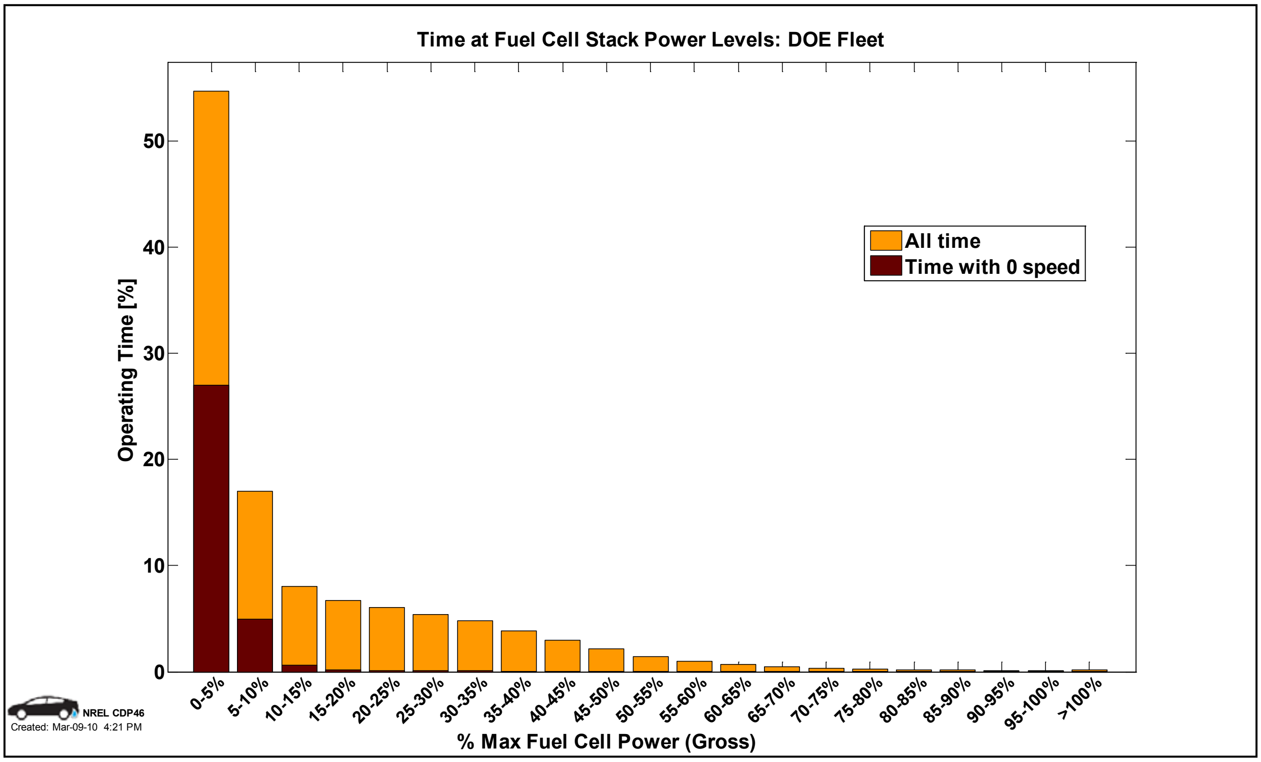



**Figure 14: Fuel cell system operating power (CDP46)**

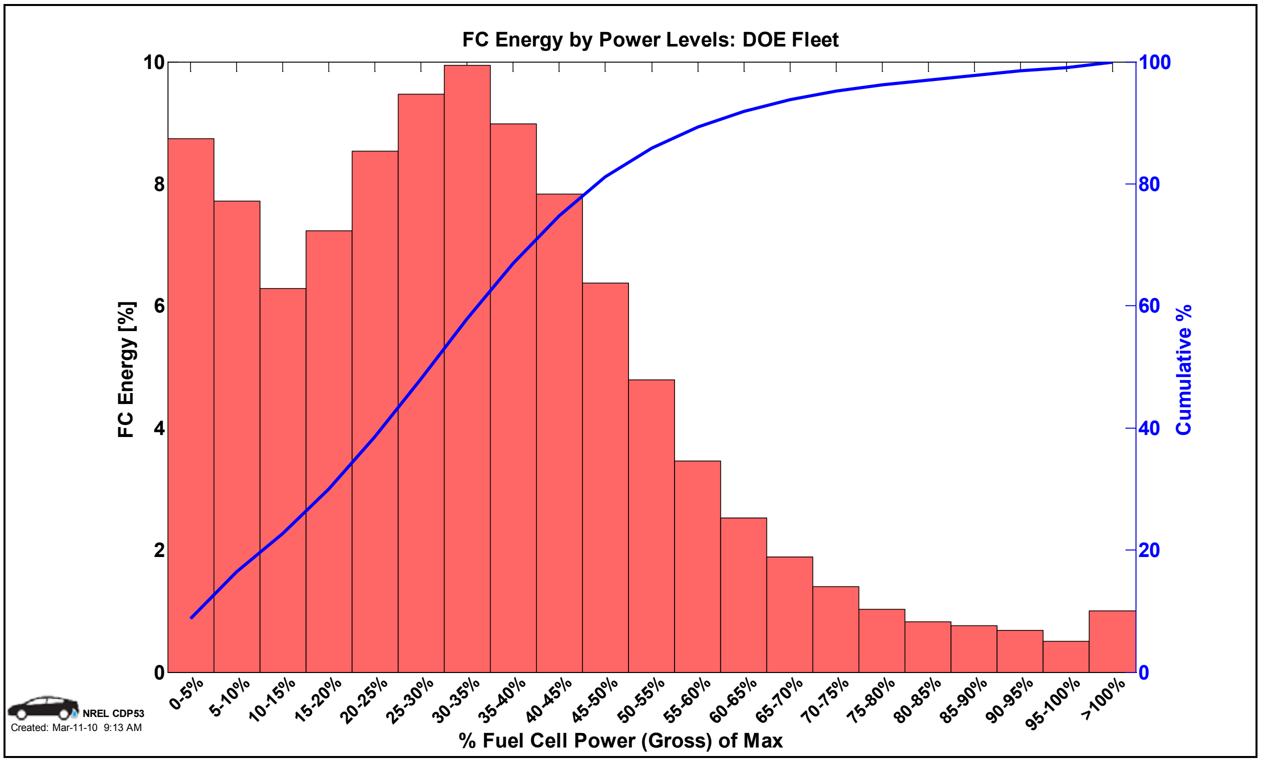



Figure 15: Fuel cell system energy within power levels (CDP53)

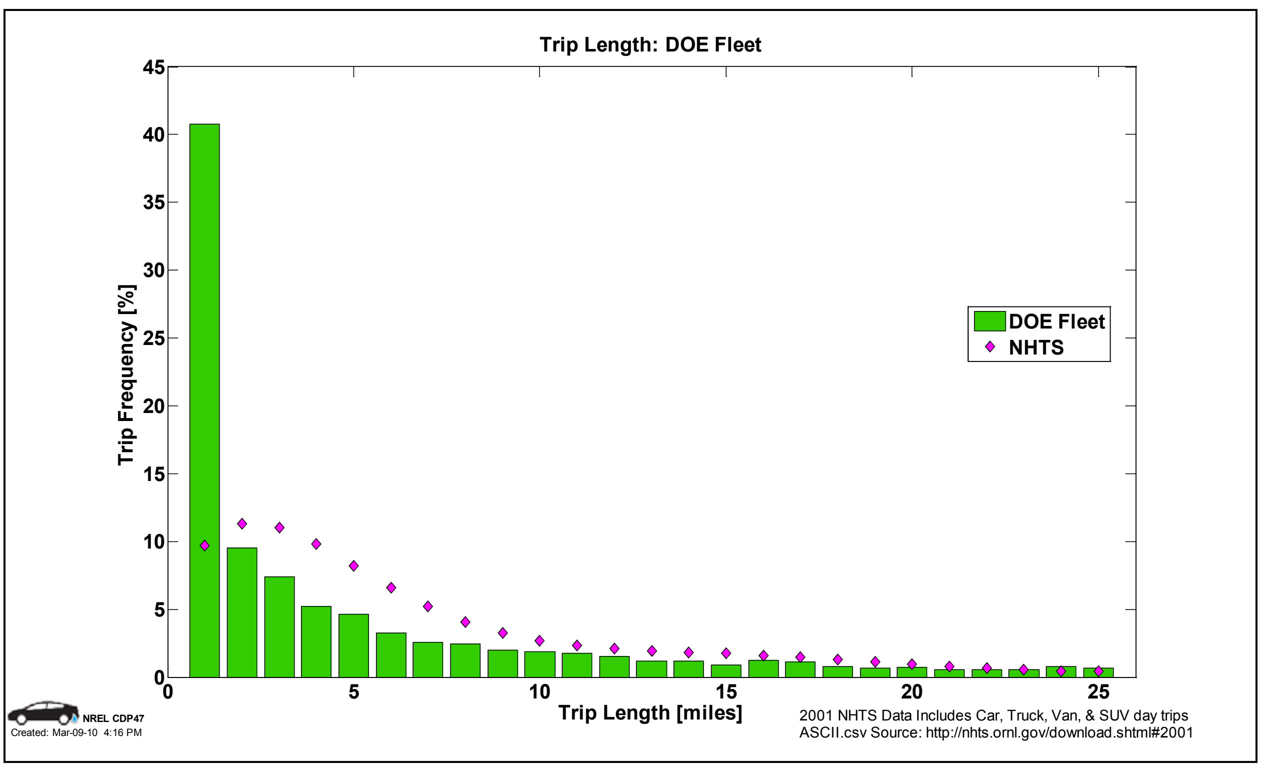



Figure 16: Trip length (CDP47)

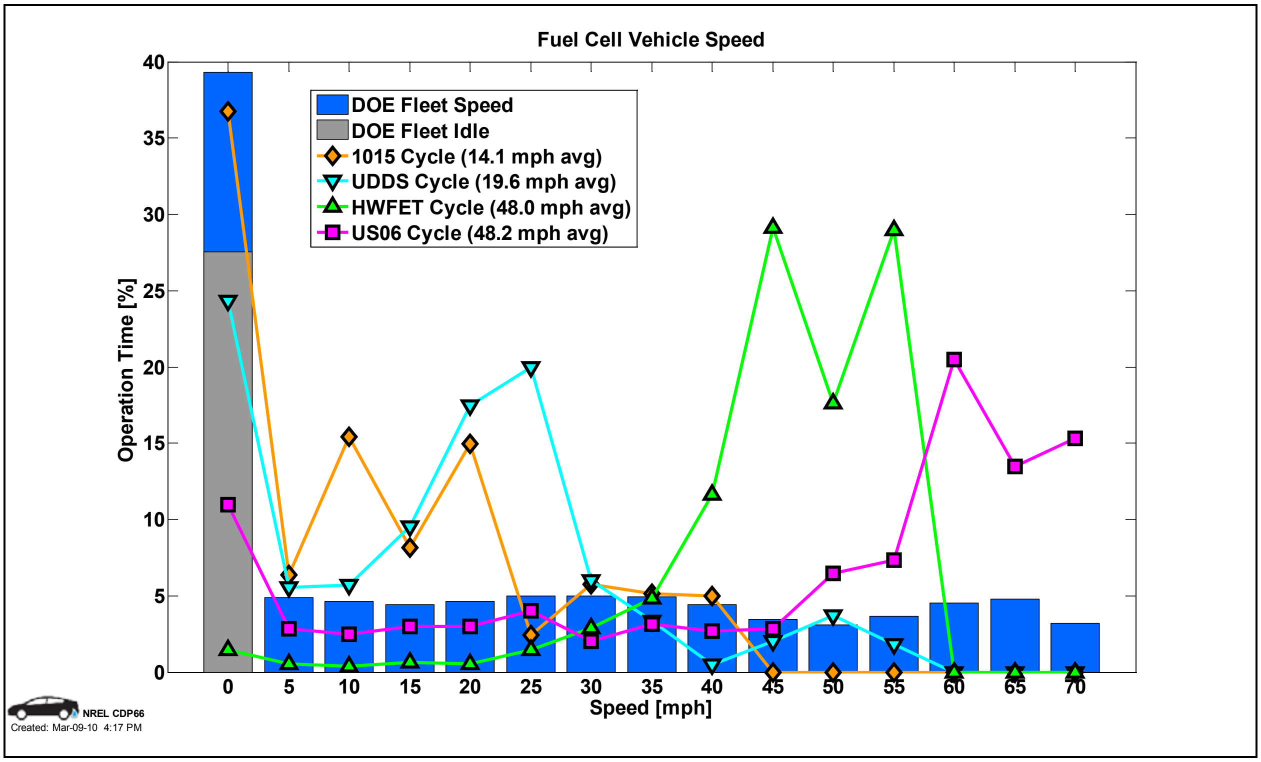



Figure 17: Fuel cell electric vehicle with comparison to standard drive cycles (CDP66)

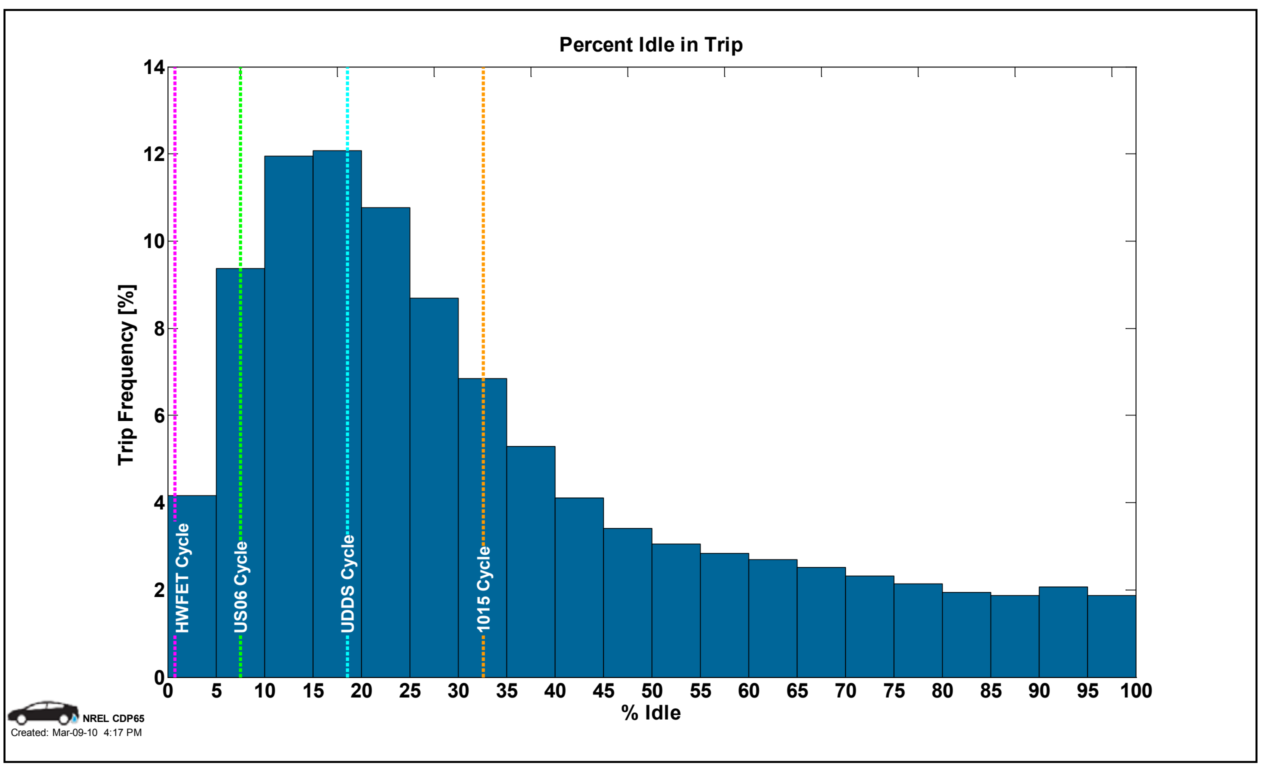



Figure 18: Percent idle in trip with comparison to standard drive cycles (CDP65)

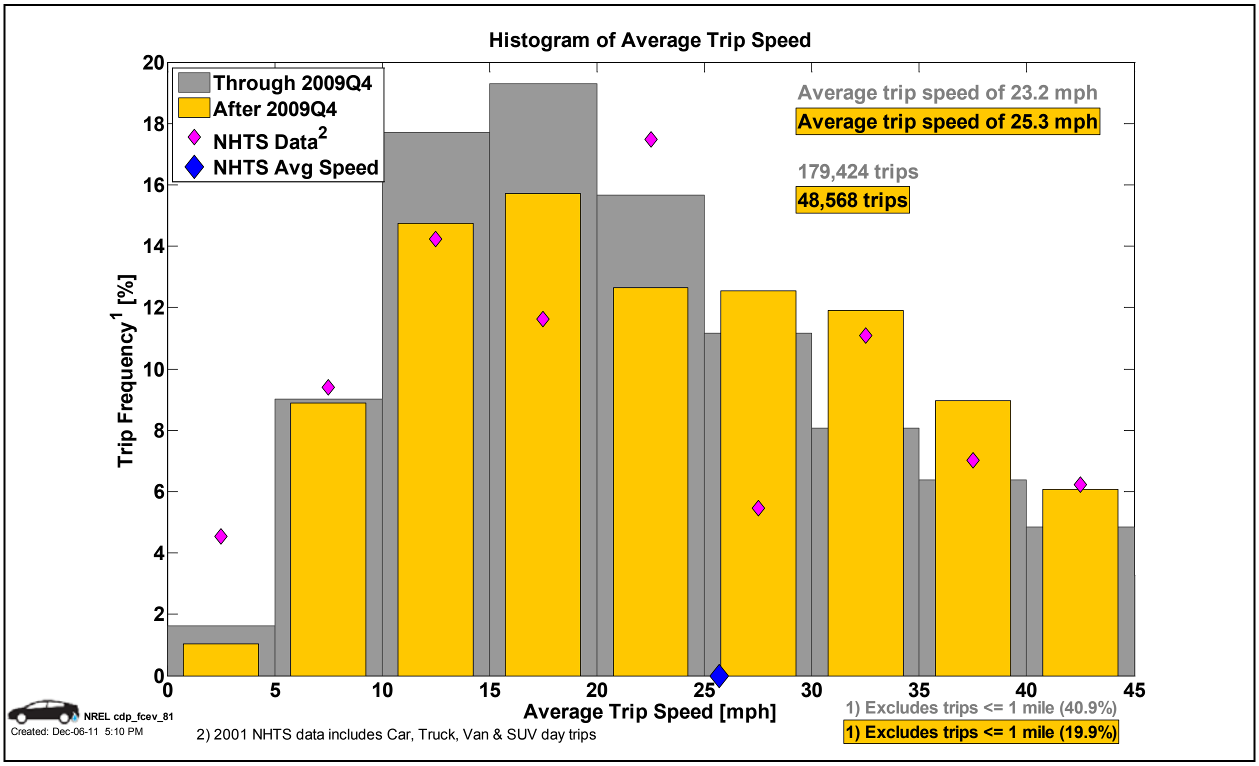



**Figure 19: Average trip speed (CDP81)**

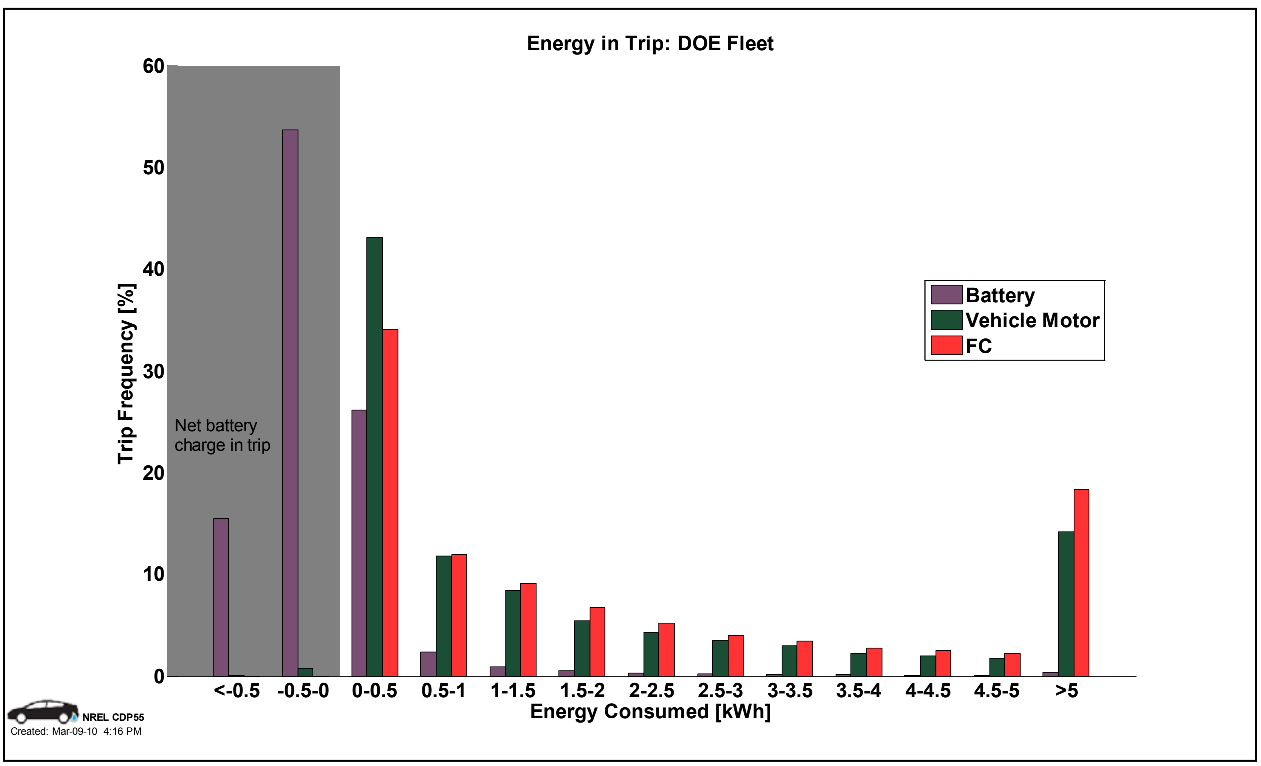



**Figure 20: Fuel cell system energy in trips (CDP55)**

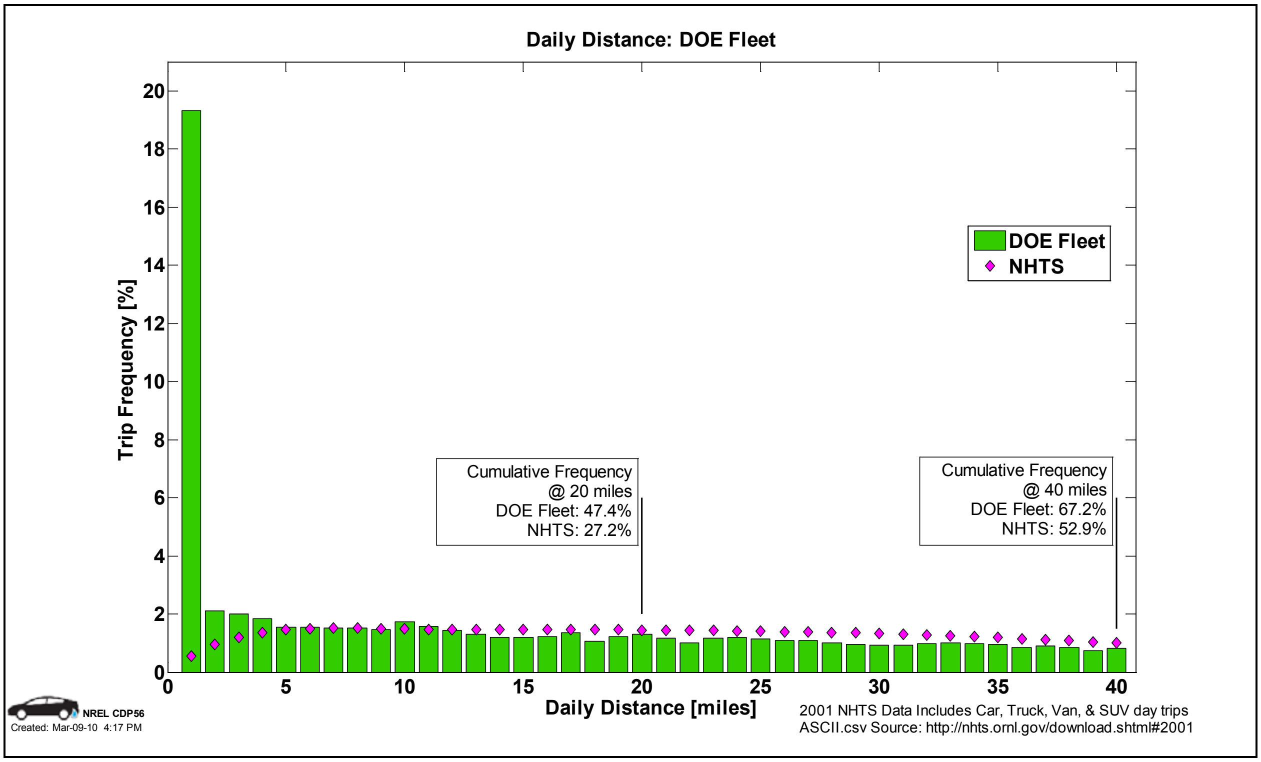



**Figure 21: Daily driving distance (CDP56)**

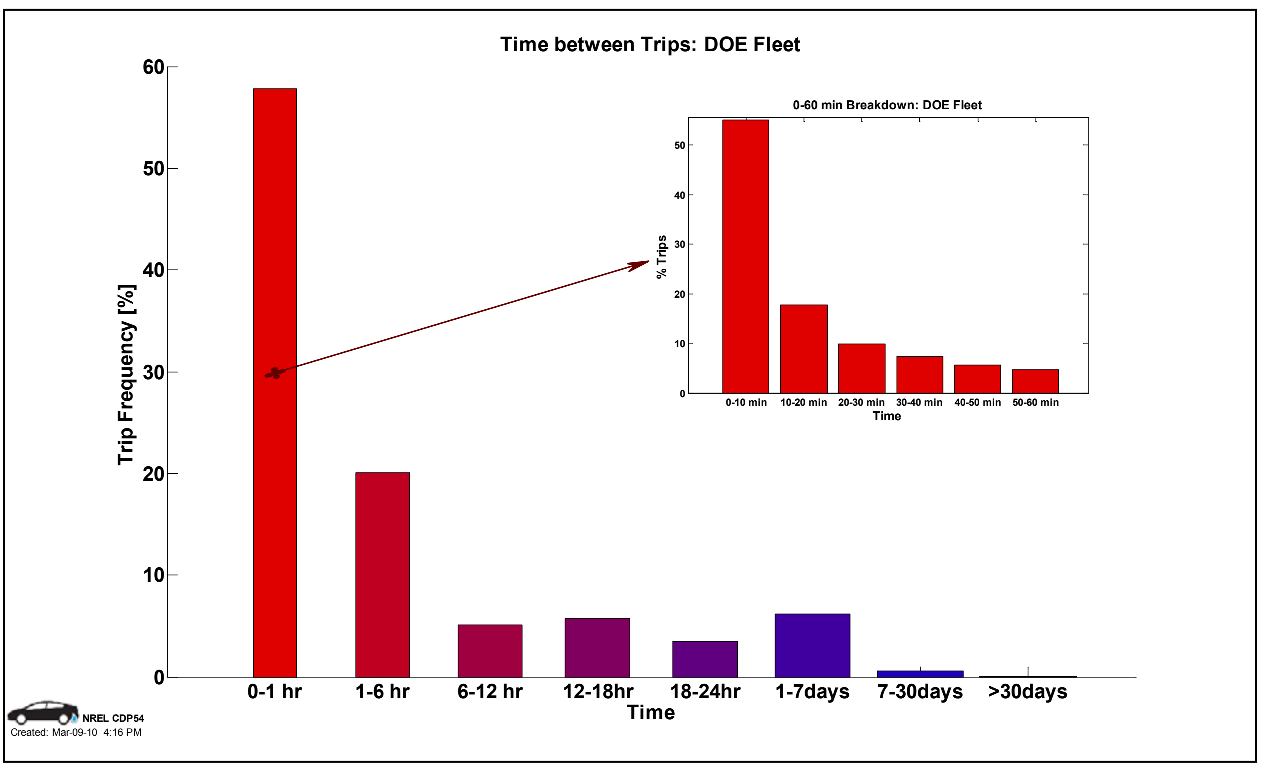



**Figure 22: Time between trips (CDP54)**

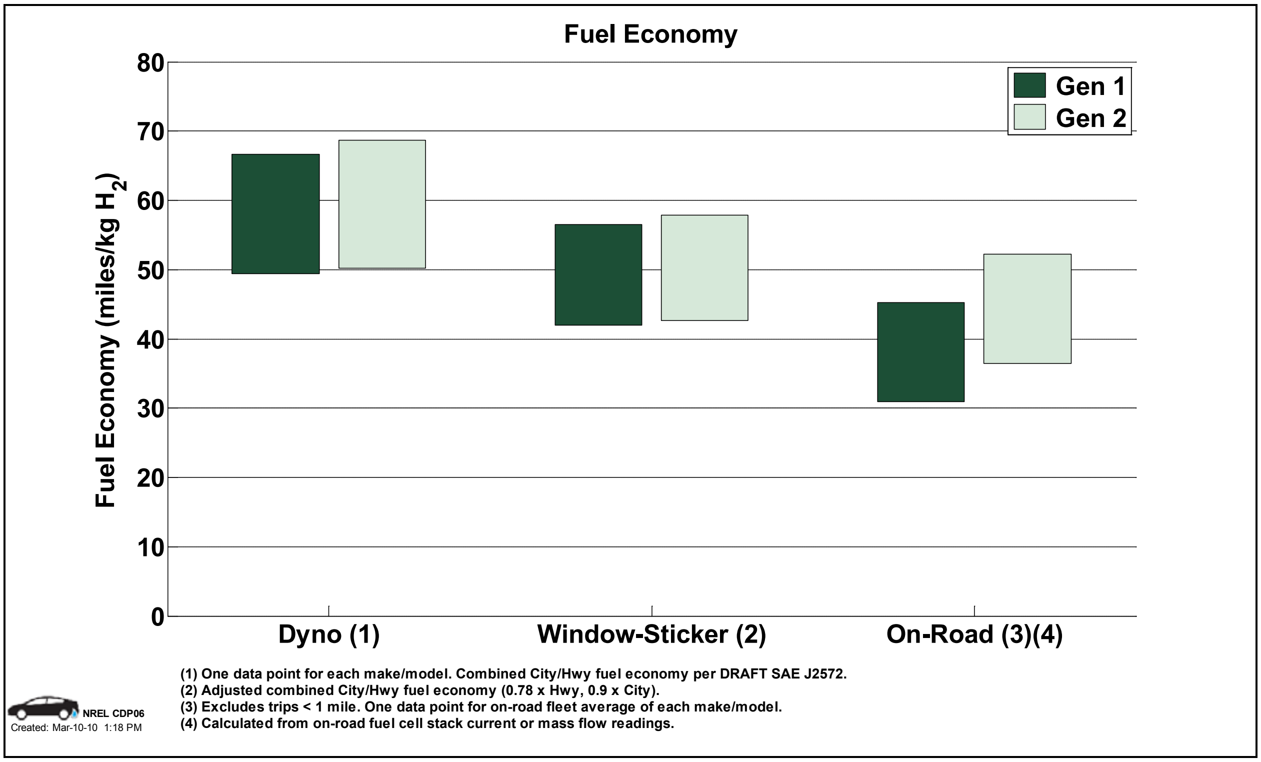



**Figure 23: Fuel economy (CDP06)**

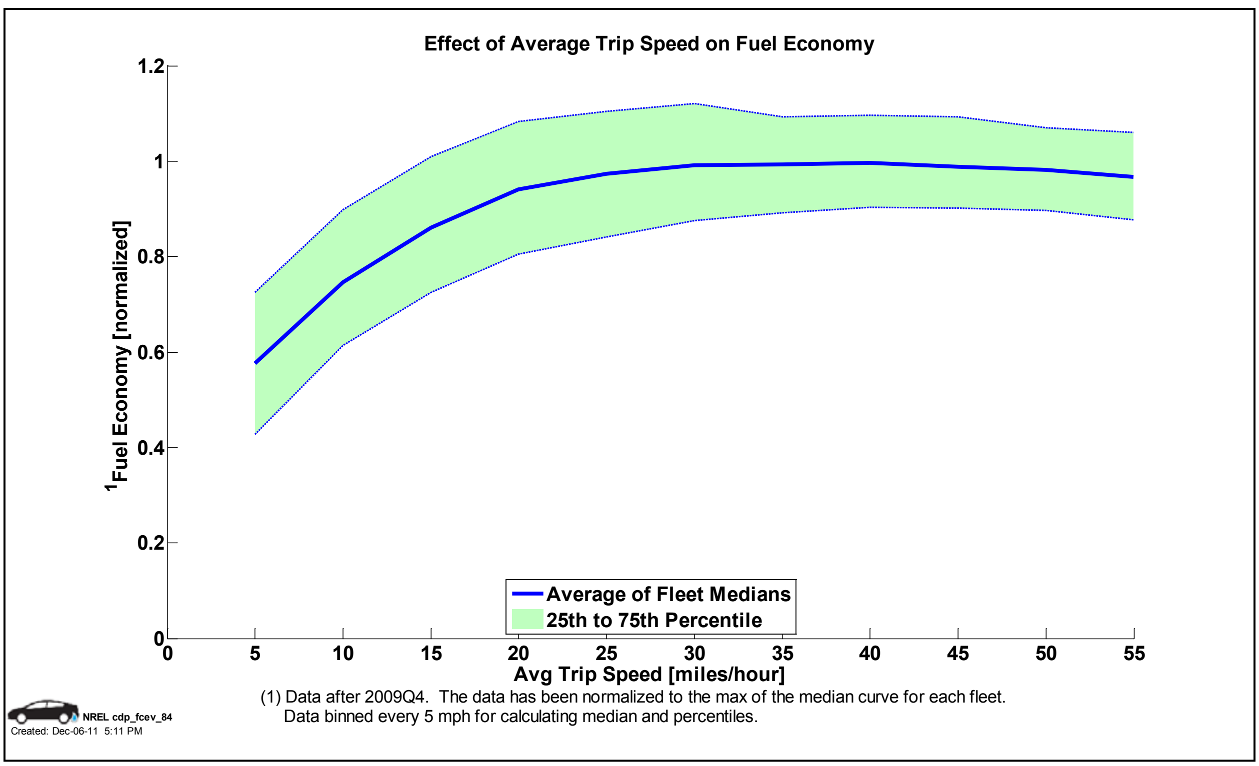



**Figure 24: Effect of average trip speed on fuel economy (CDP84)**

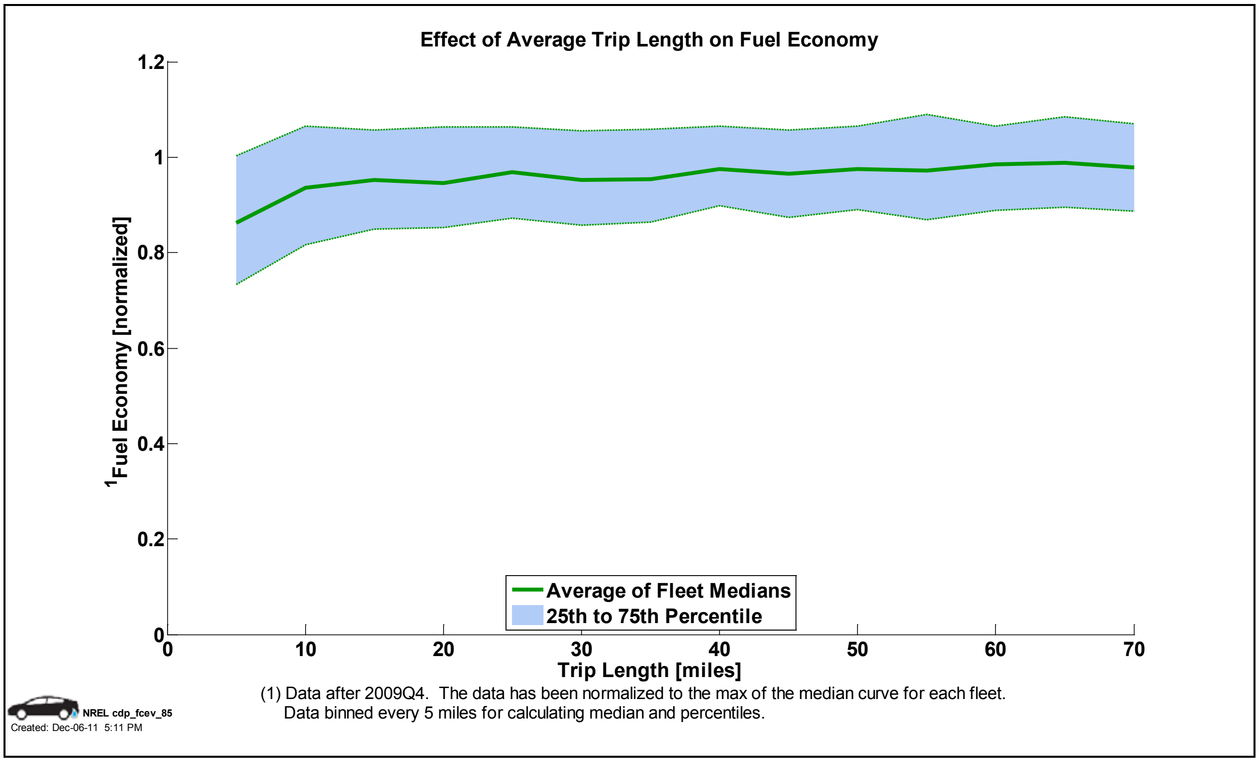



**Figure 25: Effect of trip length on fuel economy (CDP85)**

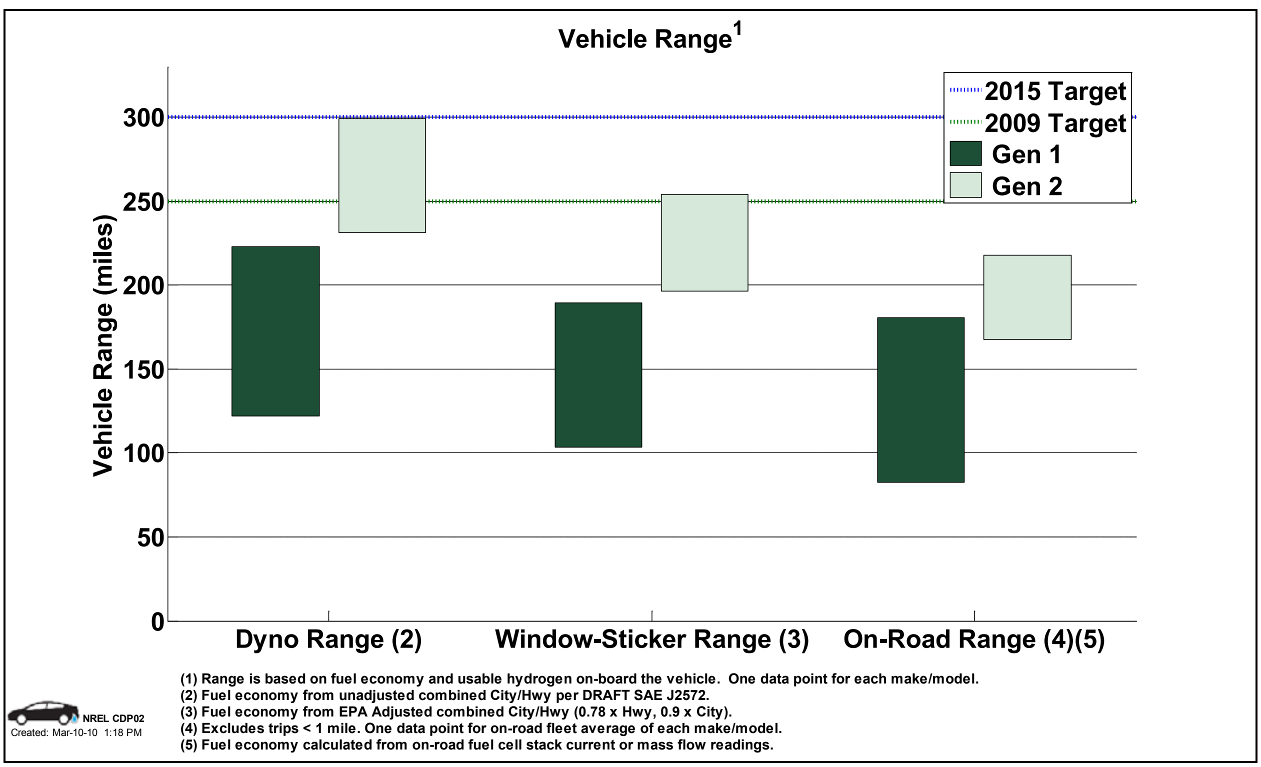



**Figure 26: Vehicle driving range (CDP02)**

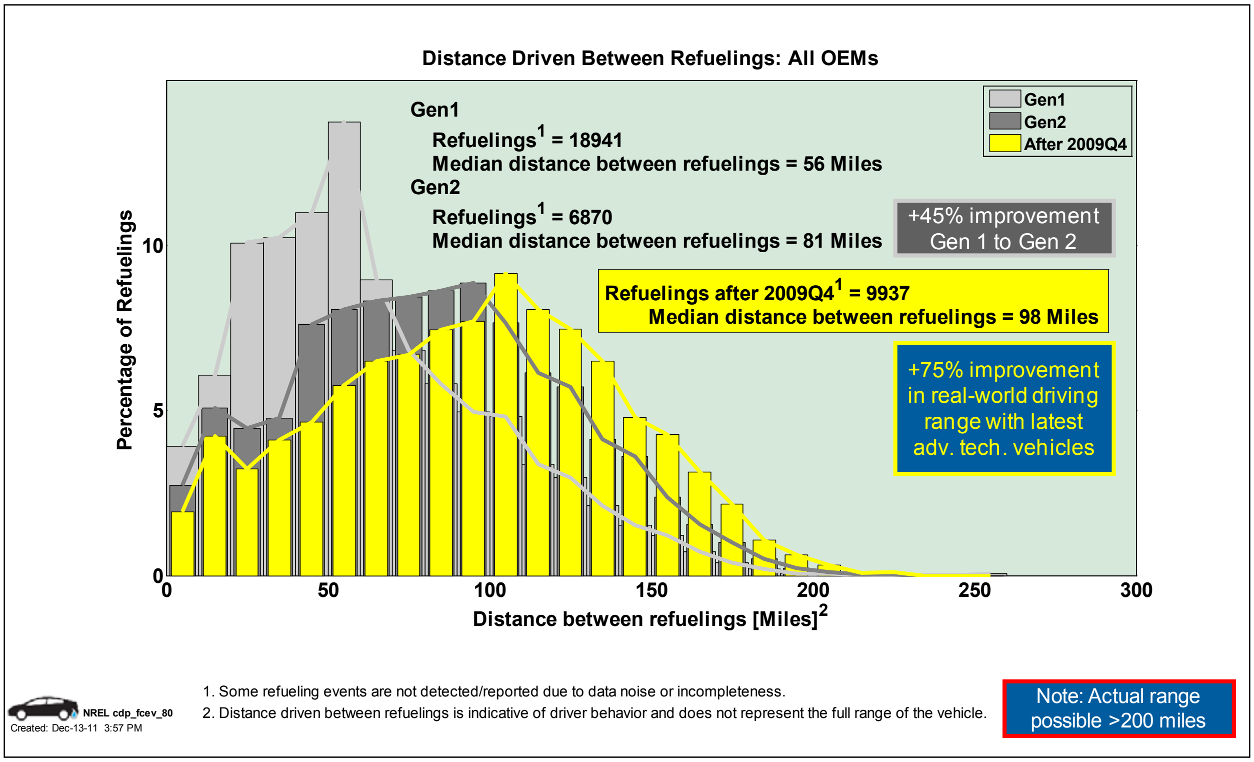



**Figure 27: Miles between refuelings (CDP80)**

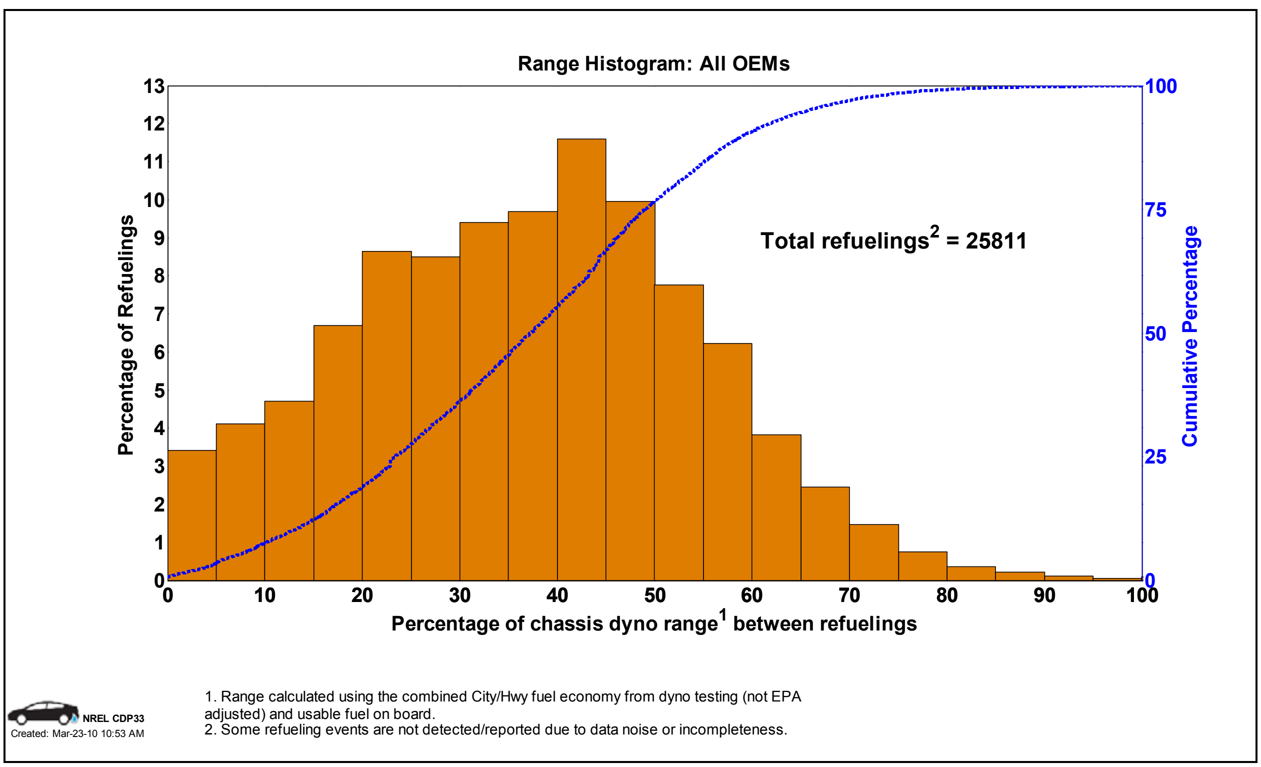



**Figure 28: Percentage of theoretical range traveled between refuelings (CDP33)**

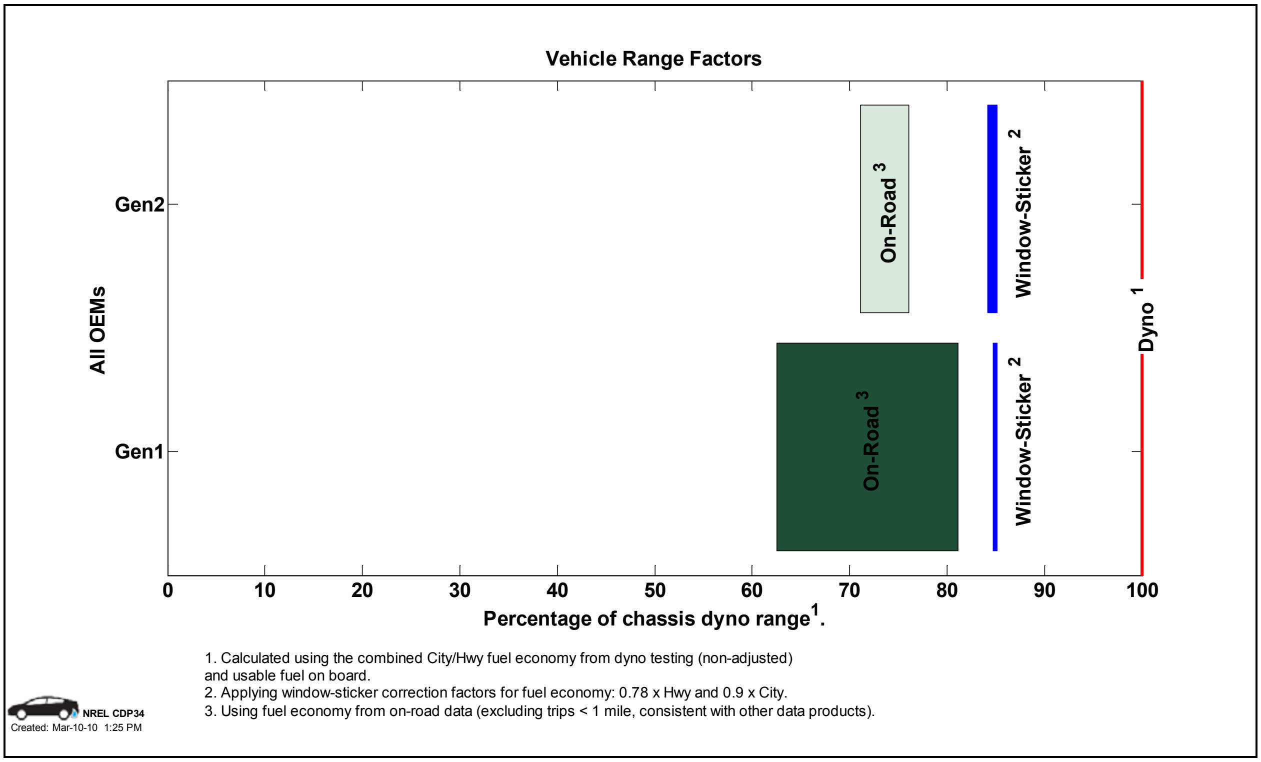



**Figure 29: Effective vehicle driving range (CDP34)**

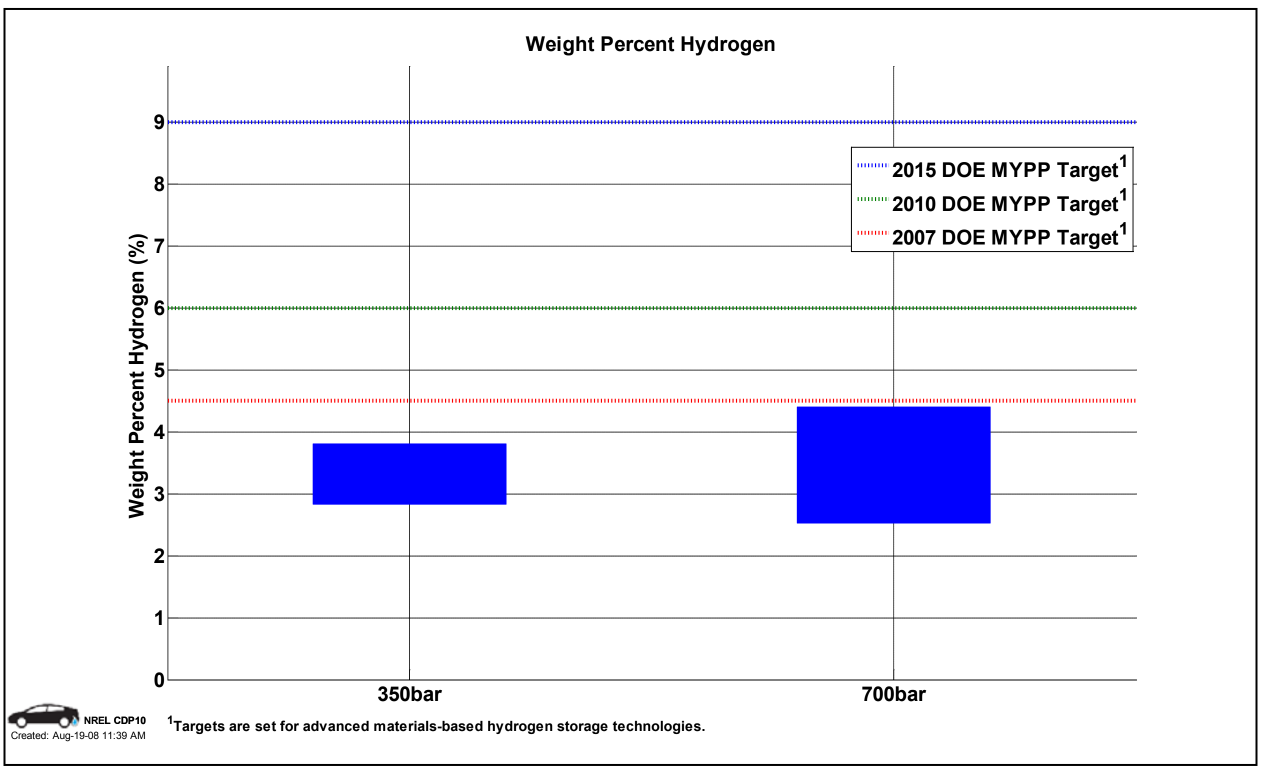



**Figure 30: Storage weight % hydrogen (CDP10)**

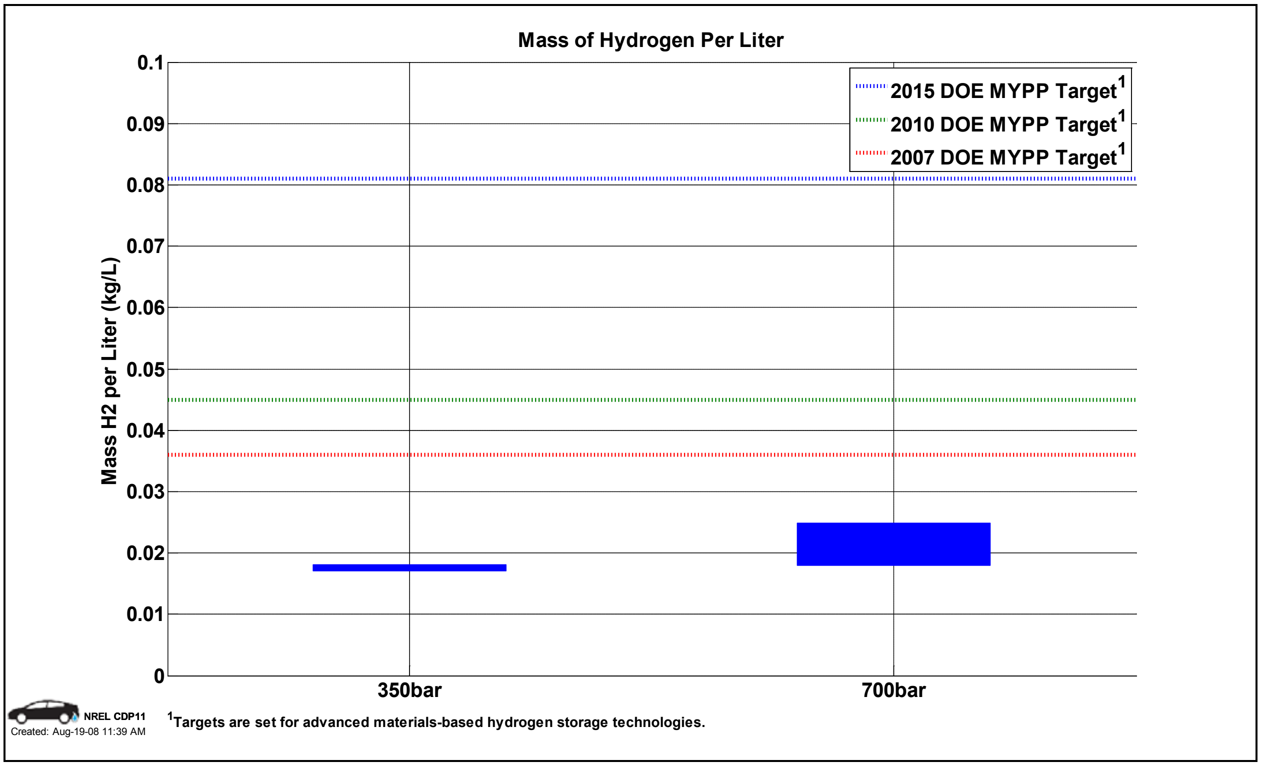



**Figure 31: Volumetric capacity of hydrogen storage (CDP11)**

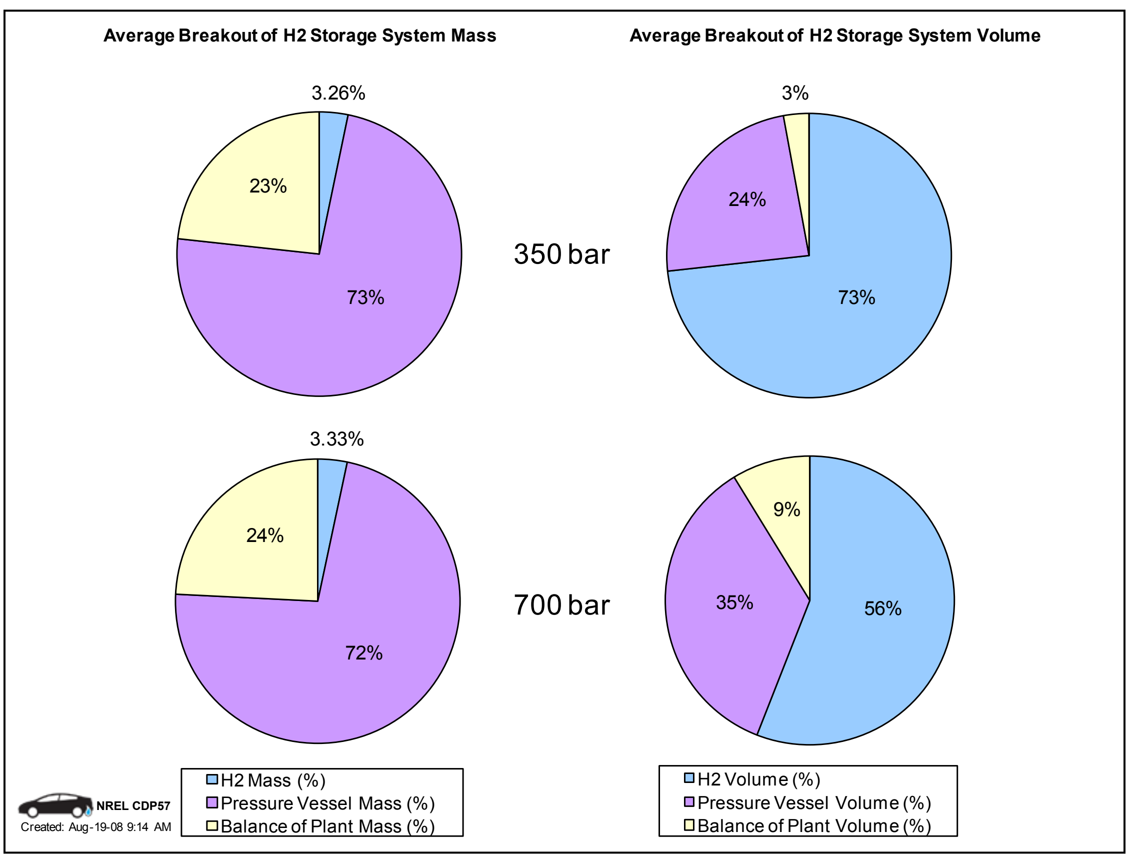



**Figure 32: Hydrogen storage system mass and volume breakdown (CDP57)**

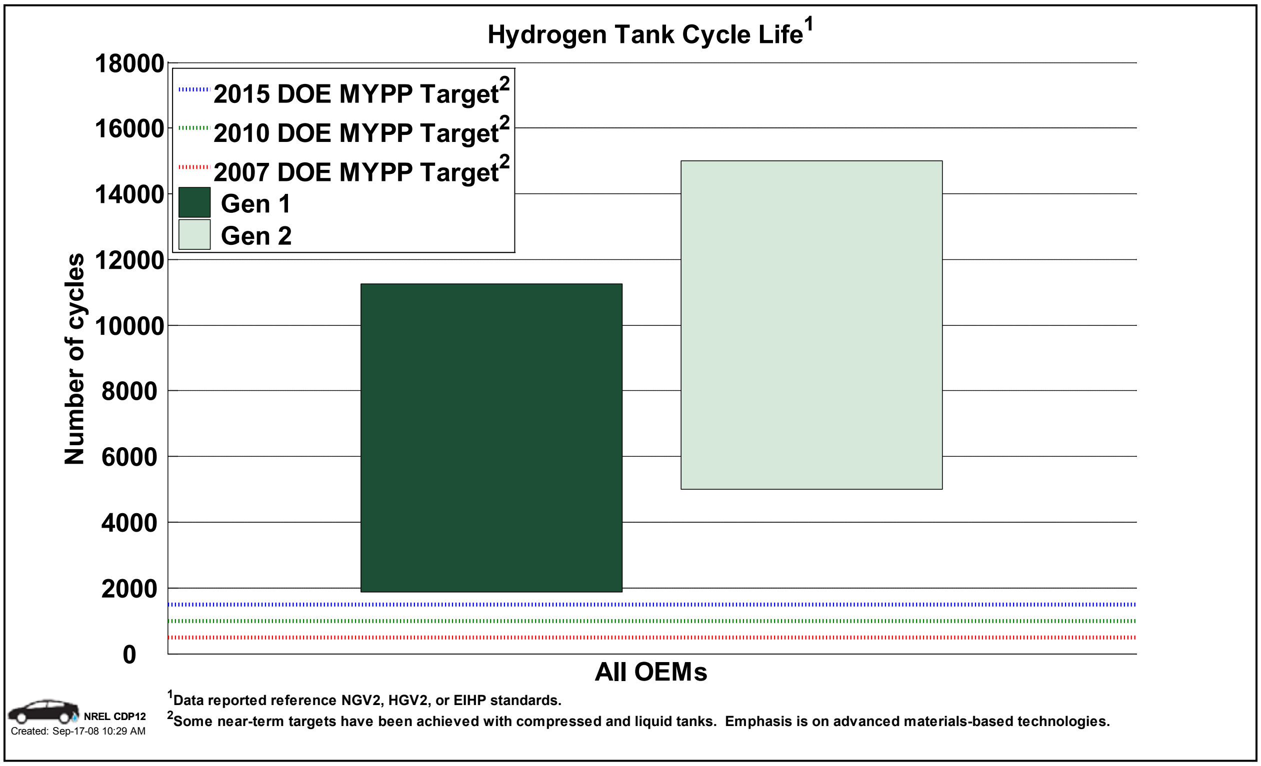



**Figure 33: Vehicle hydrogen tank cycle life (CDP12)**

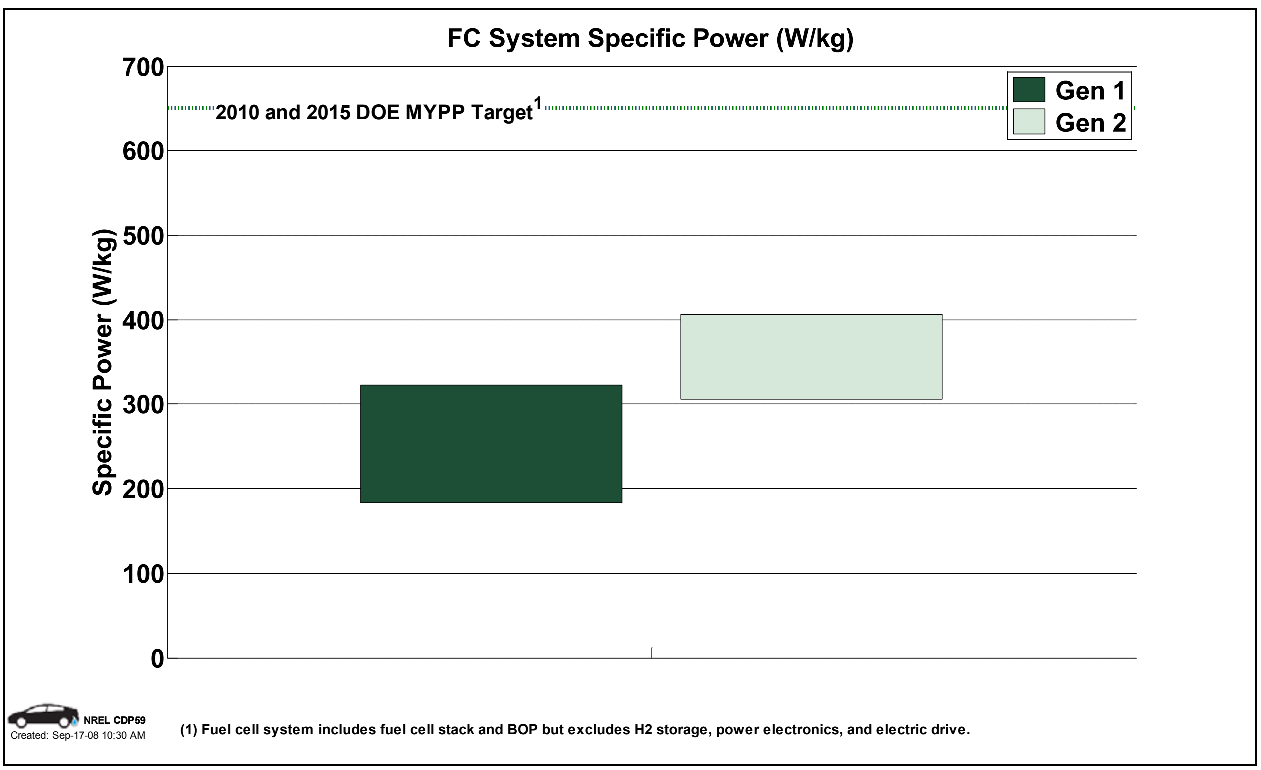



**Figure 34: Fuel cell system specific power (CDP59)**

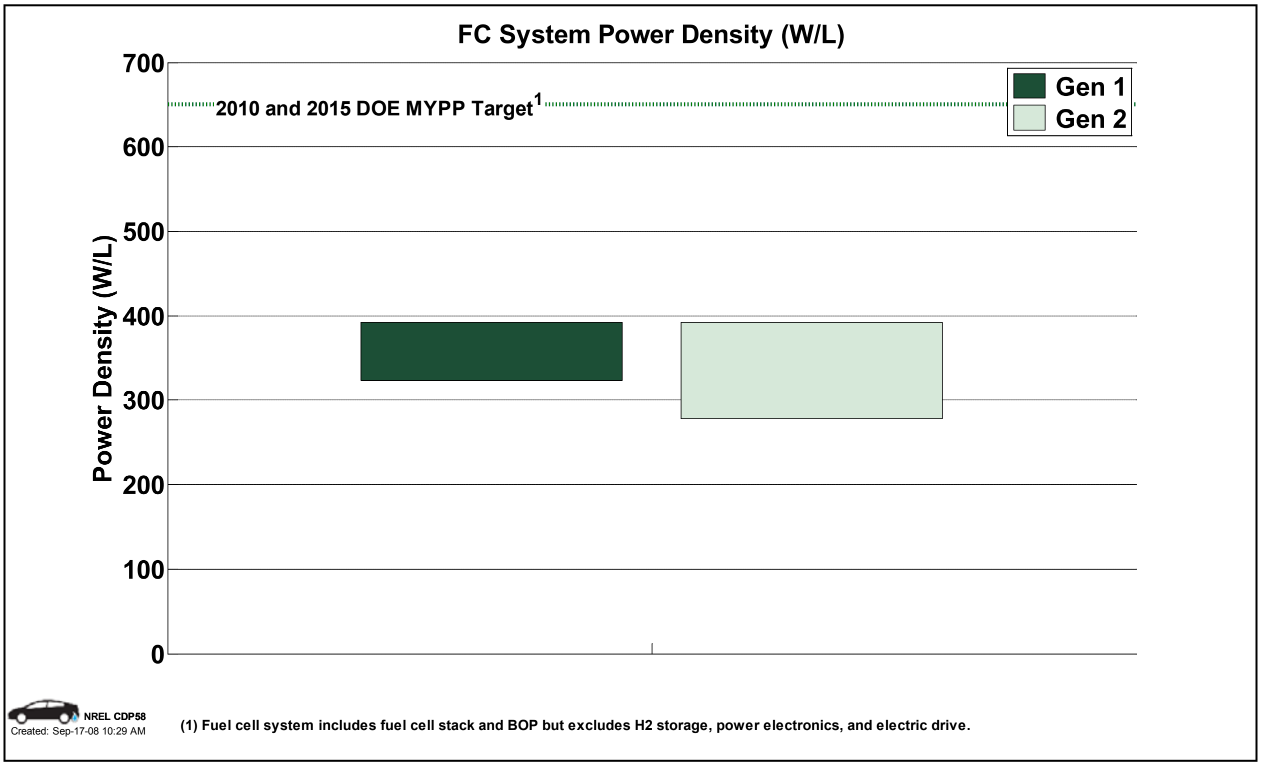



**Figure 35: Fuel cell system power density (CDP58)**

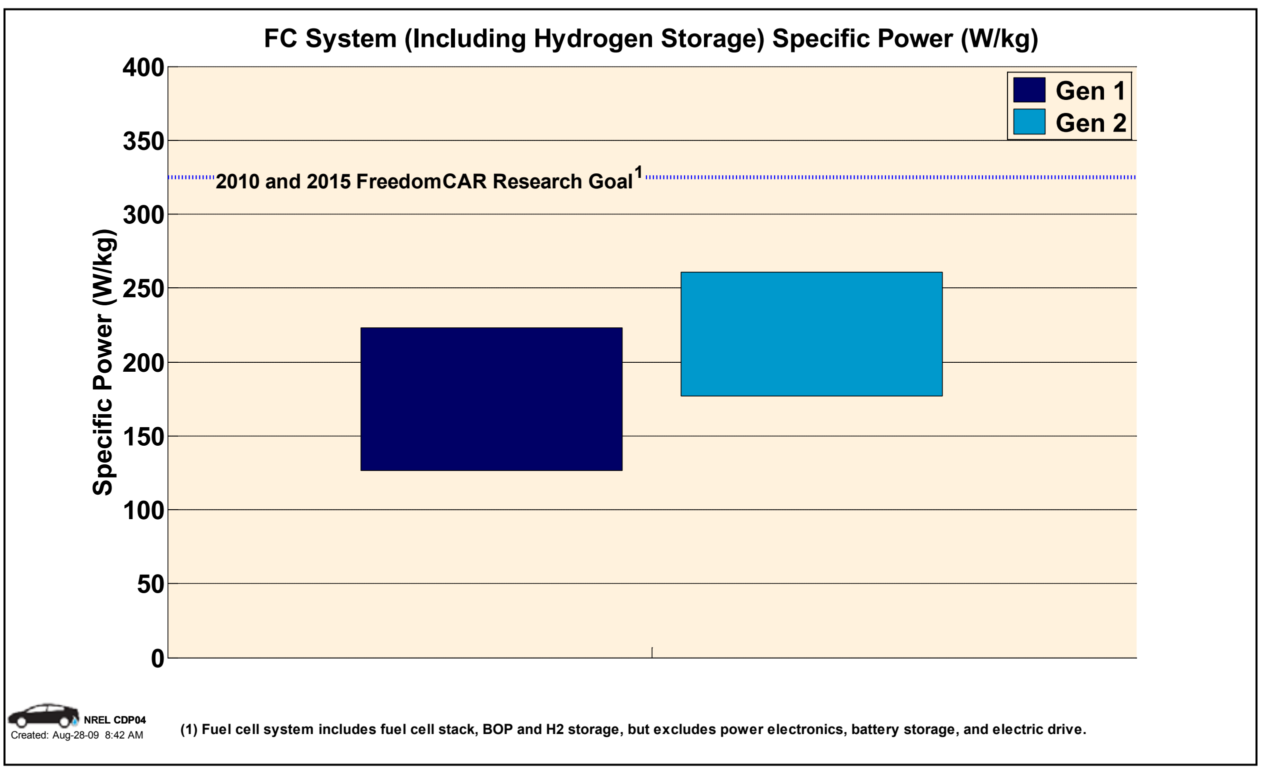



**Figure 36: Fuel cell system specific power, including hydrogen storage (CDP04)**

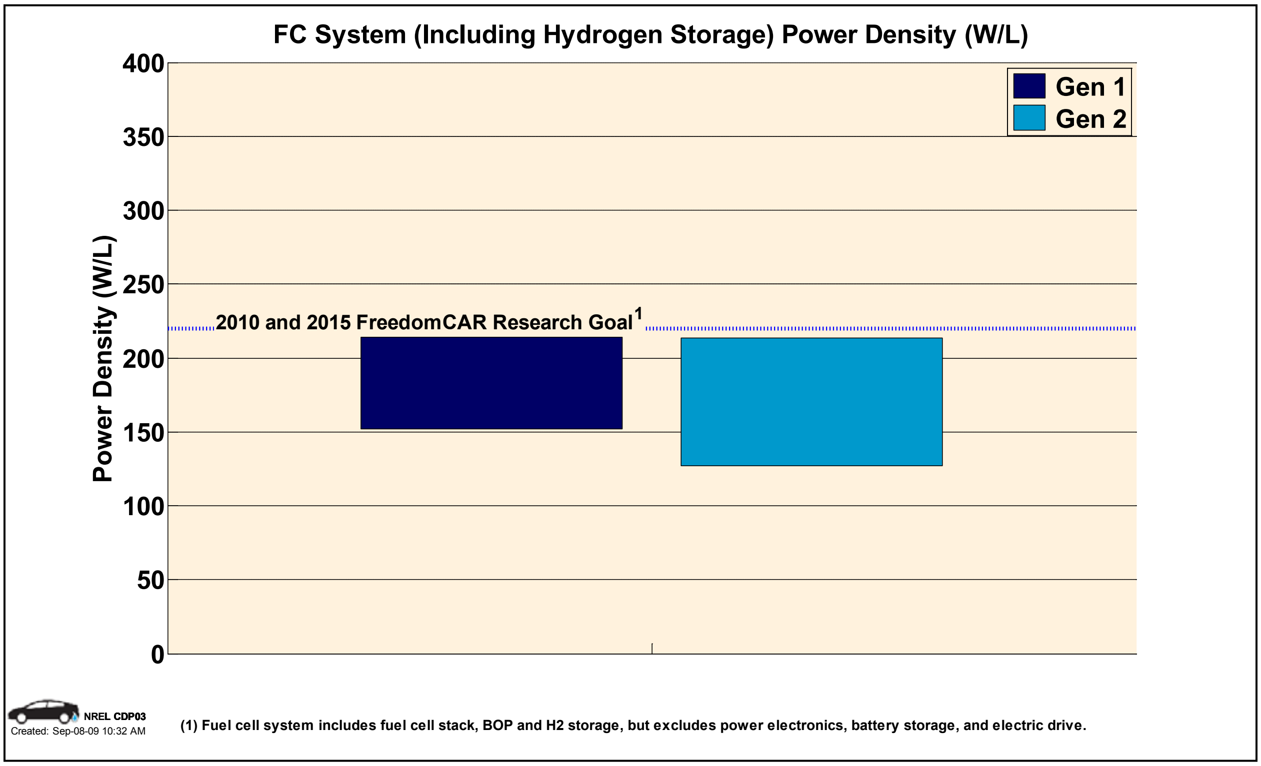



Figure 37: Fuel cell system power density, including hydrogen storage (CDP03)

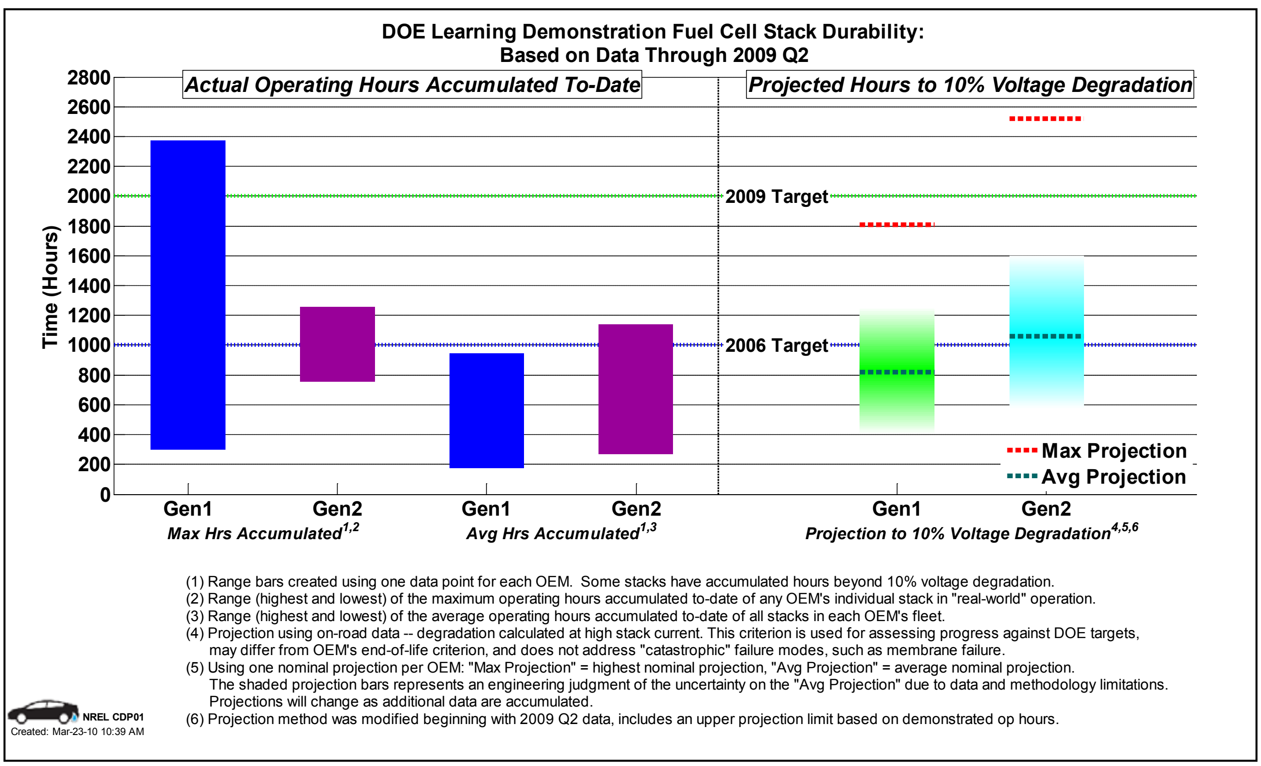



Figure 38: Hours accumulated and projected hours to 10% stack voltage degradation (CDP01)

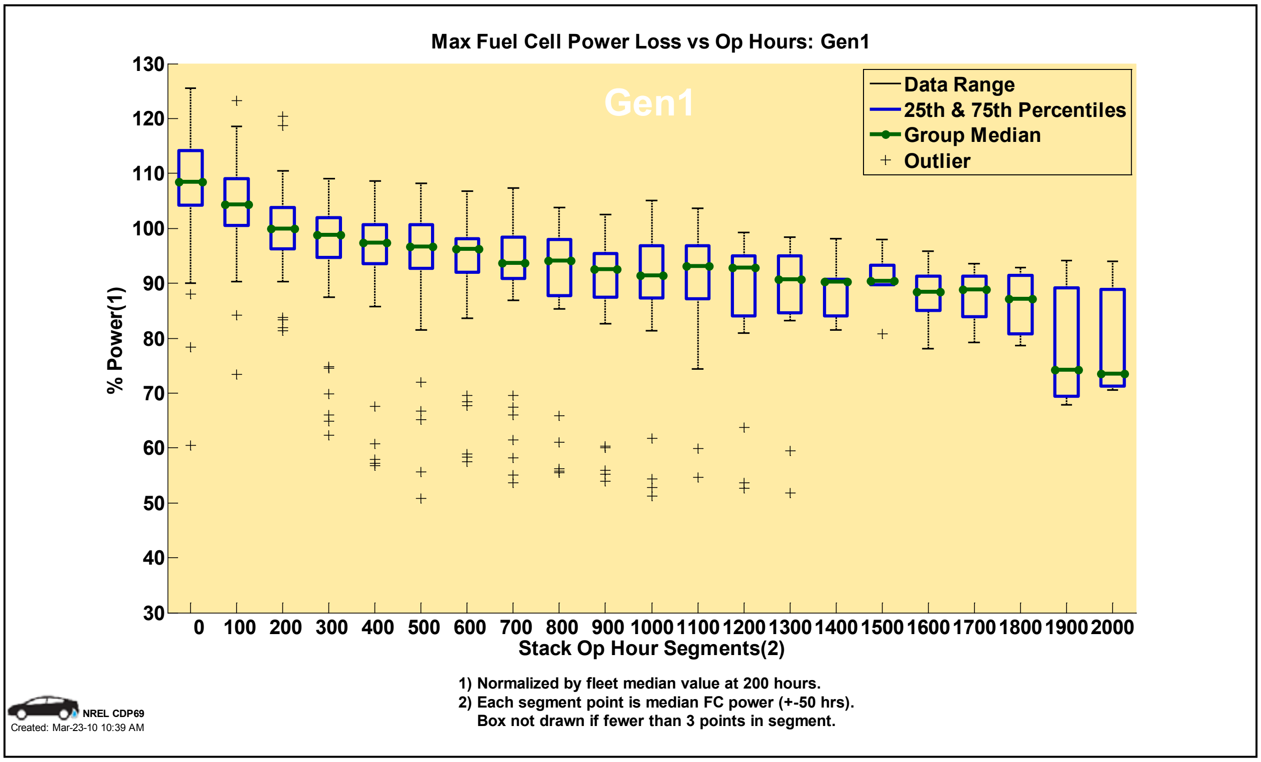



**Figure 39: Maximum fuel cell power degradation—Gen 1 (CDP69)**

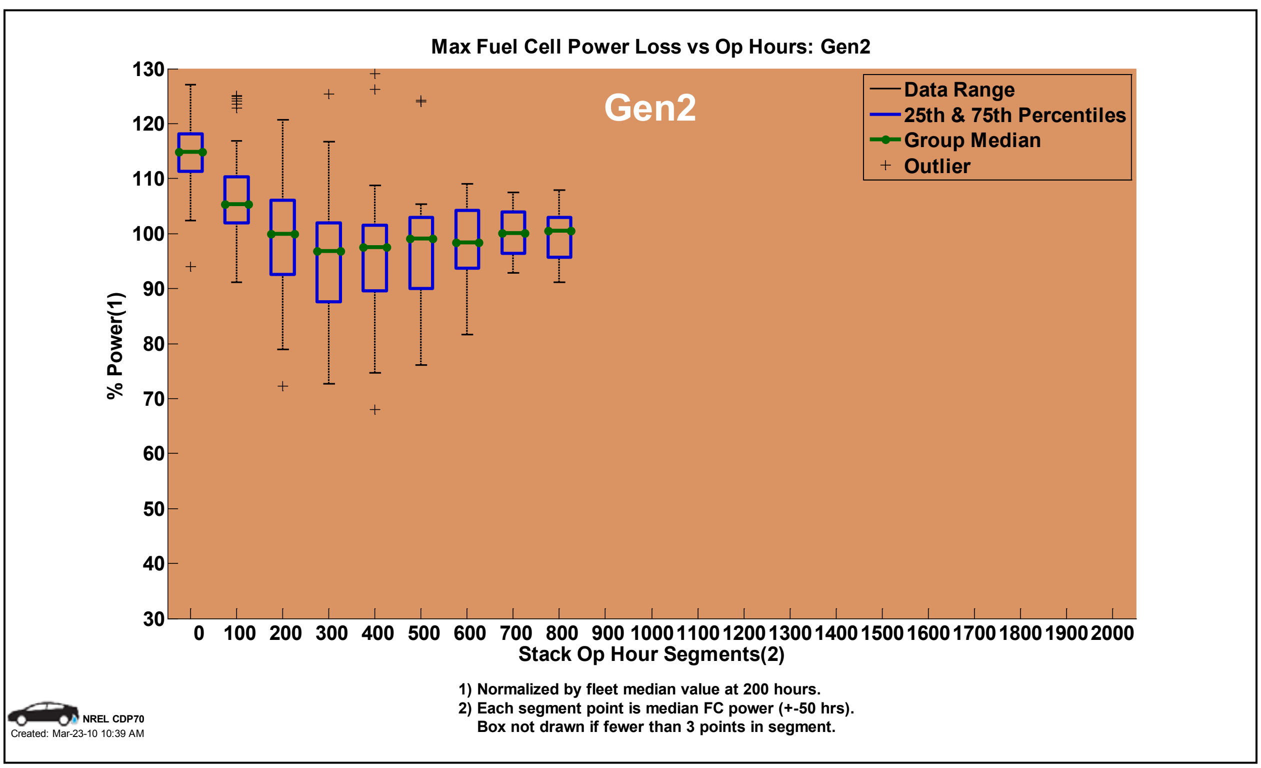



**Figure 40: Maximum fuel cell power degradation—Gen 2 (CDP70)**

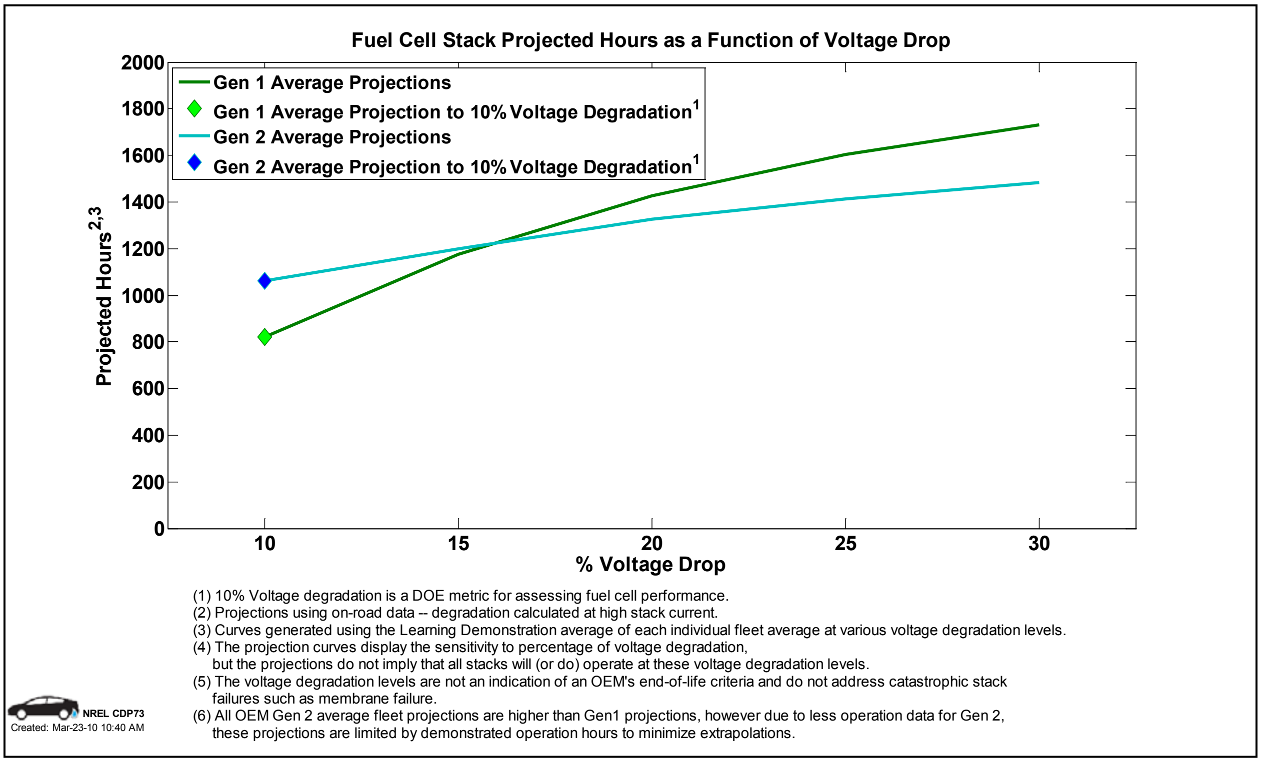



**Figure 41: Fuel cell stack projected hours as a function of voltage drop (CDP73)**

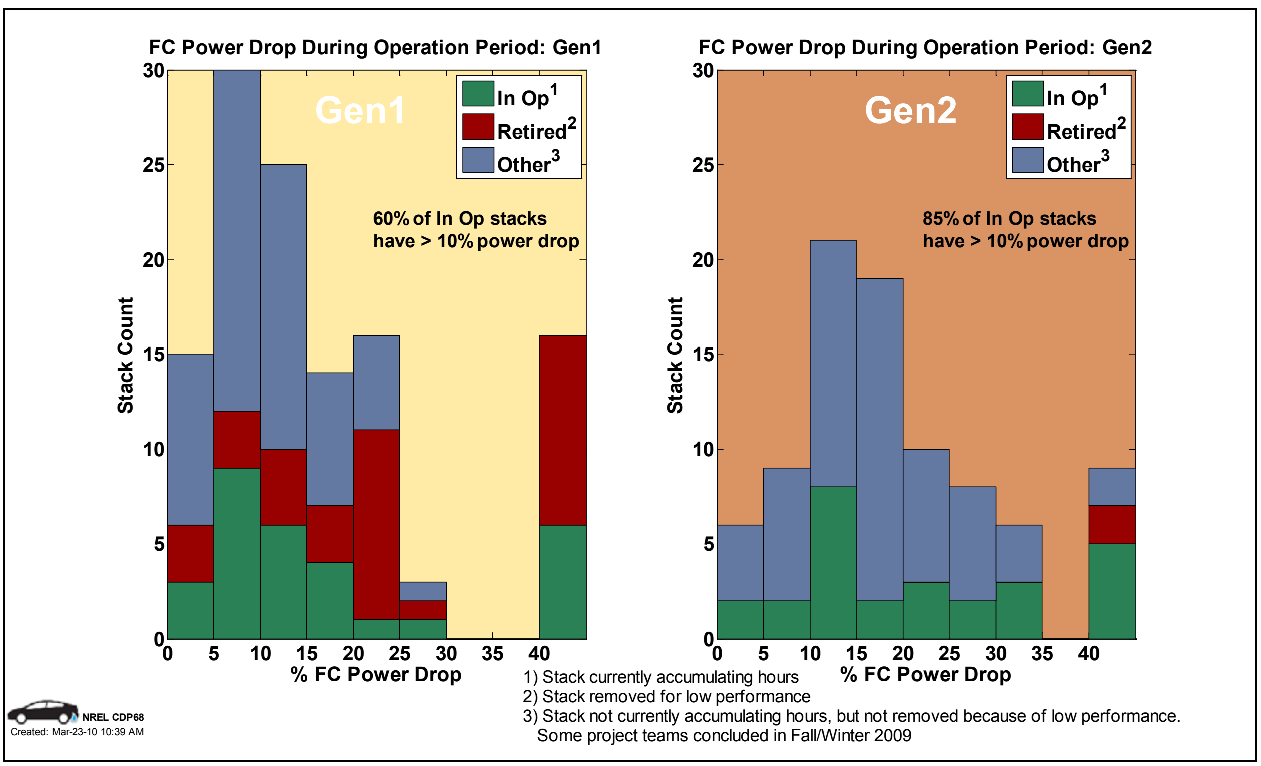



**Figure 42: Power drop during fuel cell stack operating period (CDP68)**

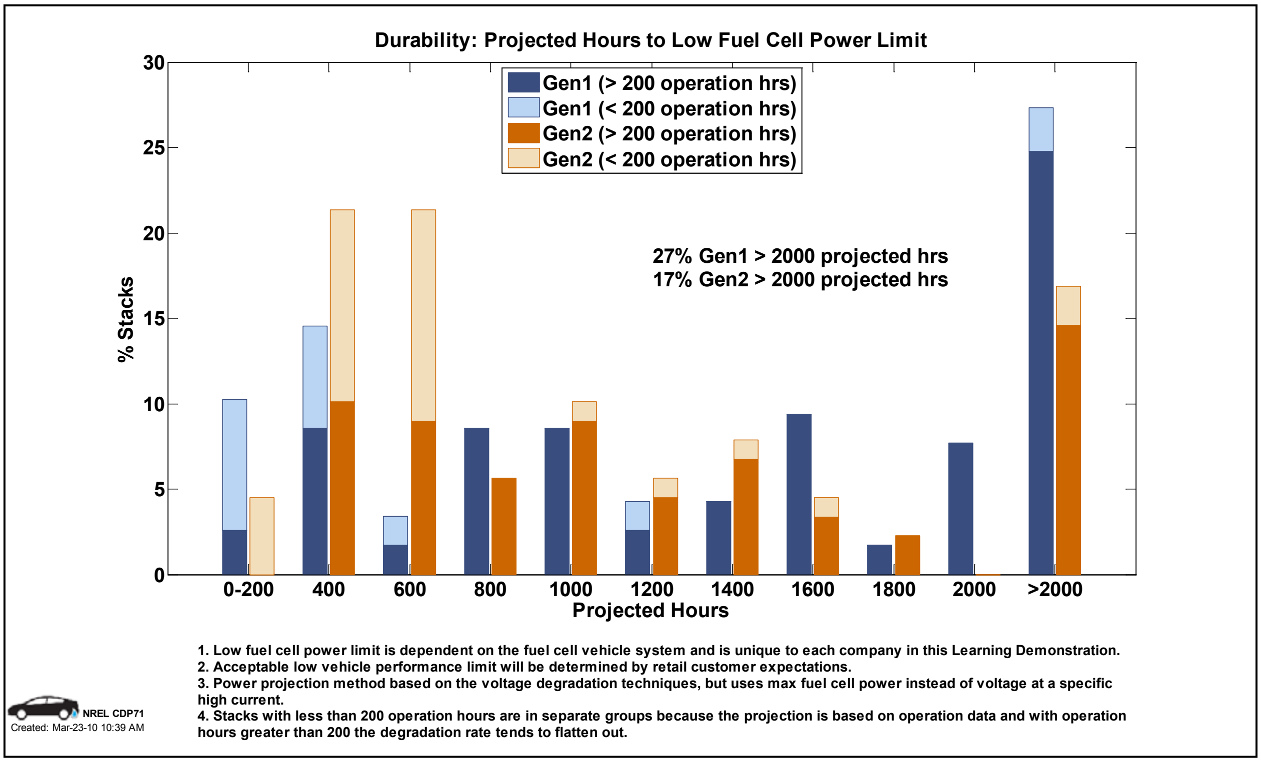



**Figure 43: Projected hours to OEM low power operation limit (CDP71)**

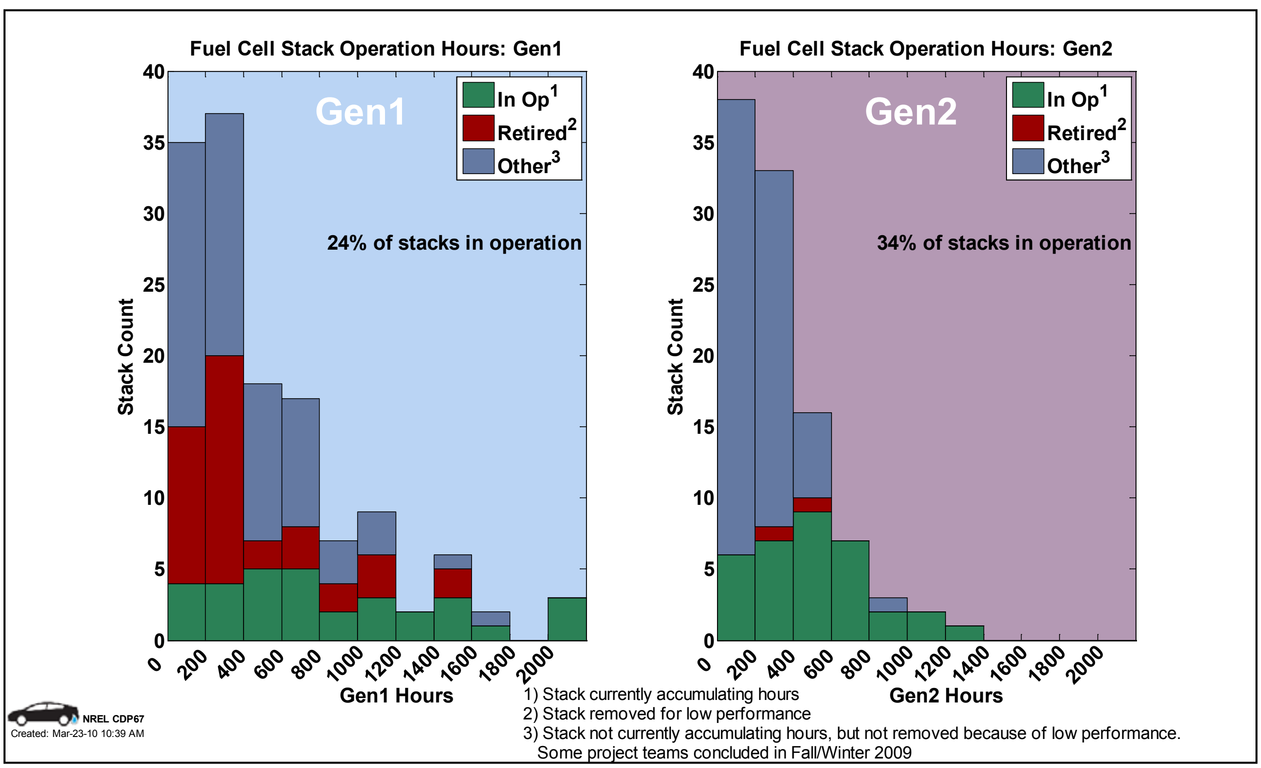



**Figure 44: Fuel cell stack operation hours (CDP67)**

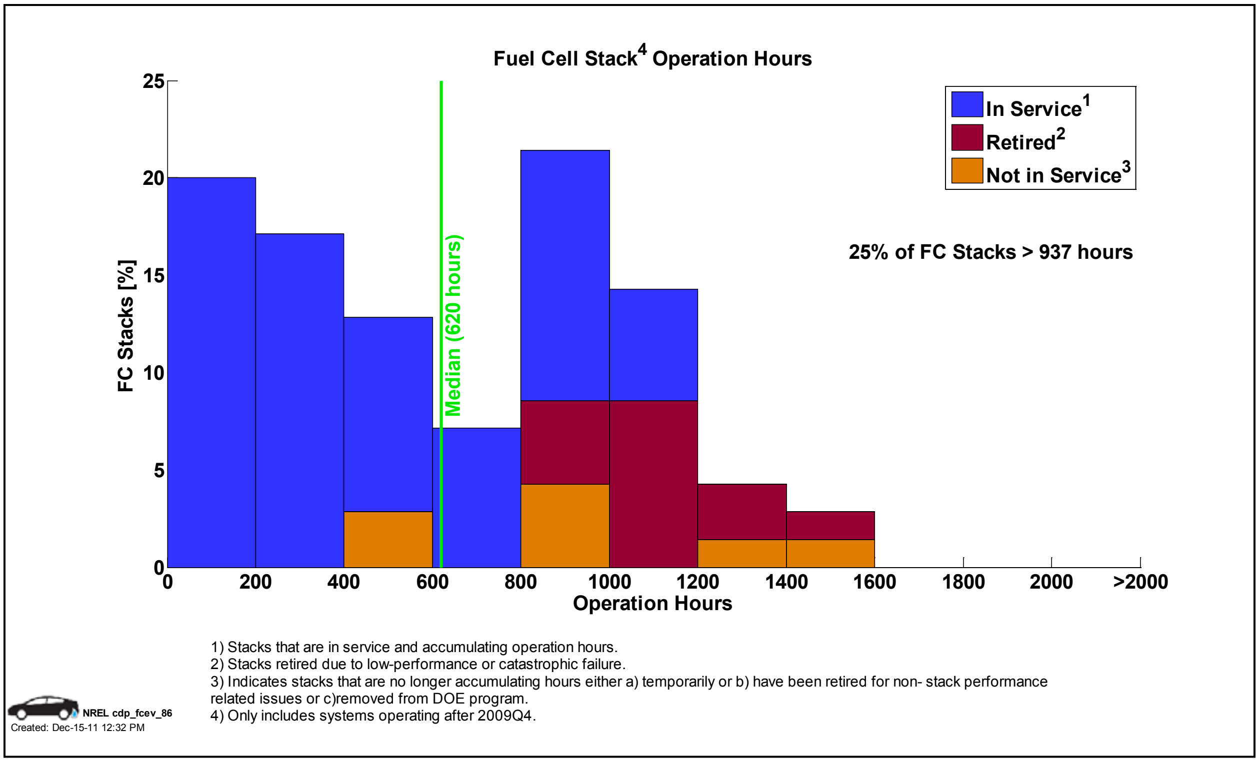



**Figure 45: Fuel cell stack operation hours after 2009Q4 (CDP86)**

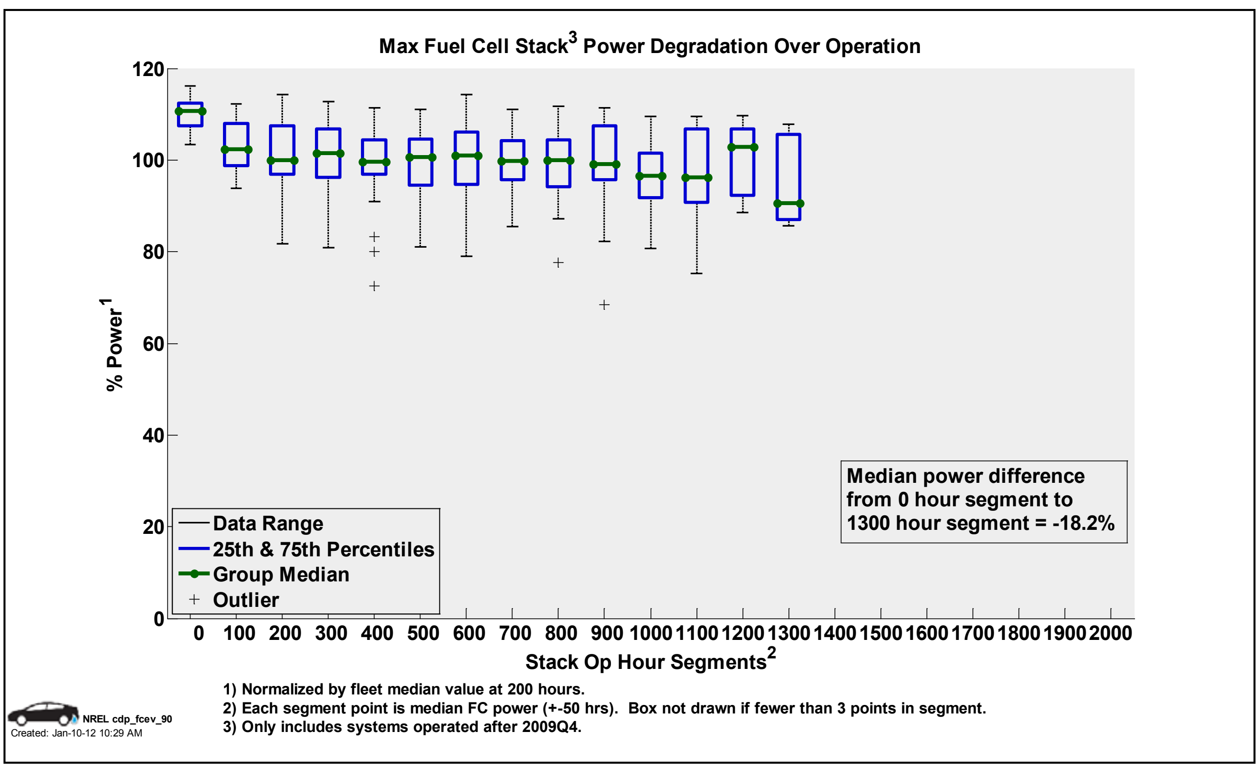



**Figure 46: Maximum fuel cell stack power degradation over operation from vehicles after 2009Q4 (CDP90)**

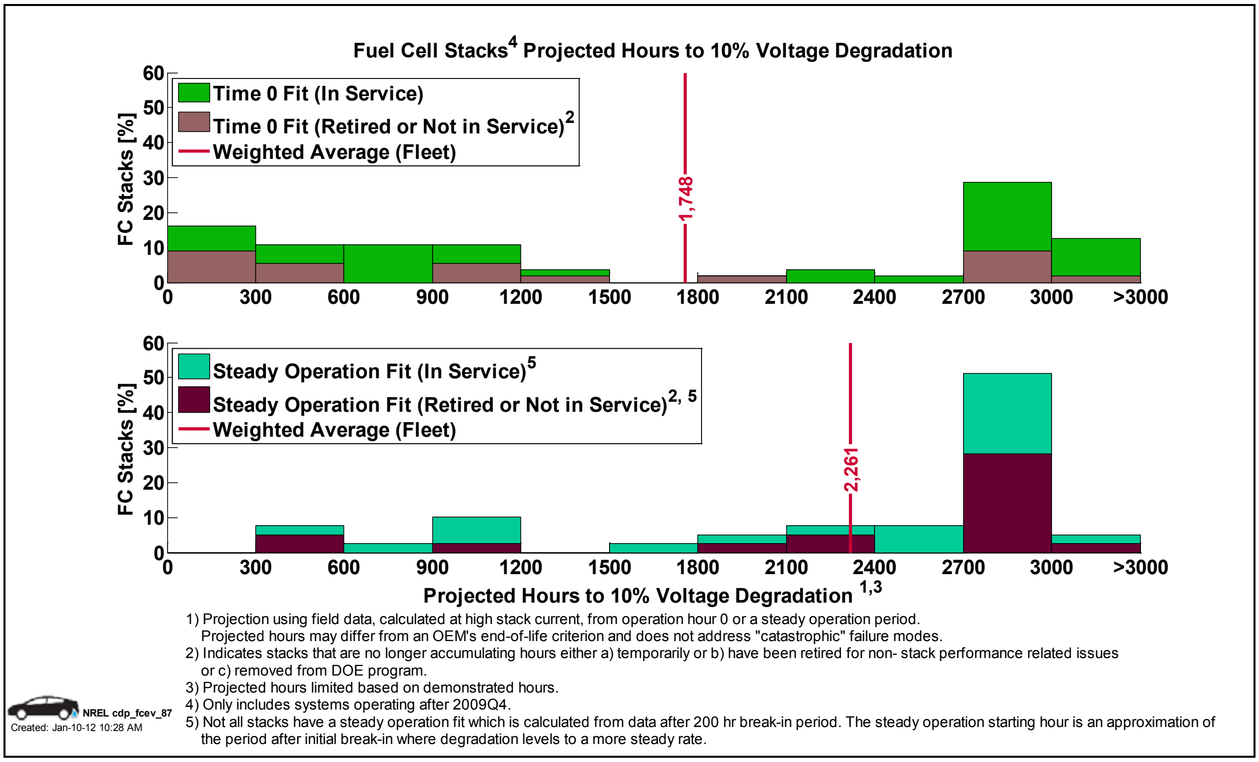



**Figure 47: Fuel cell stacks projected hours to 10% voltage degradation with two fits after 2009Q4 (CDP87)**

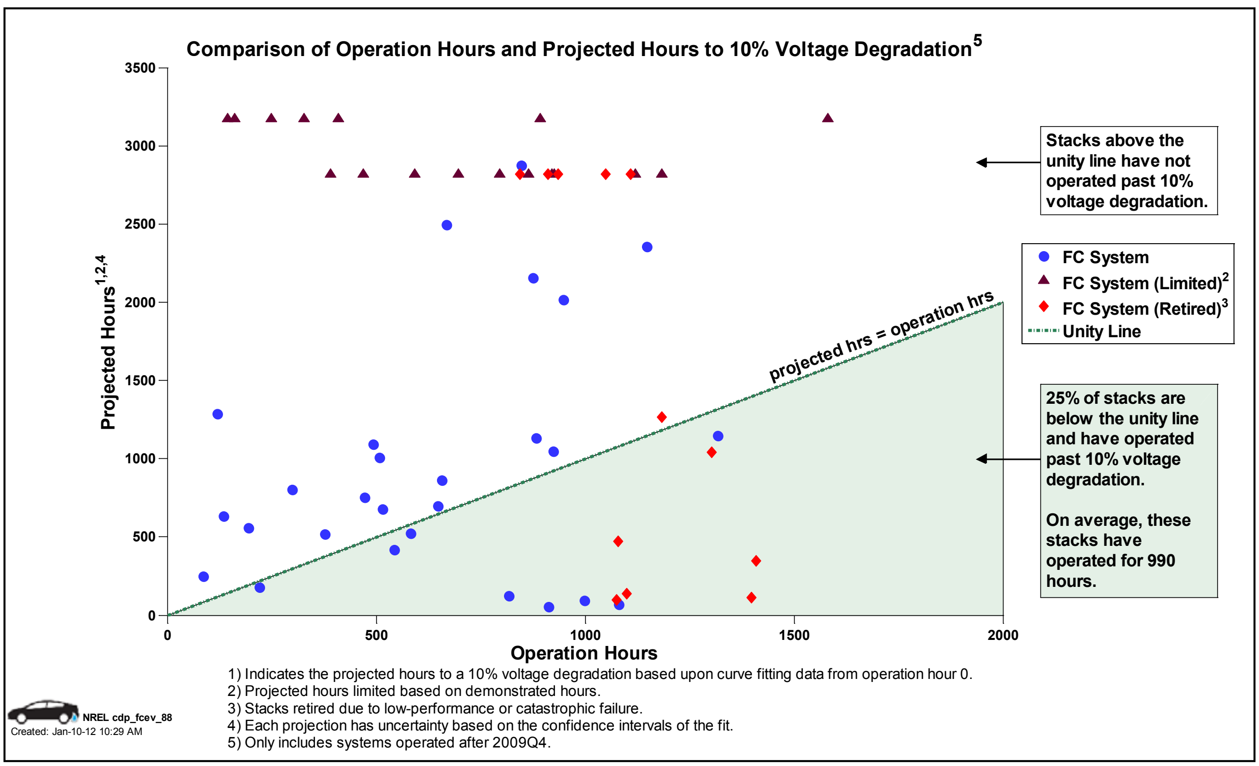



**Figure 48: Comparison of fuel cell operation hours and projected hours to 10% voltage degradation after 2009Q4 (CDP88)**

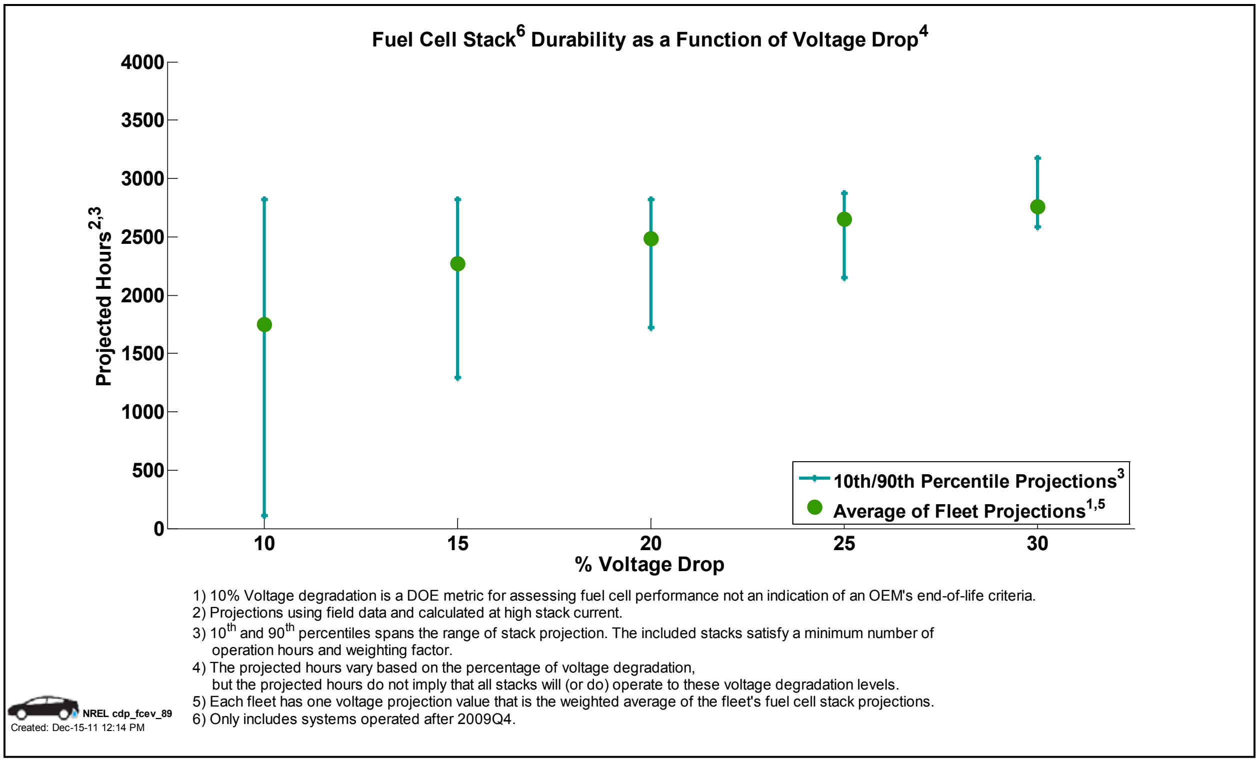



**Figure 49: Fuel cell stack durability as a function of voltage drop after 2009Q4 (CDP89)**

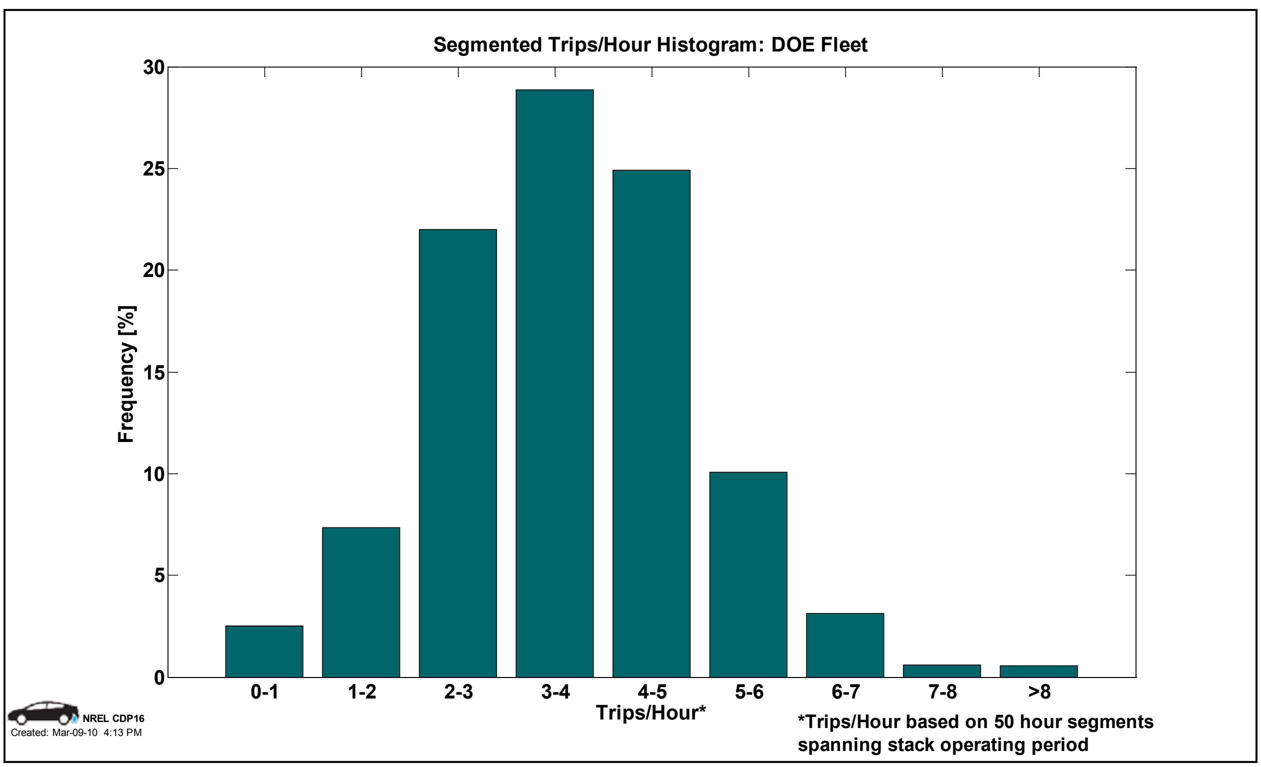



**Figure 50: Fuel cell stack trips per hour histogram (CDP16)**

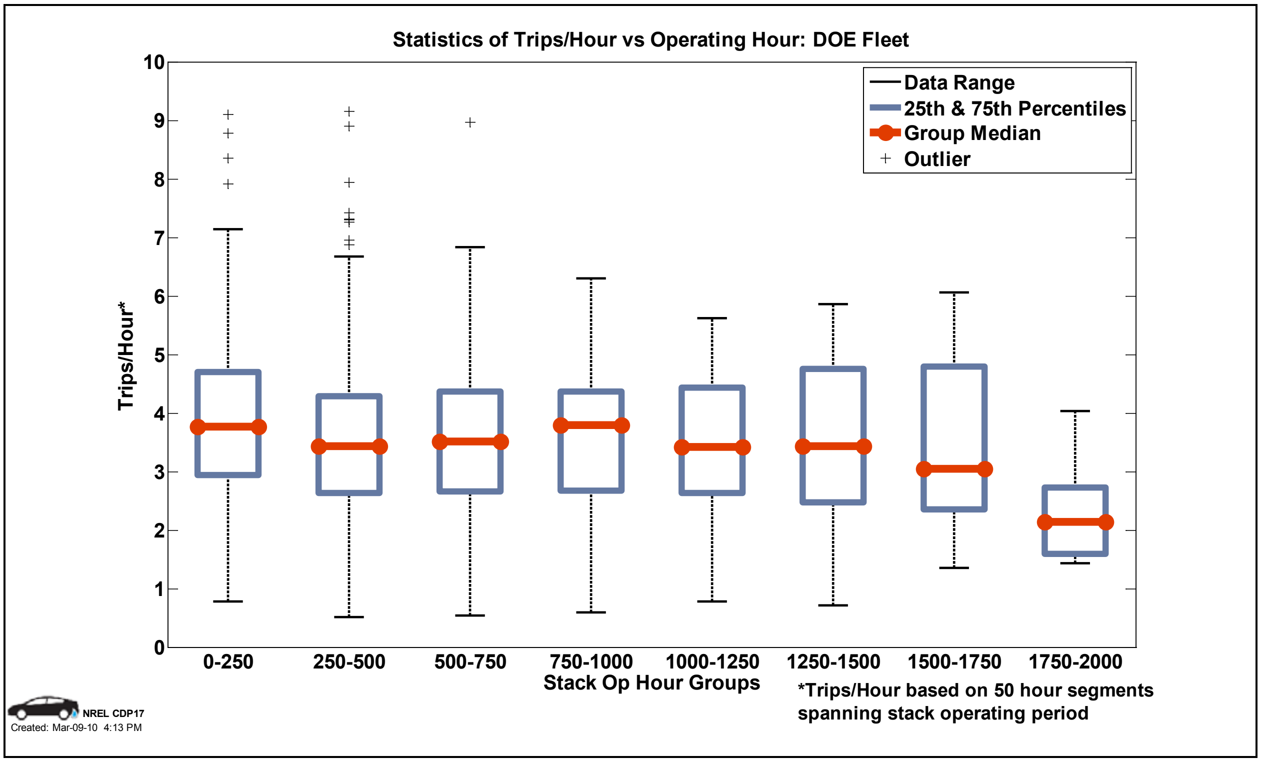



**Figure 51: Statistics of trips/hour vs. operating hour (CDP17)**

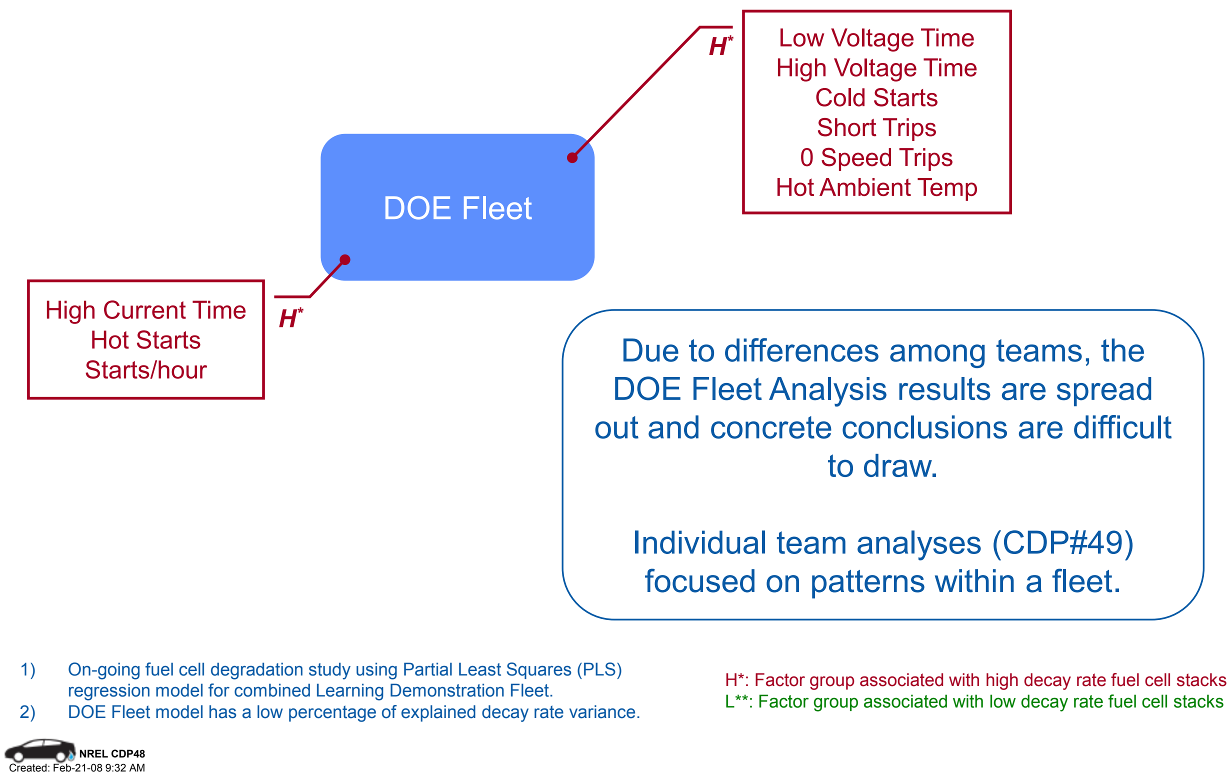



**Figure 52: Primary factors affecting Learning Demonstration fleet fuel cell degradation (CDP48)**

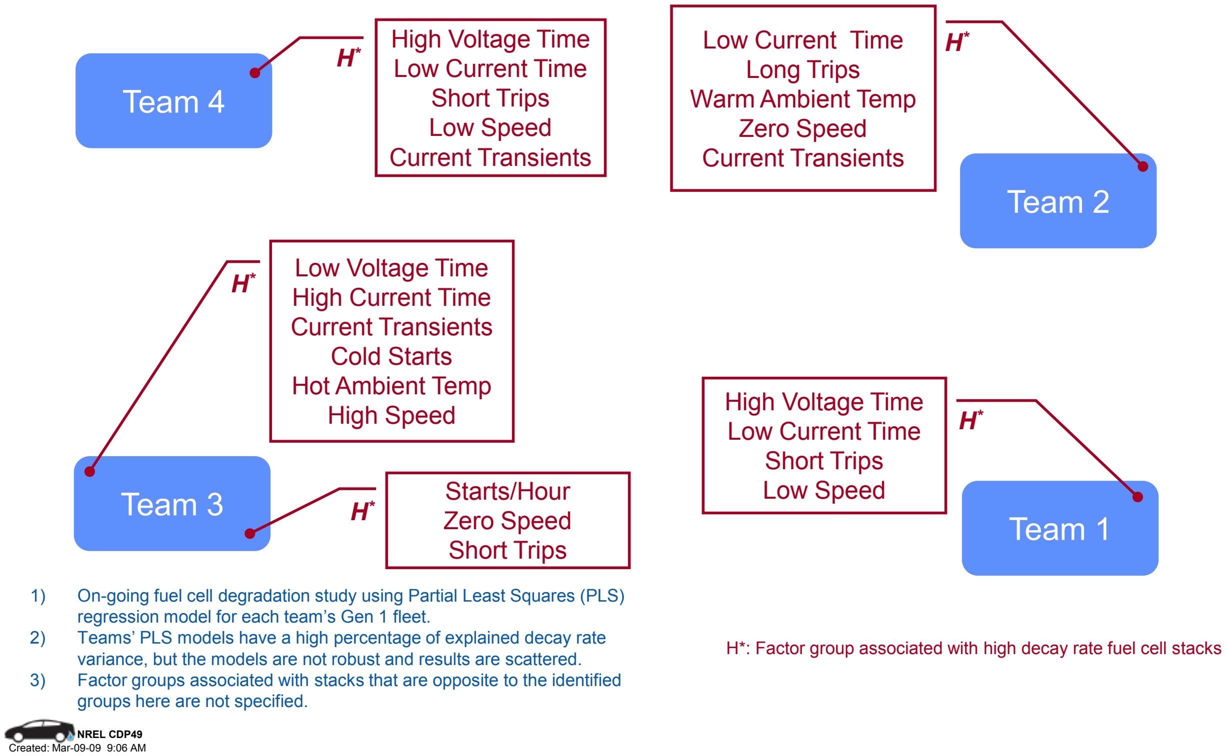



**Figure 53: Primary factors affecting Learning Demonstration team fuel cell degradation (CDP49)**

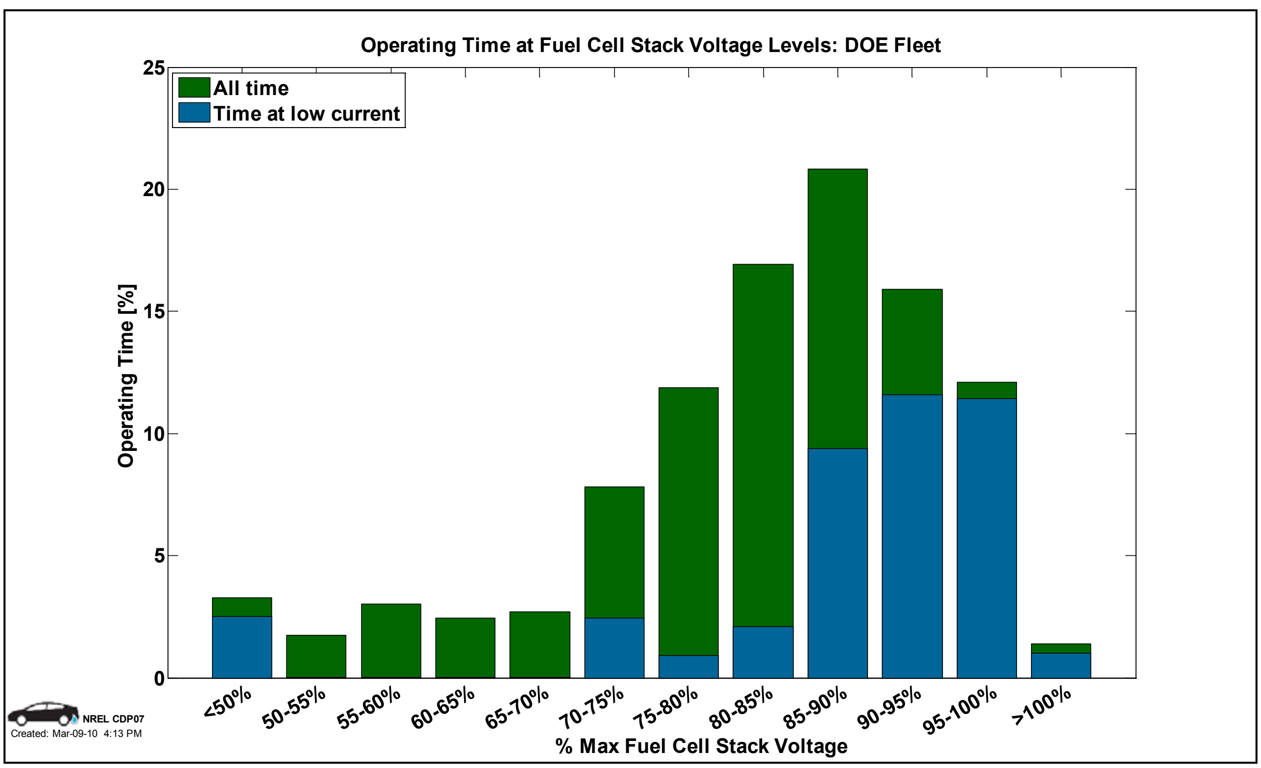



**Figure 54: Operating time at different fuel cell voltages (CDP07)**

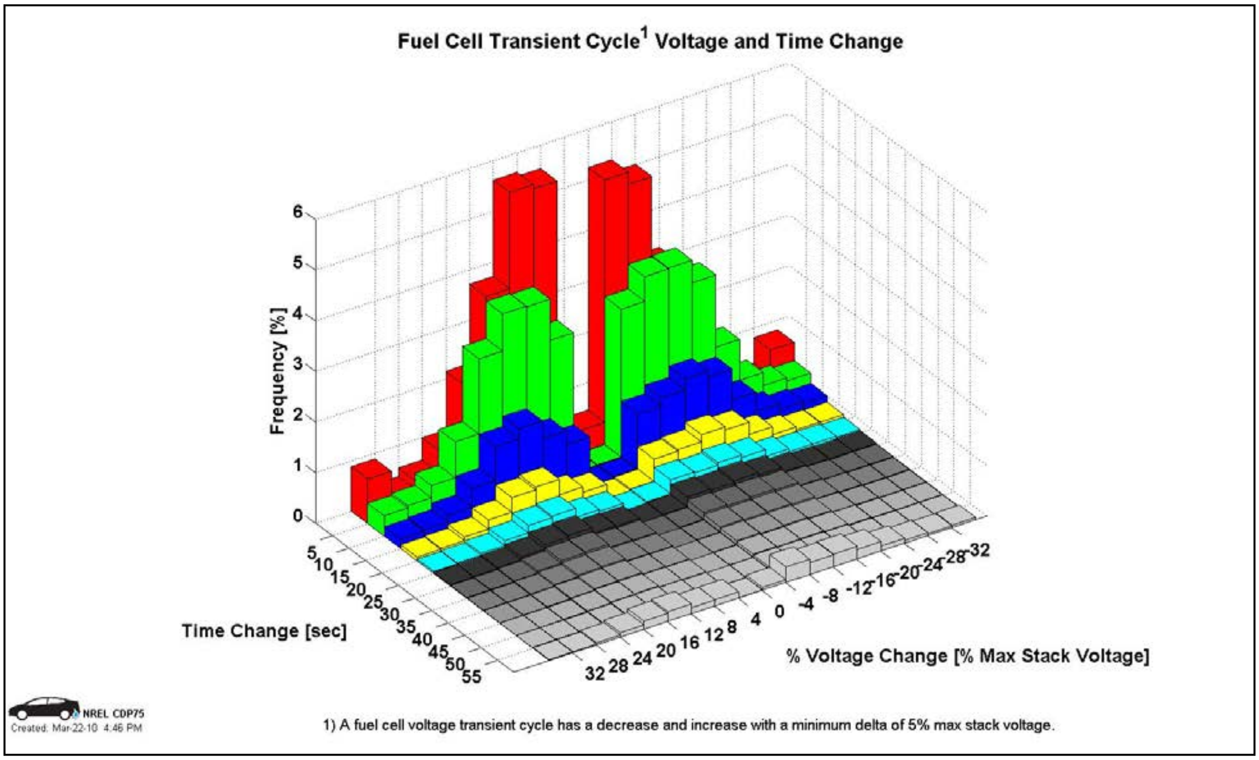



**Figure 55: Fuel cell transient voltage and time change (CDP75)**

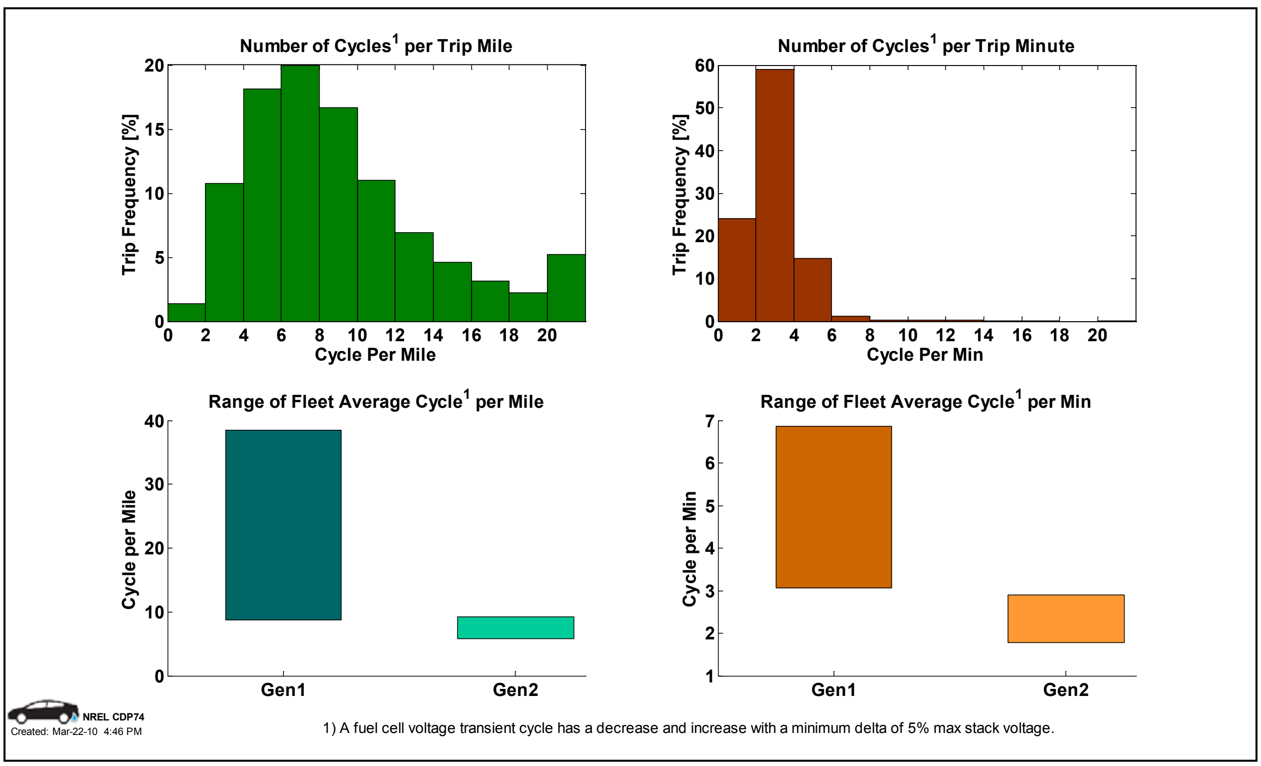



**Figure 56: Fuel cell transient cycles by mile and by minute (CDP74)**

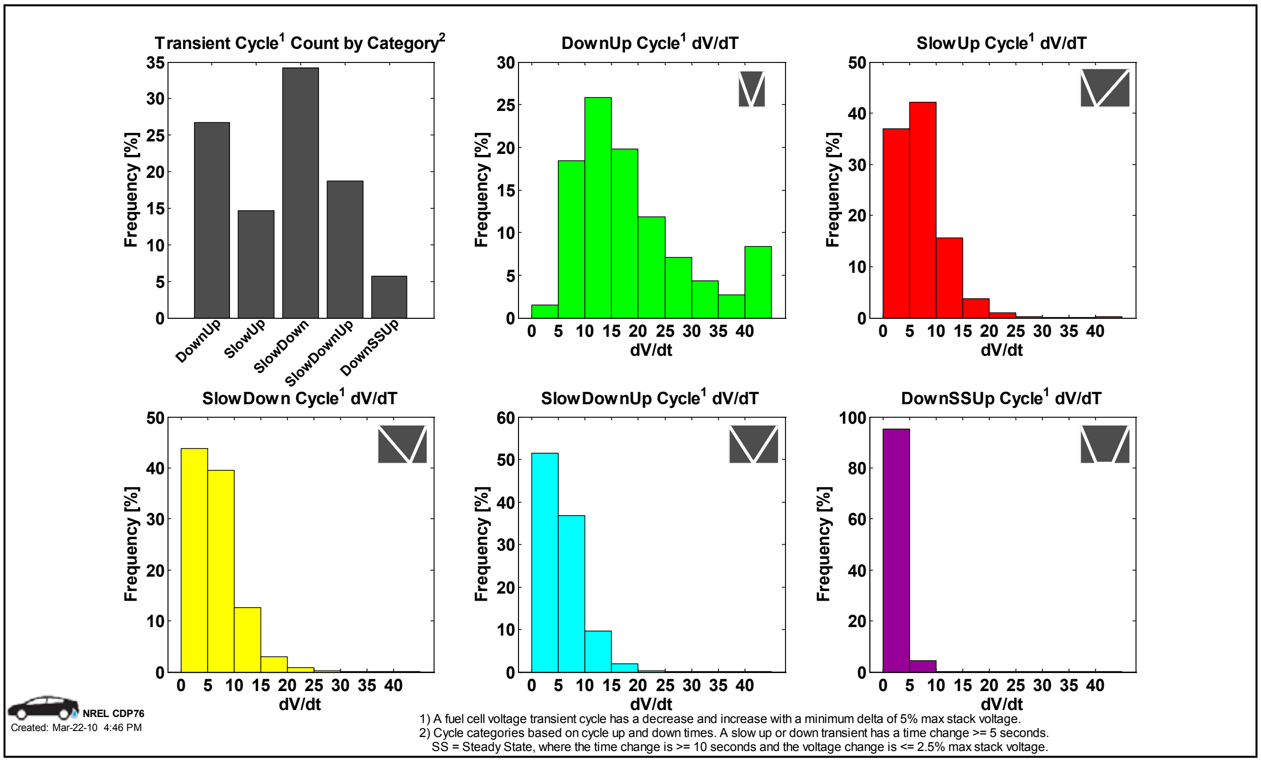



**Figure 57: Fuel cell transient rate by cycle category (CDP76)**

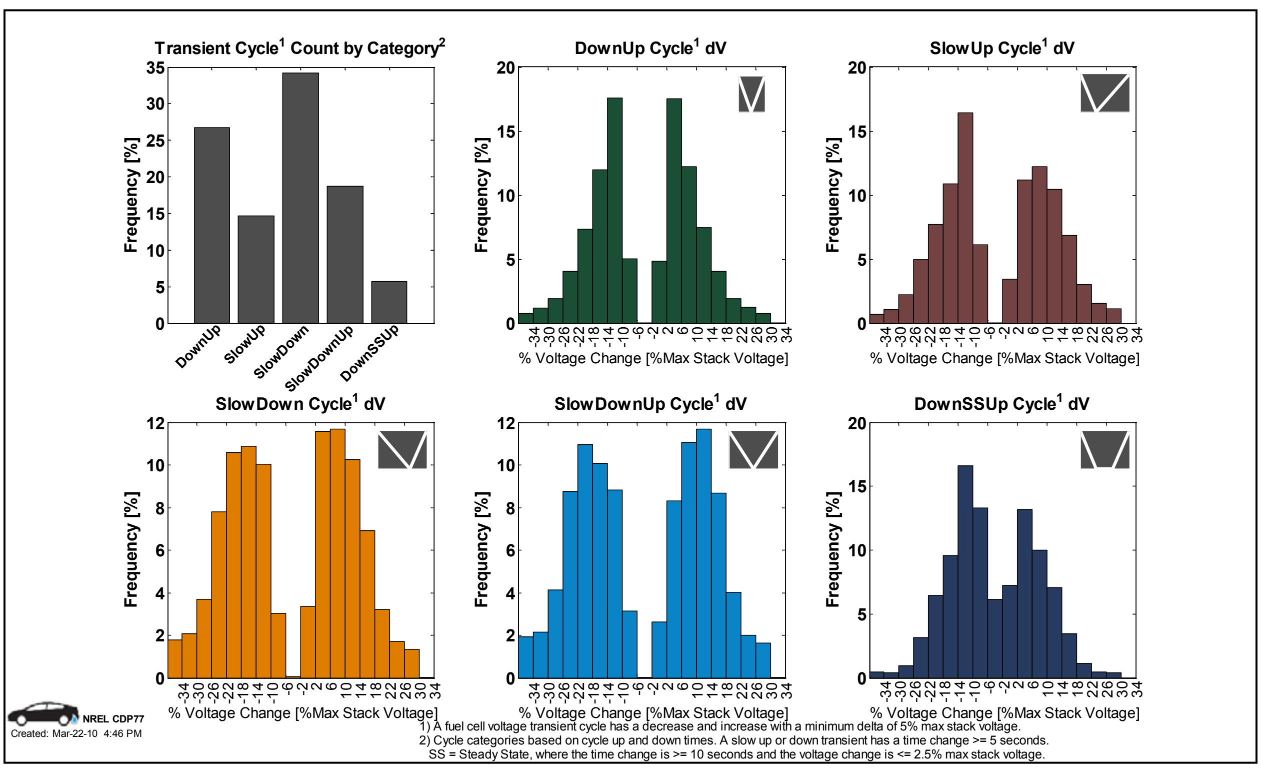



**Figure 58: Fuel cell transient voltage changes by cycle category (CDP77)**

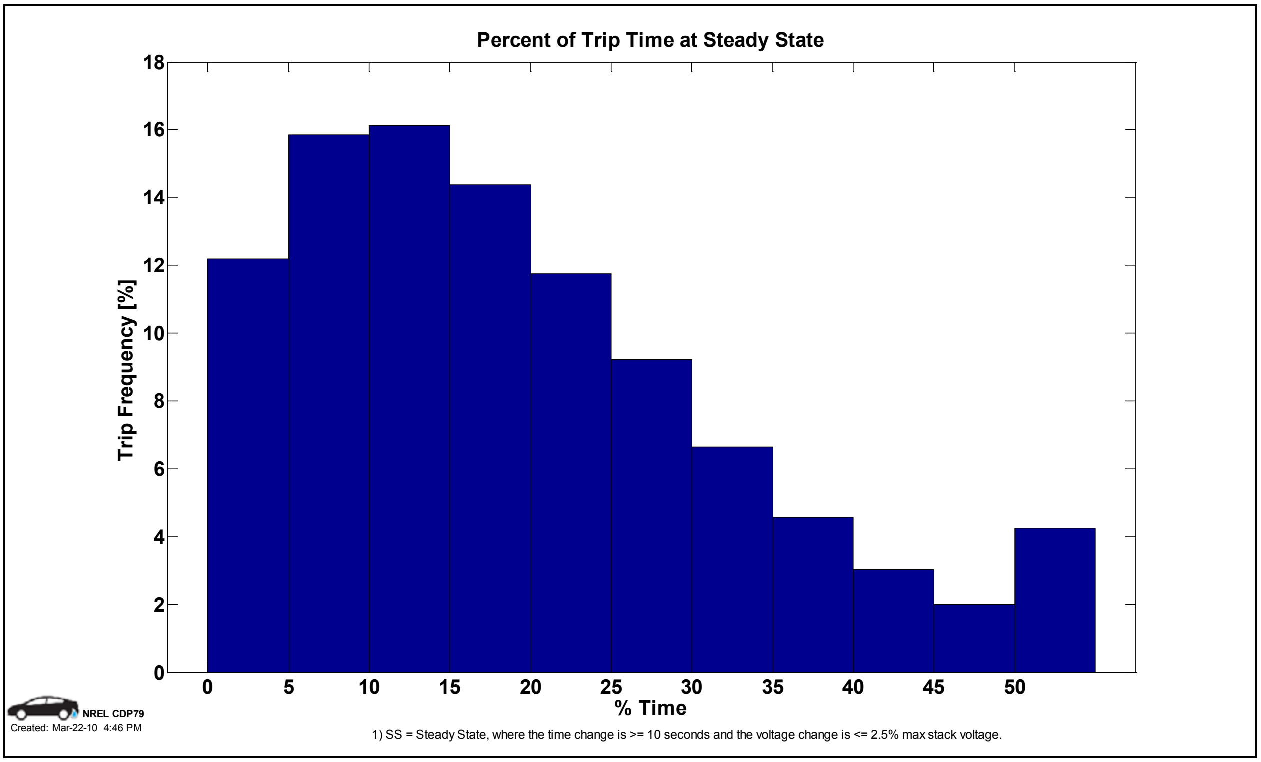



**Figure 59: Percentage of trip time at steady state (CDP79)**

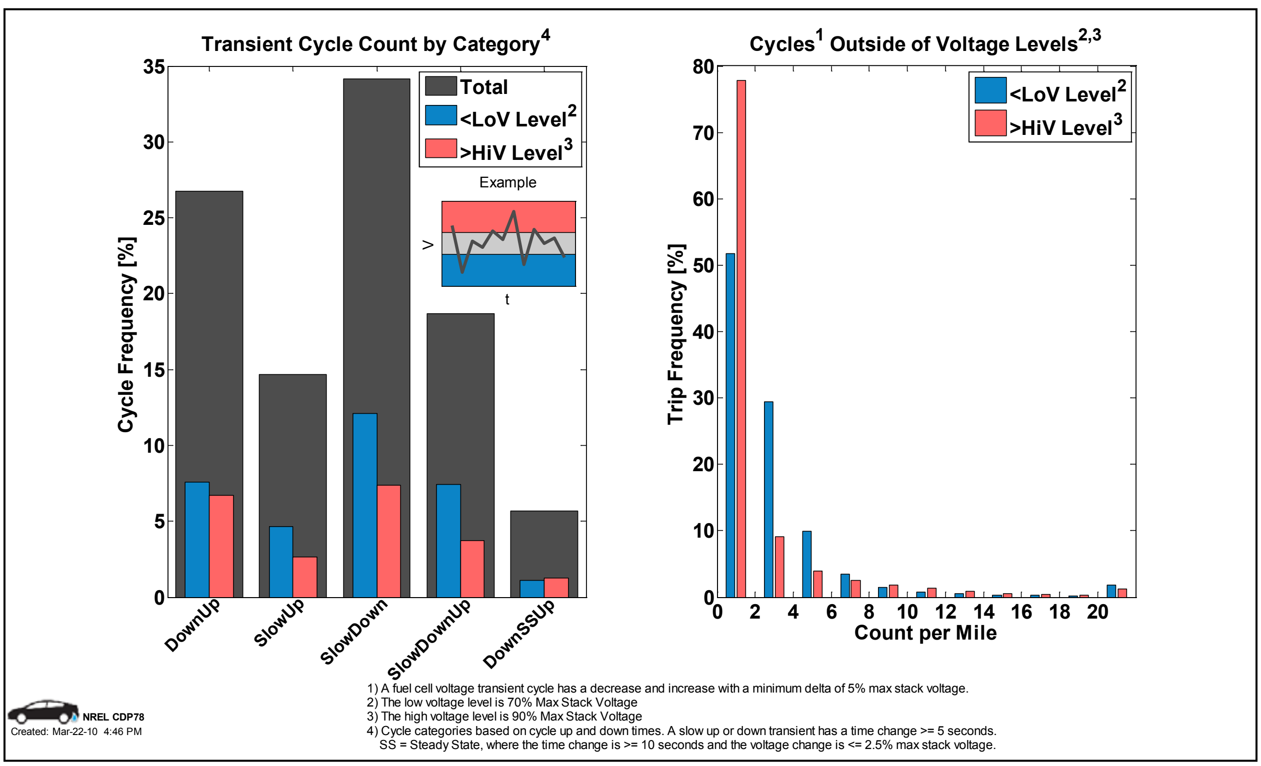



**Figure 60: Fuel cell transient cycles outside of specified voltage levels (CDP78)**

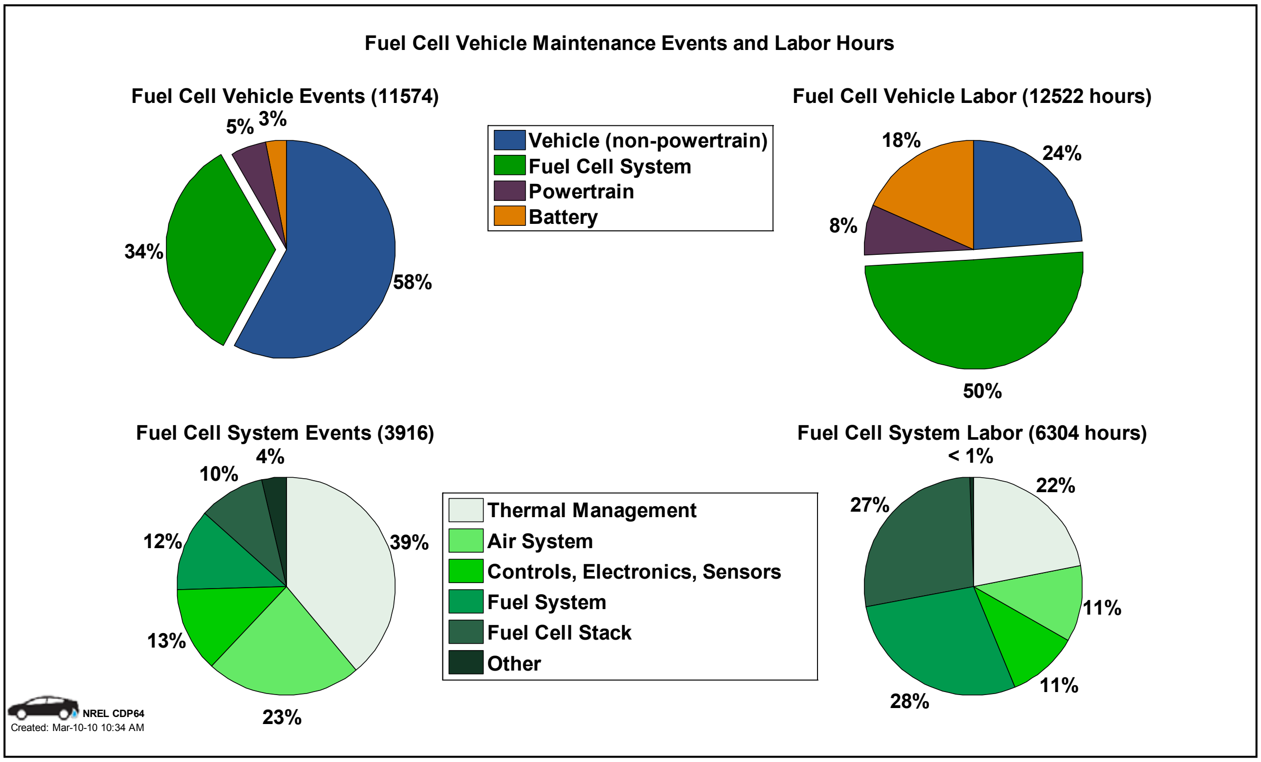



**Figure 61: Fuel cell electric vehicle maintenance by system (CDP64)**

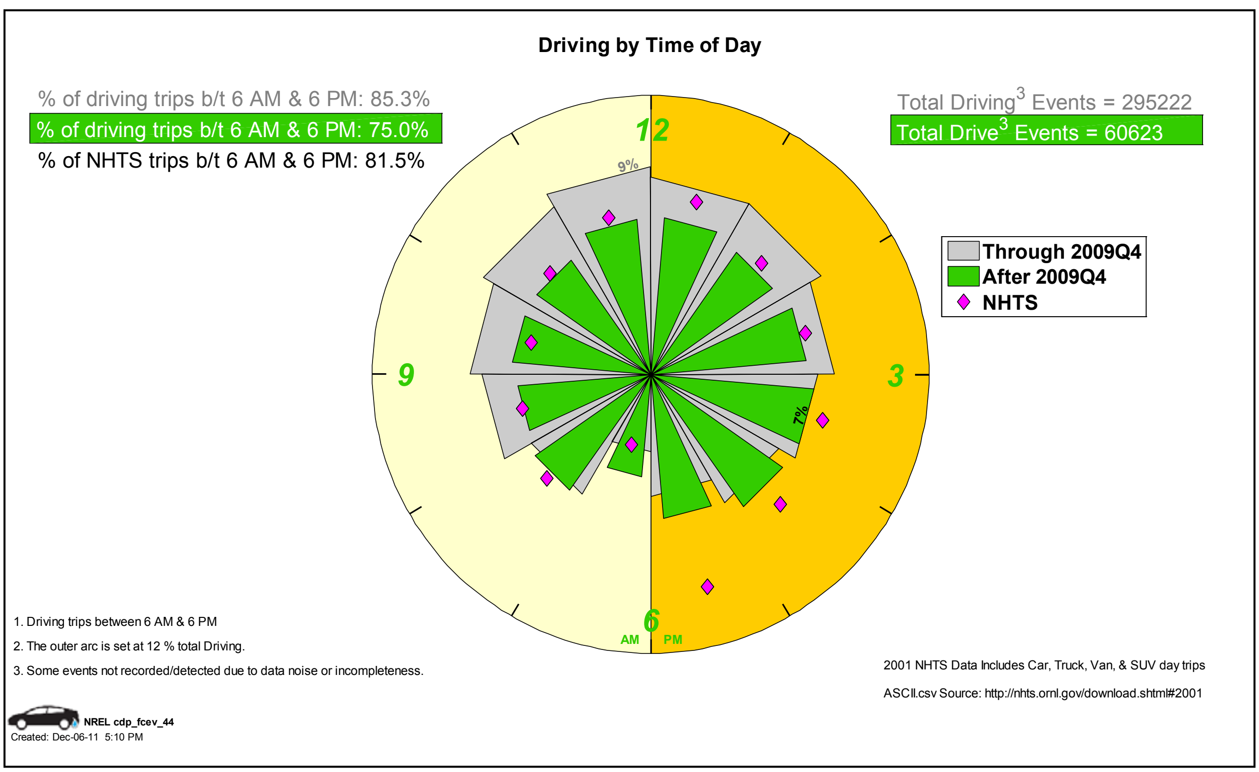



**Figure 62: Driving start time – day (CDP44)**

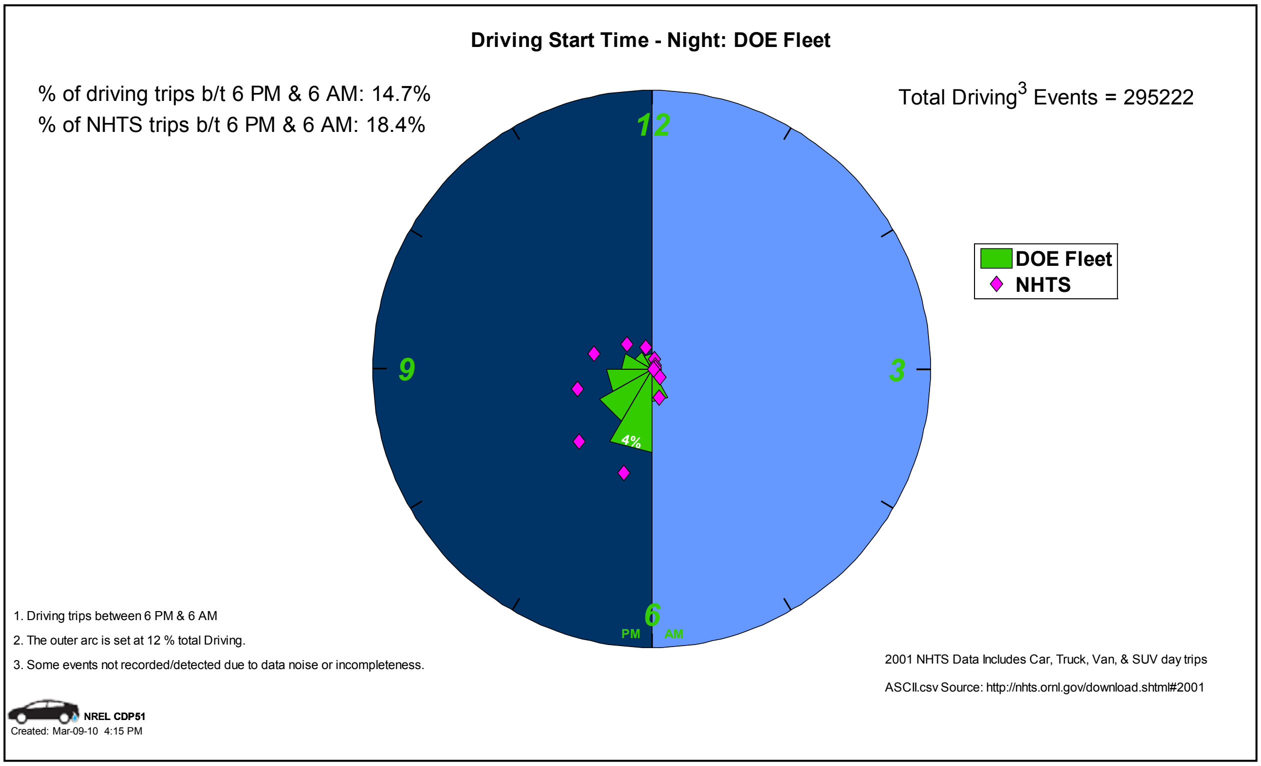



**Figure 63: Driving start time – night (CDP51)**

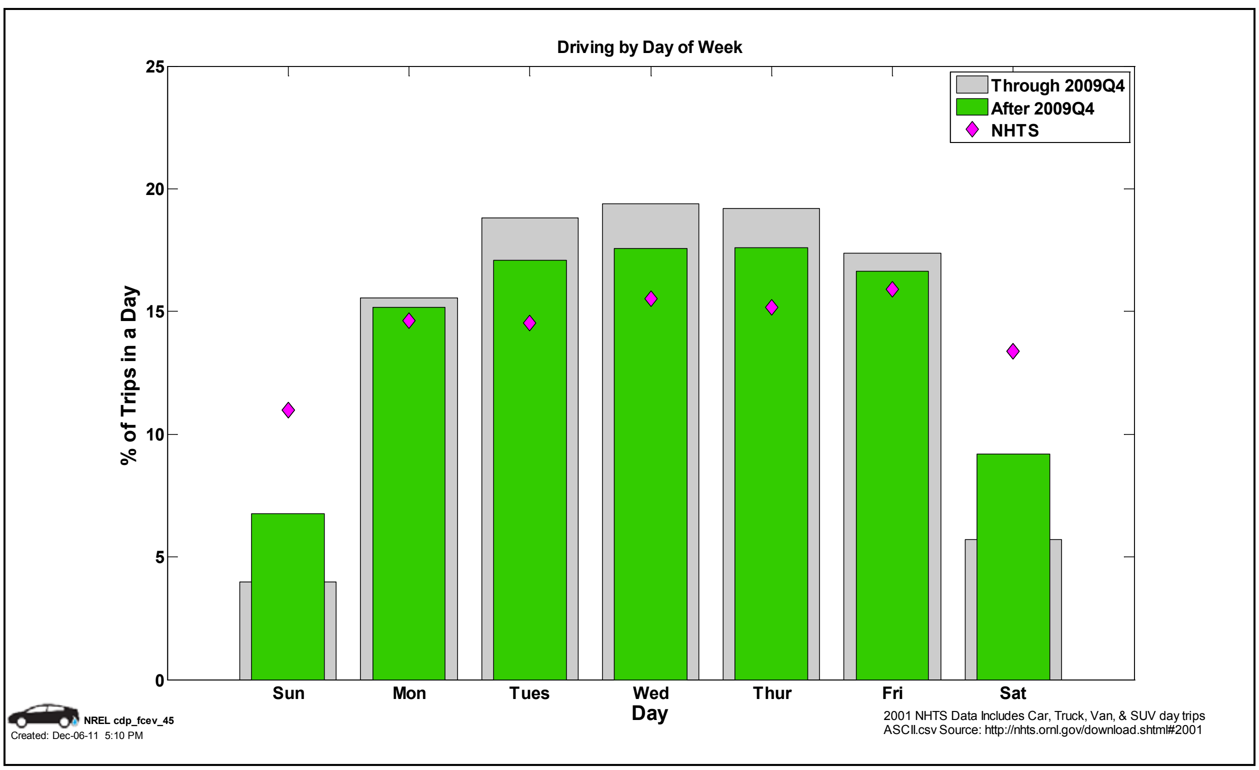



**Figure 64: Driving by day of week (CDP45)**

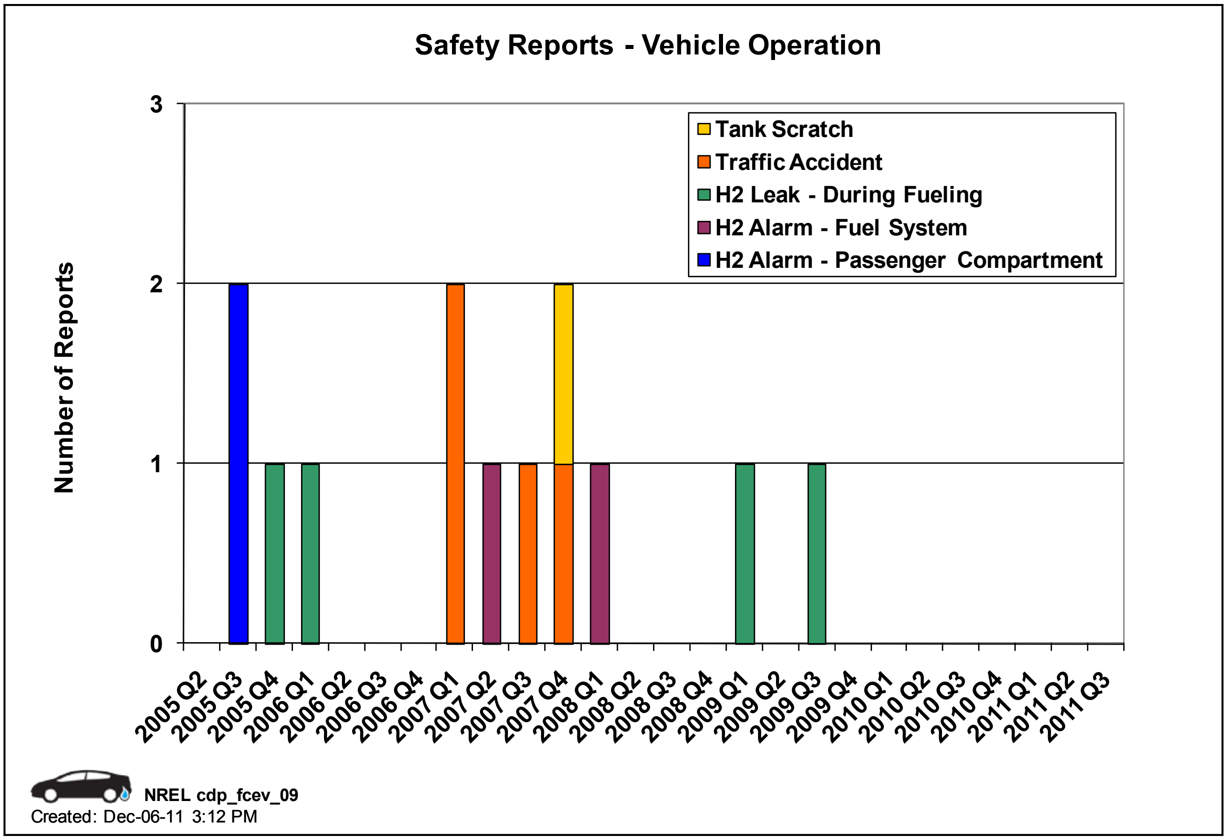



**Figure 65: Safety reports – vehicles (CDP09)**

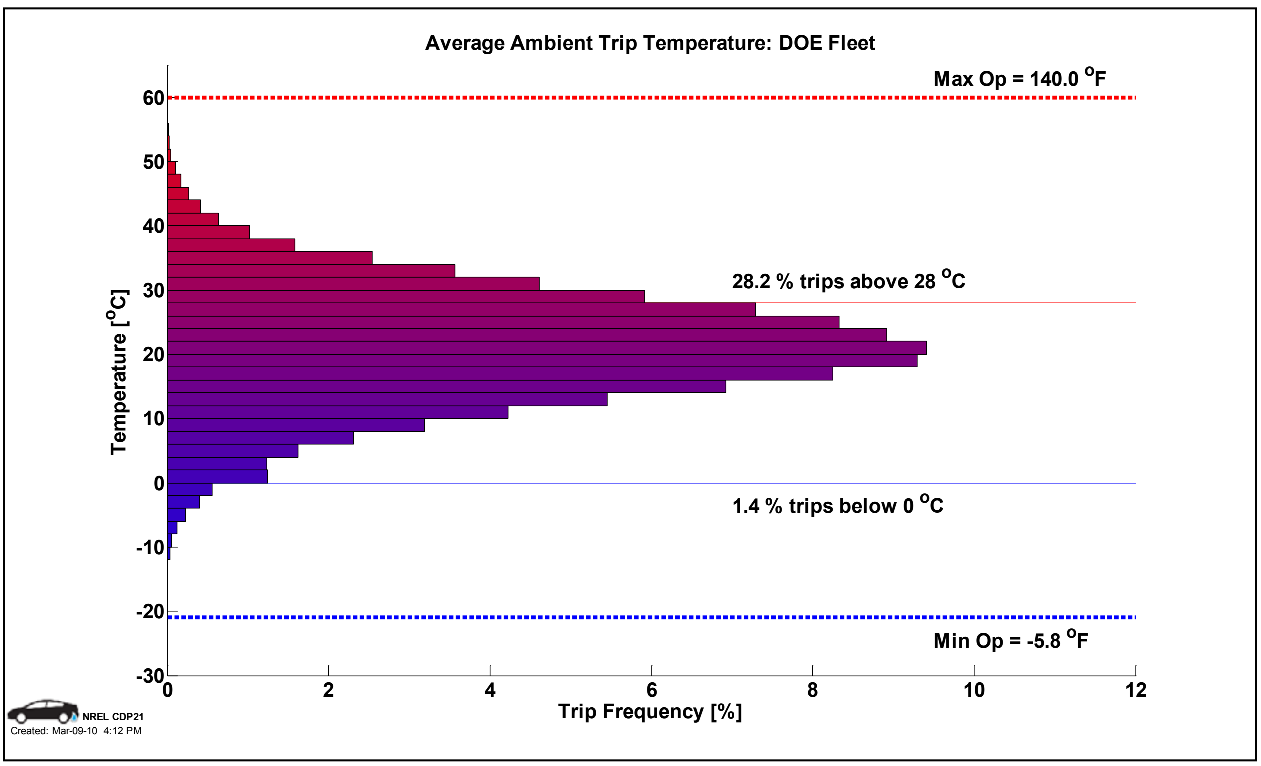



**Figure 66: Range of ambient temperature during vehicle operation (CDP21)**

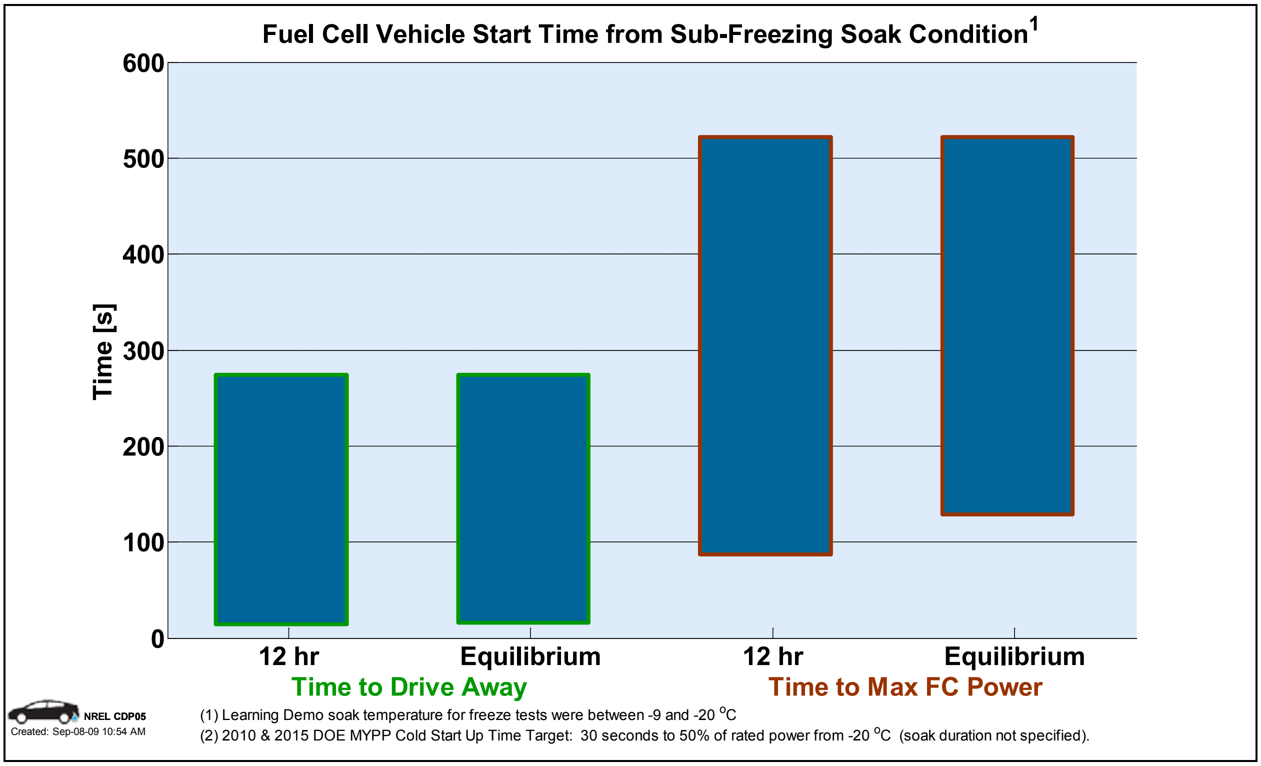



**Figure 67: Fuel cell start times from sub-freezing soak conditions (CDP05)**

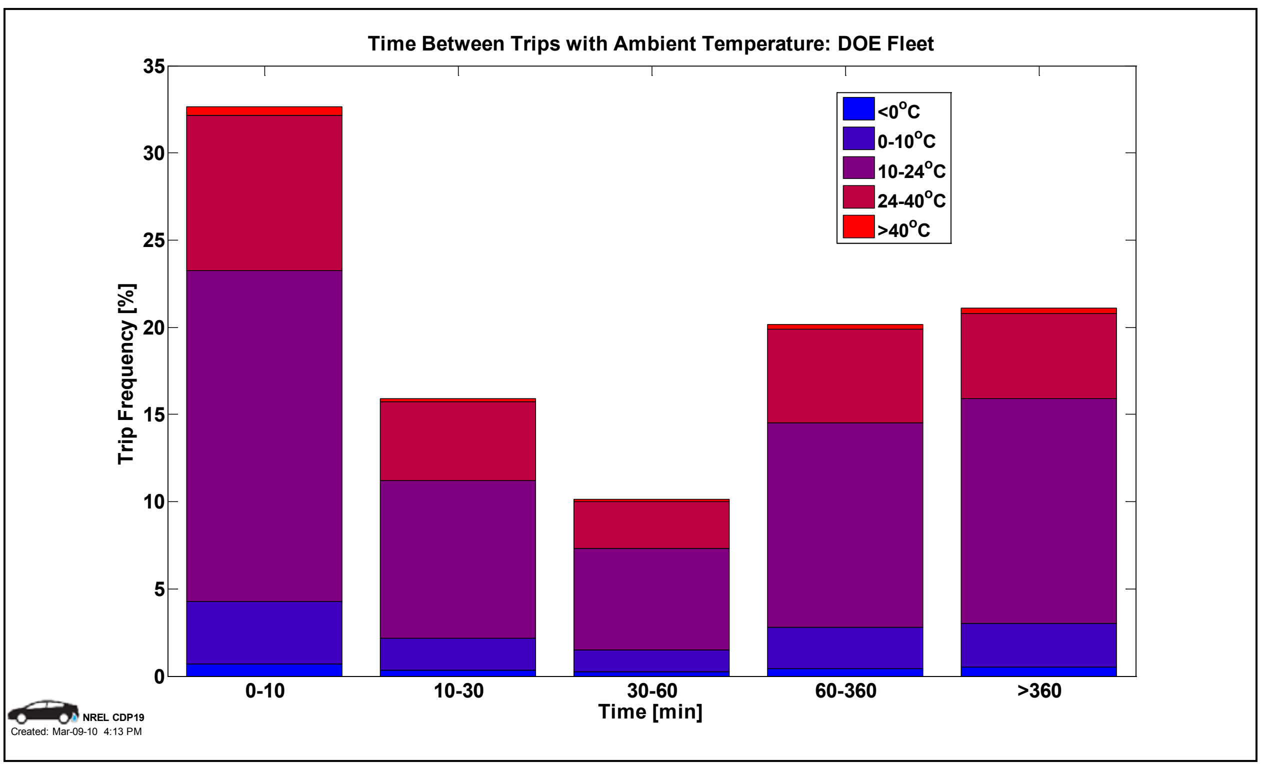



**Figure 68: Time between trips & ambient temperature (CDP19)**

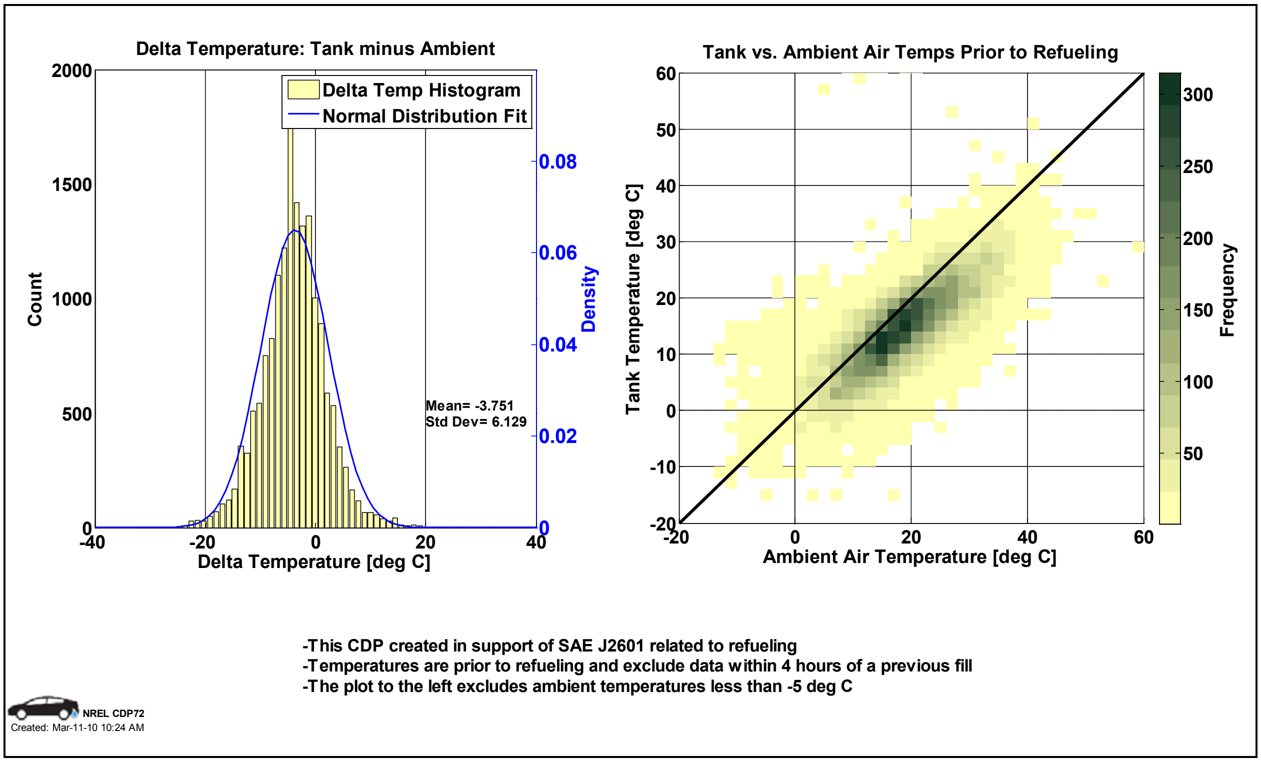



Figure 69: Difference between tank and ambient temperature prior to refueling (CDP72)

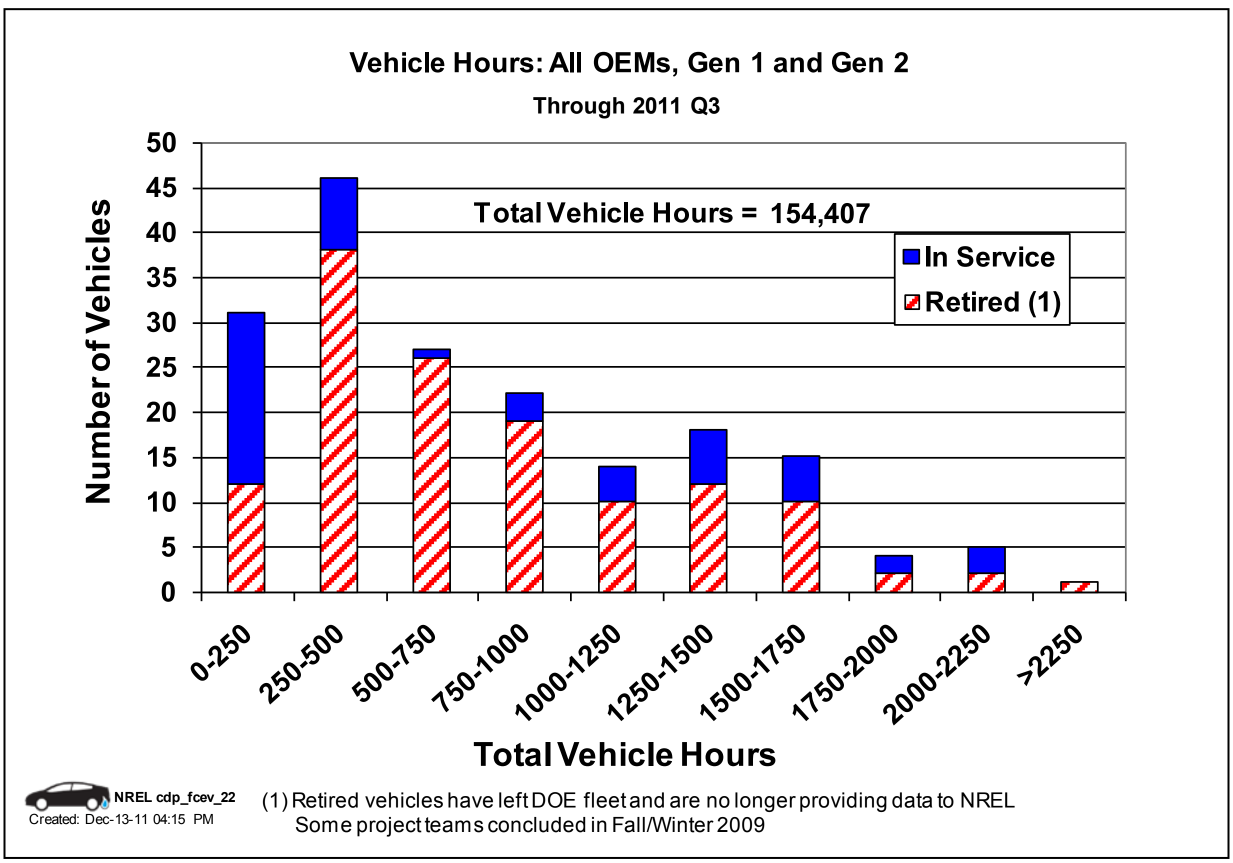



Figure 70: Vehicle operating hours (CDP22)

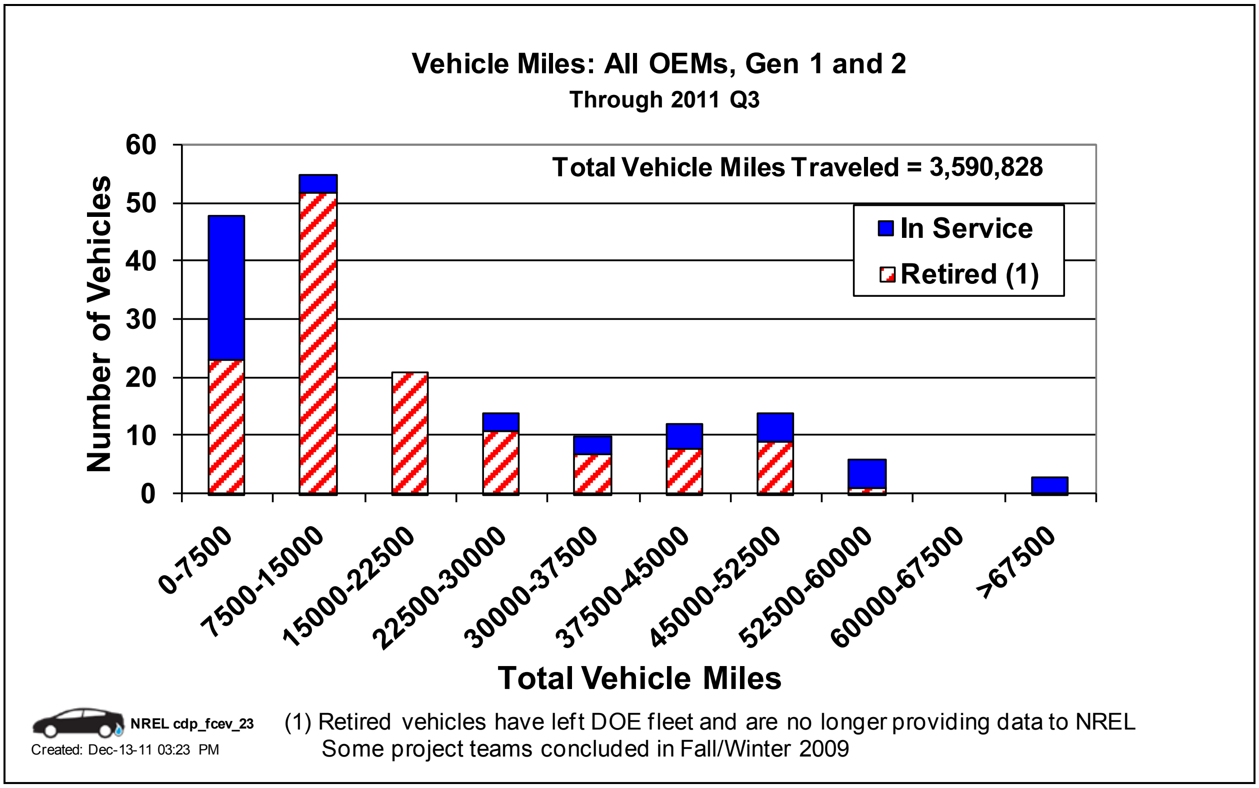



**Figure 71: Vehicles vs. miles traveled (CDP23)**

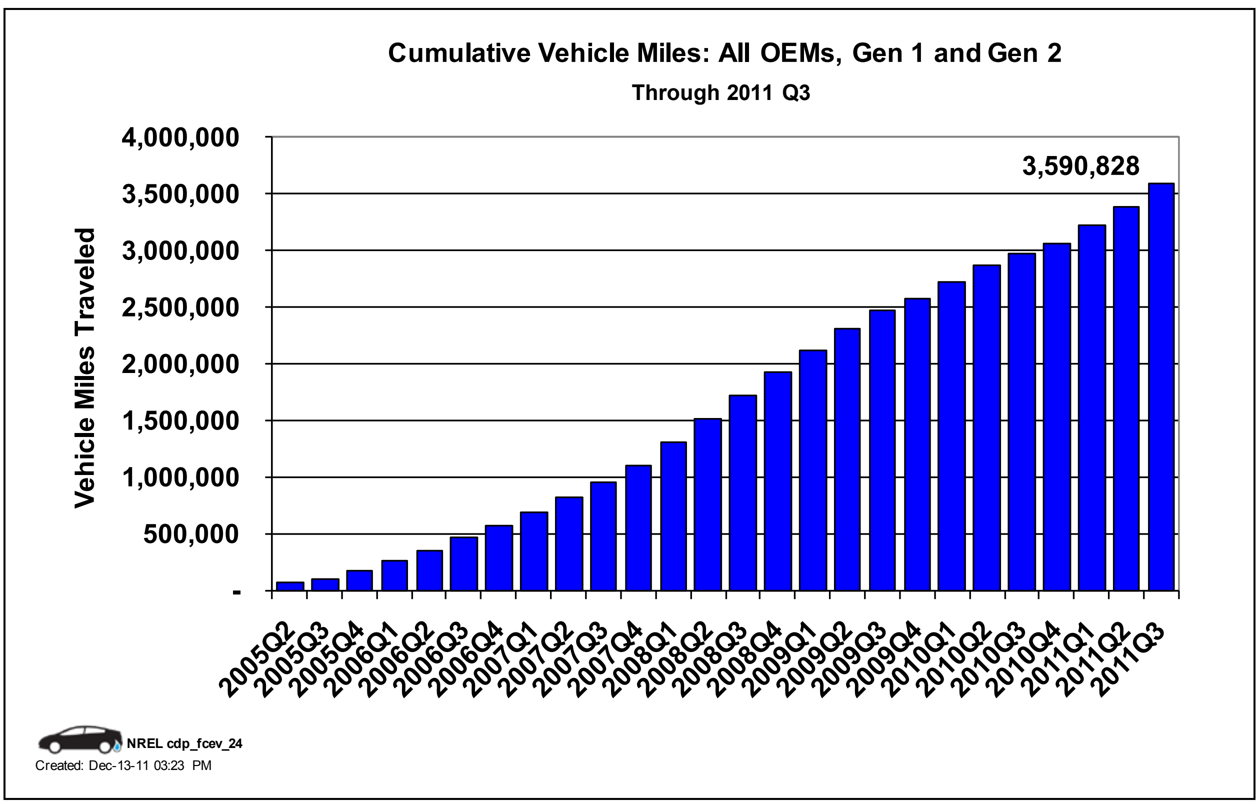



**Figure 72: Cumulative vehicle miles traveled (CDP24)**

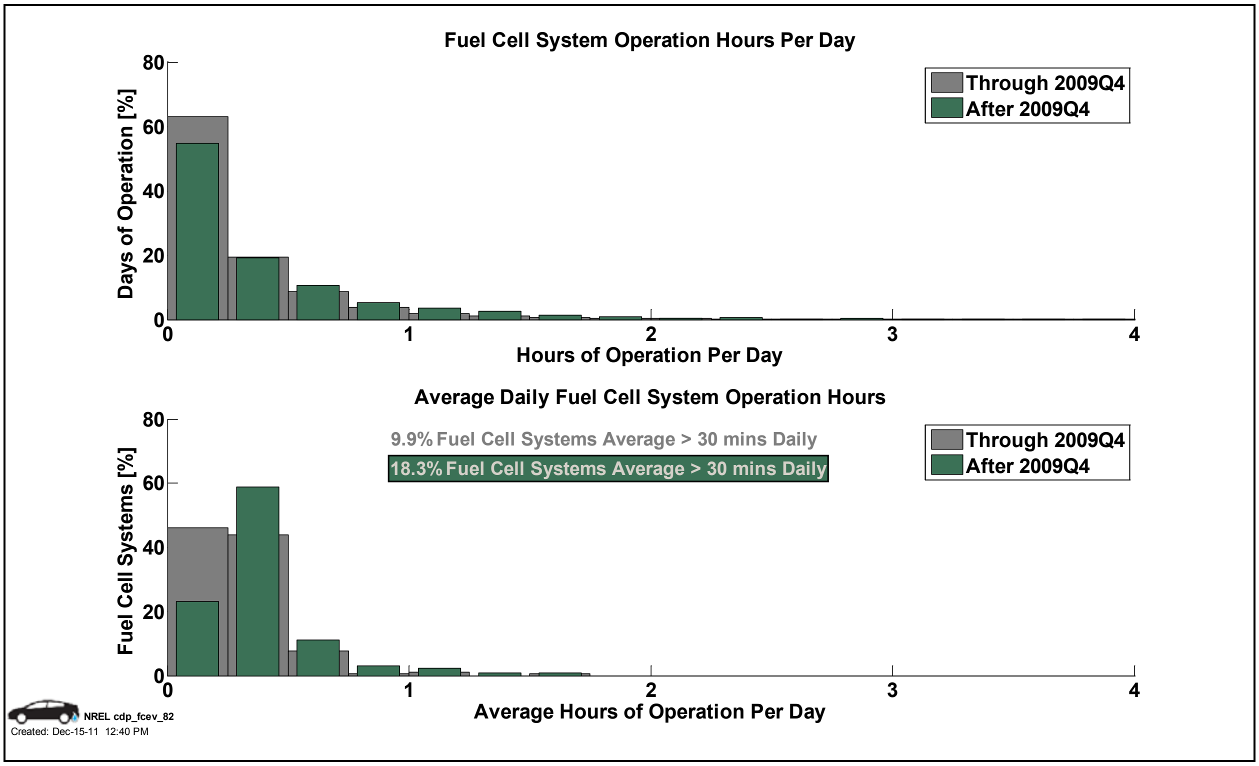



Figure 73: Daily fuel cell operation hours in this automotive application (CDP82)

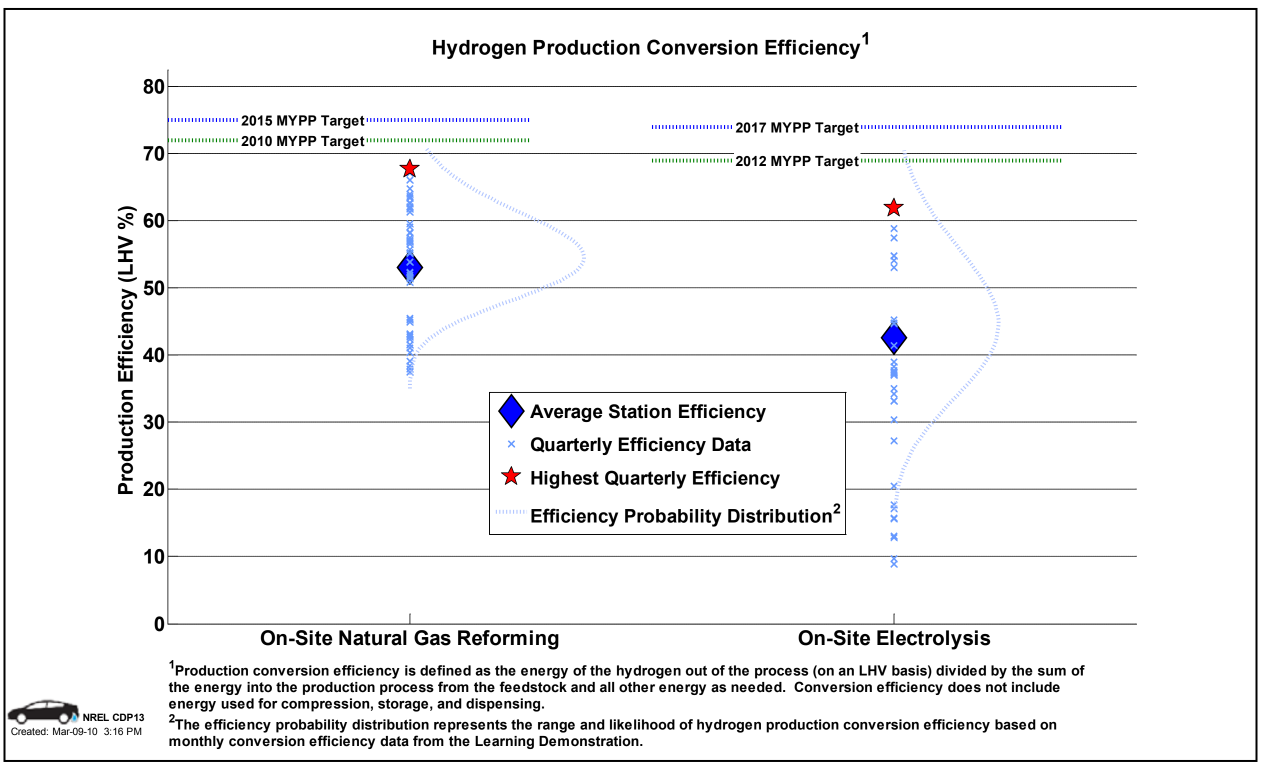



Figure 74: On-site hydrogen production efficiency (CDP13)

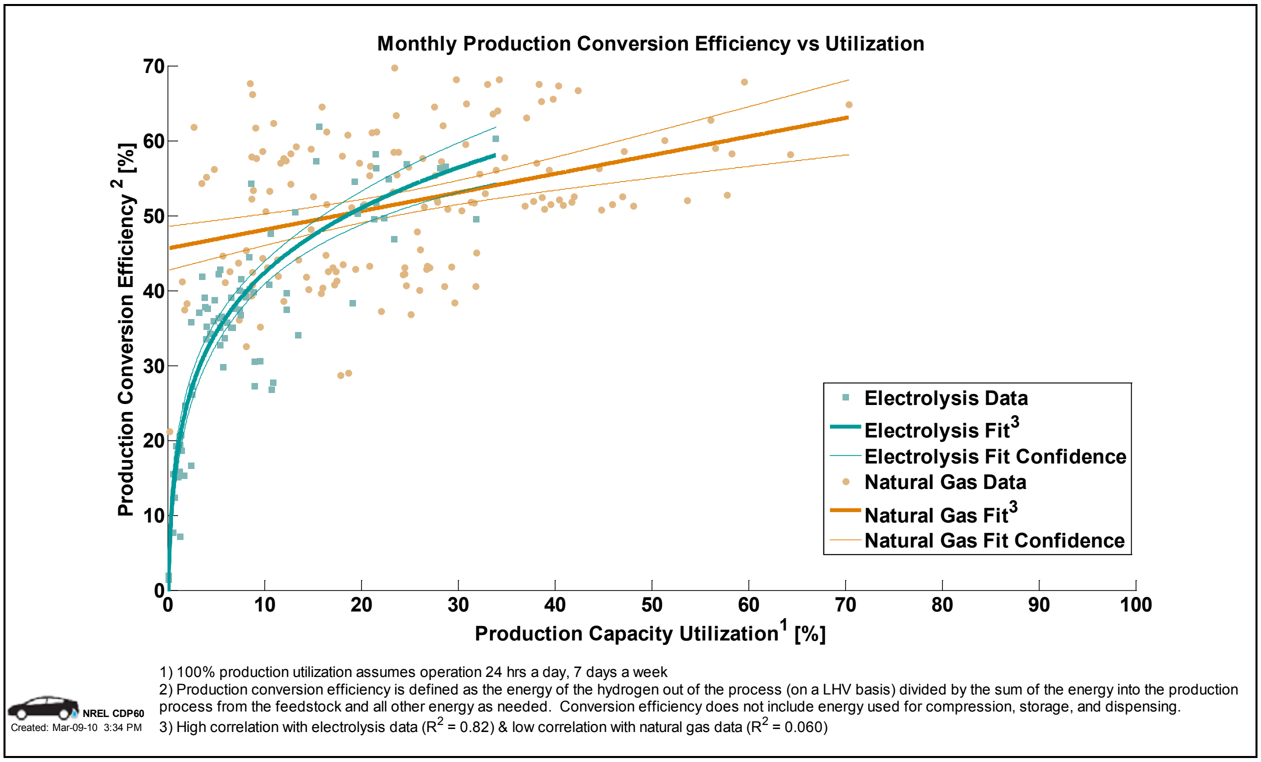



**Figure 75: On-site hydrogen production efficiency vs. capacity utilization (CDP60)**

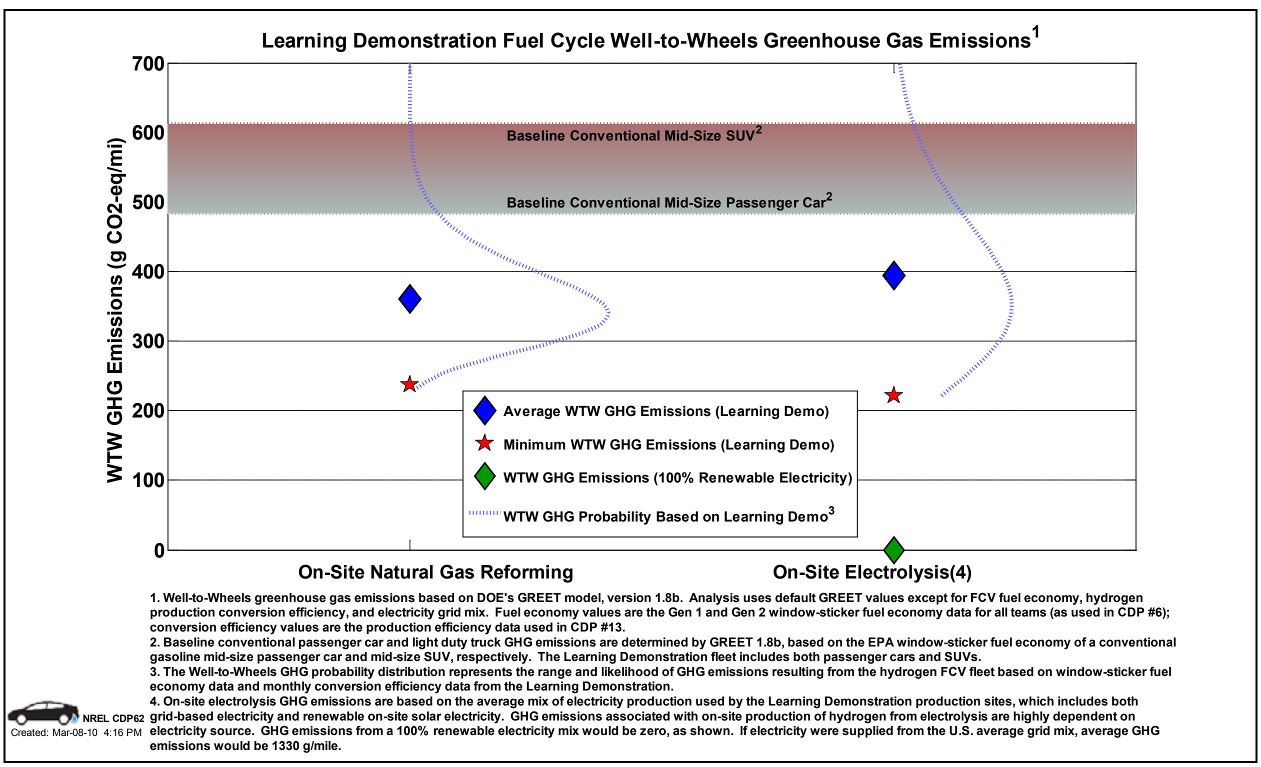
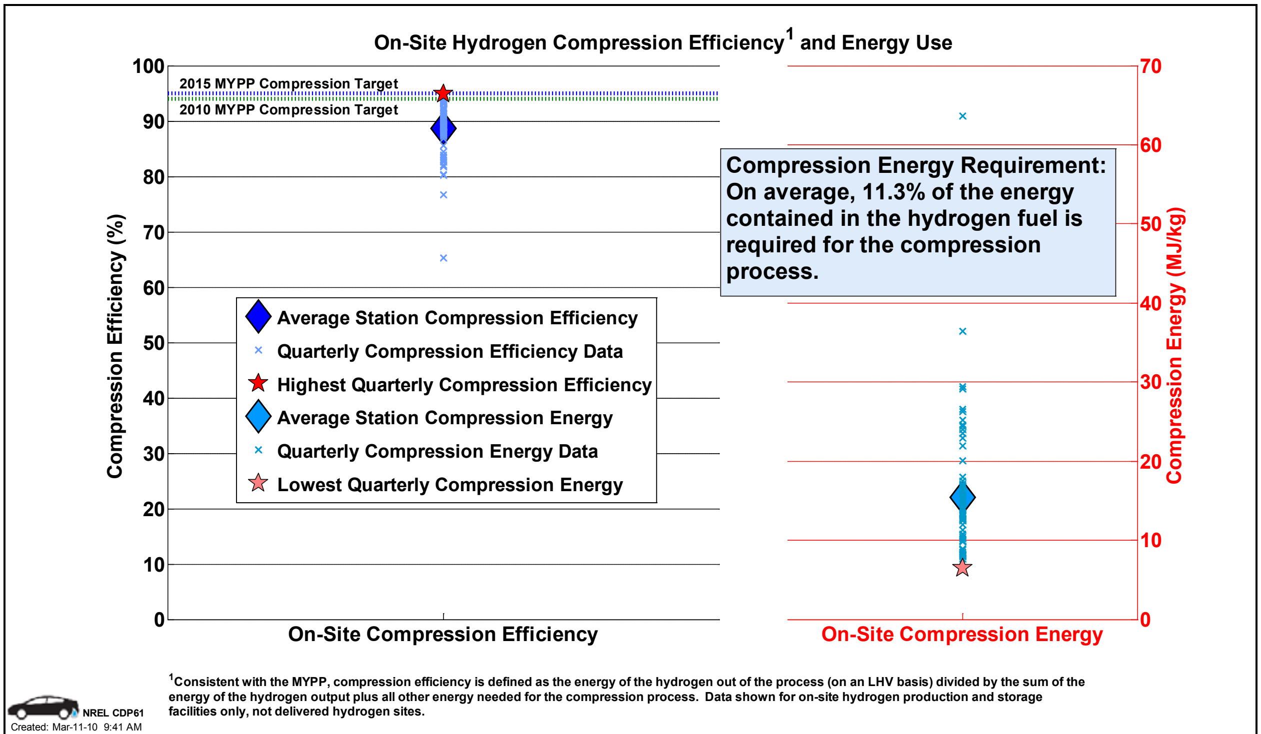
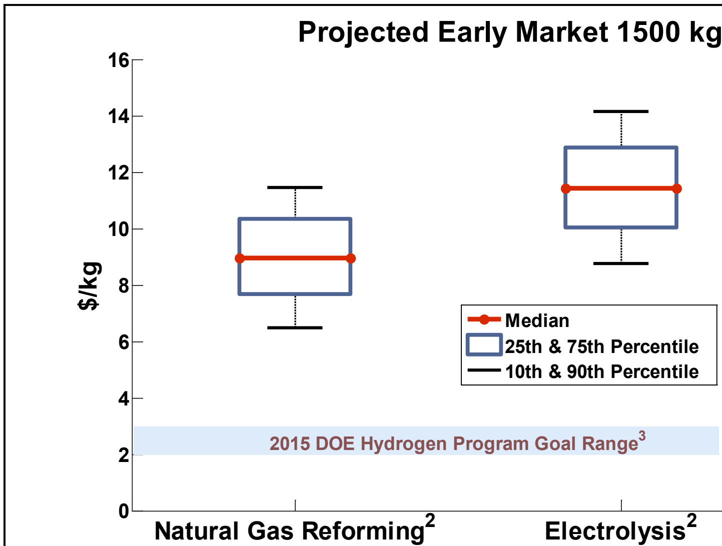



**Figure 76: Learning Demonstration vehicle greenhouse gas emissions (CDP62)**




[1]Consistent with the MYPP, compression efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy of the hydrogen output plus all other energy needed for the compression process. Data shown for on-site hydrogen production and storage facilities only, not delivered hydrogen sites.

**Figure 77: Refueling station compressor efficiency (CDP61)**




**Key H2 Cost Elements and Ranges**

| Input Parameter | Minimum (P10) | Maximum (P90) |
|---|---|---|
| Facility Direct Capital Cost | $10M | $25M |
| Facility Capacity Utilization | 85% | 95% |
| Annual Maintenance & Repairs | $150K | $600K |
| Annual Other O&M | $100K | $200K |
| Annual Facility Land Rent | $50K | $200K |
| Natural Gas Prod. Efficiency (LHV) | 65% | 75% |
| Electrolysis Prod. Efficiency (LHV) | 35% | 62% |

(1) Reported hydrogen costs are based on estimates of key cost elements from Learning Demonstration energy company partners and represent the cost of producing hydrogen on-site at the fueling station, using either natural gas reformation or water electrolysis, dispensed to the vehicle. Costs reflect an assessment of hydrogen production technologies, not an assessment of hydrogen market demand.
(2) Hydrogen production costs for 1500 kg/day stations developed using DOE's H2A Production model, version 2.1. Cost modeling represents the lifetime cost of producing hydrogen at fueling stations installed during an early market rollout of hydrogen infrastructure and are not reflective of the costs that might be seen in a fully mature market for hydrogen installations. Modeling uses default H2A Production model inputs supplemented with feedback from Learning Demonstration energy company partners, based on their experience operating on-site hydrogen production stations. H2A-based Monte Carlo simulations (2,000 trials) were completed for both natural gas reforming and electrolysis stations using default H2A values and 10th percentile to 90th percentile estimated ranges for key cost parameters as shown in the table. Capacity utilization range is based on the capabilities of the production technologies and could be significantly lower if there is inadequate demand for hydrogen.
(3) DOE has a hydrogen cost goal of $2-$3/kg for future (2015) 1500 kg/day hydrogen production stations installed at a rate of 500 stations per year.

**Figure 78: Hydrogen production cost vs. process (CDP15)**

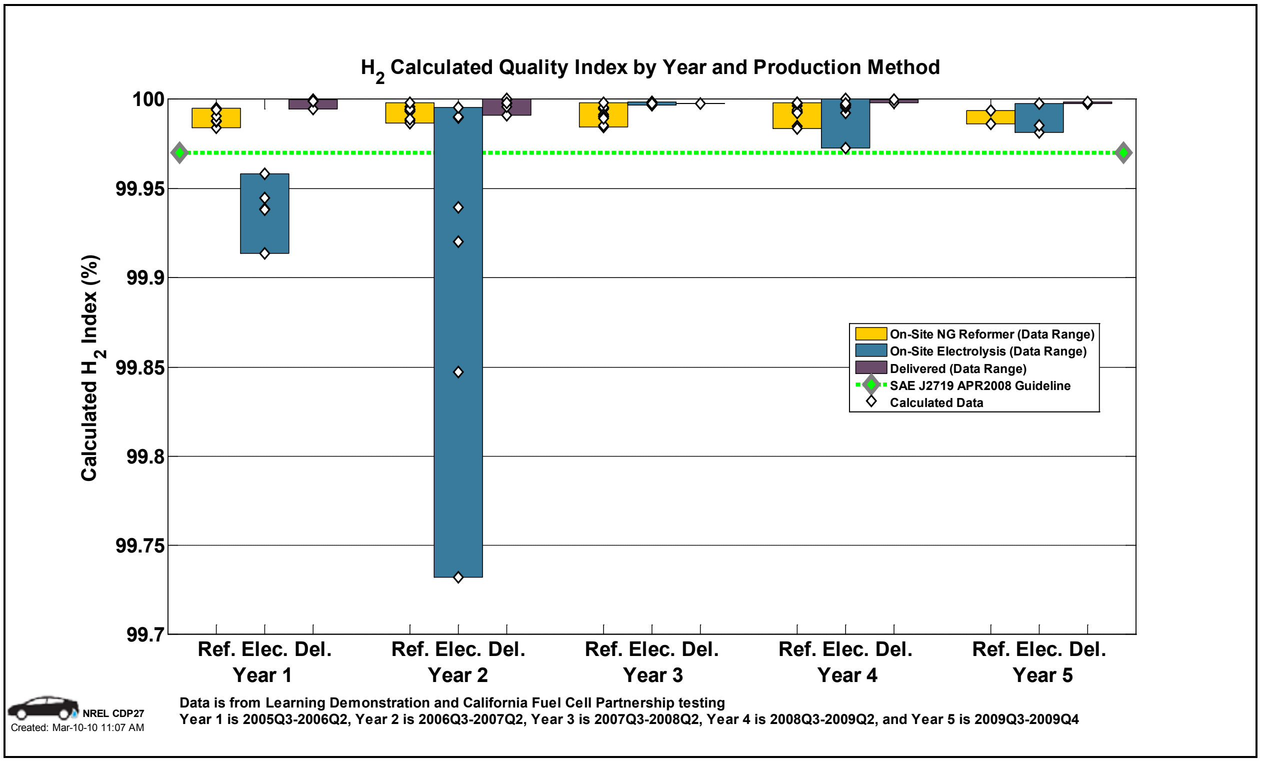



**Figure 79: Hydrogen quality index (CDP27)**

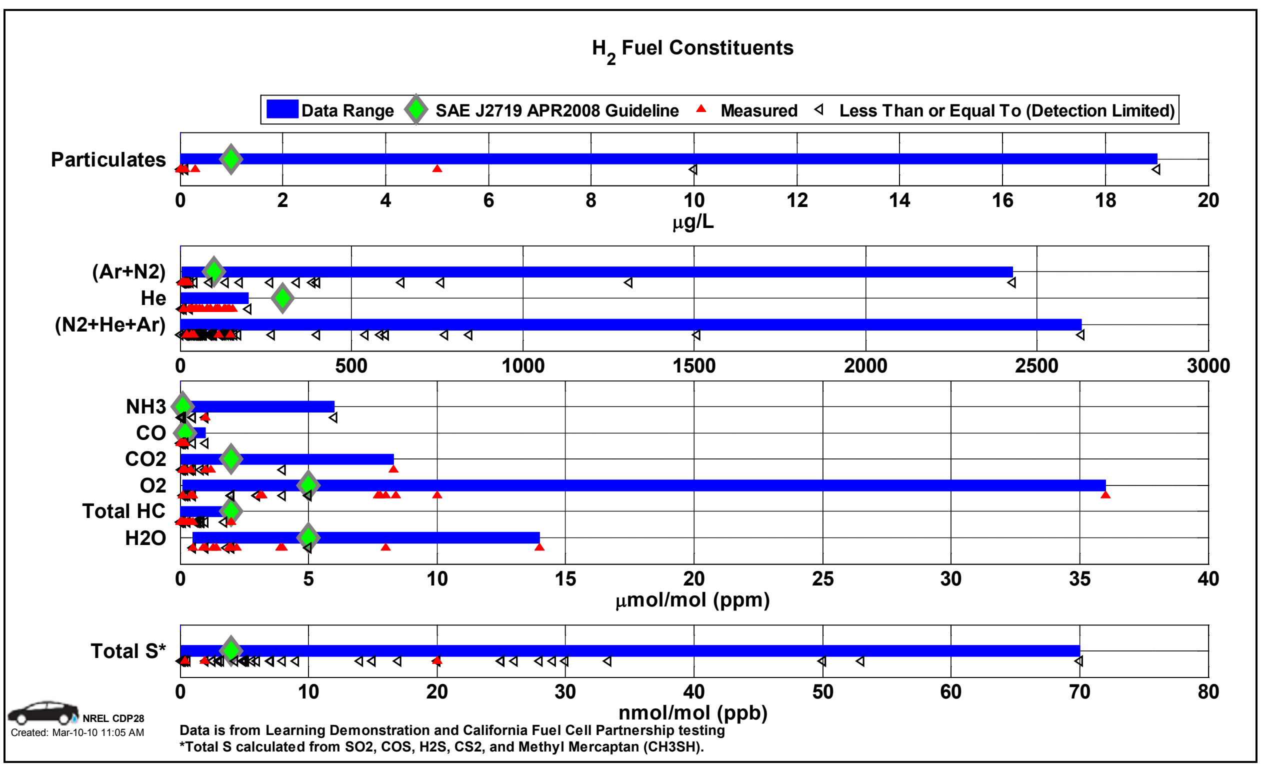



**Figure 80: Hydrogen fuel constituents – all (CDP28)**

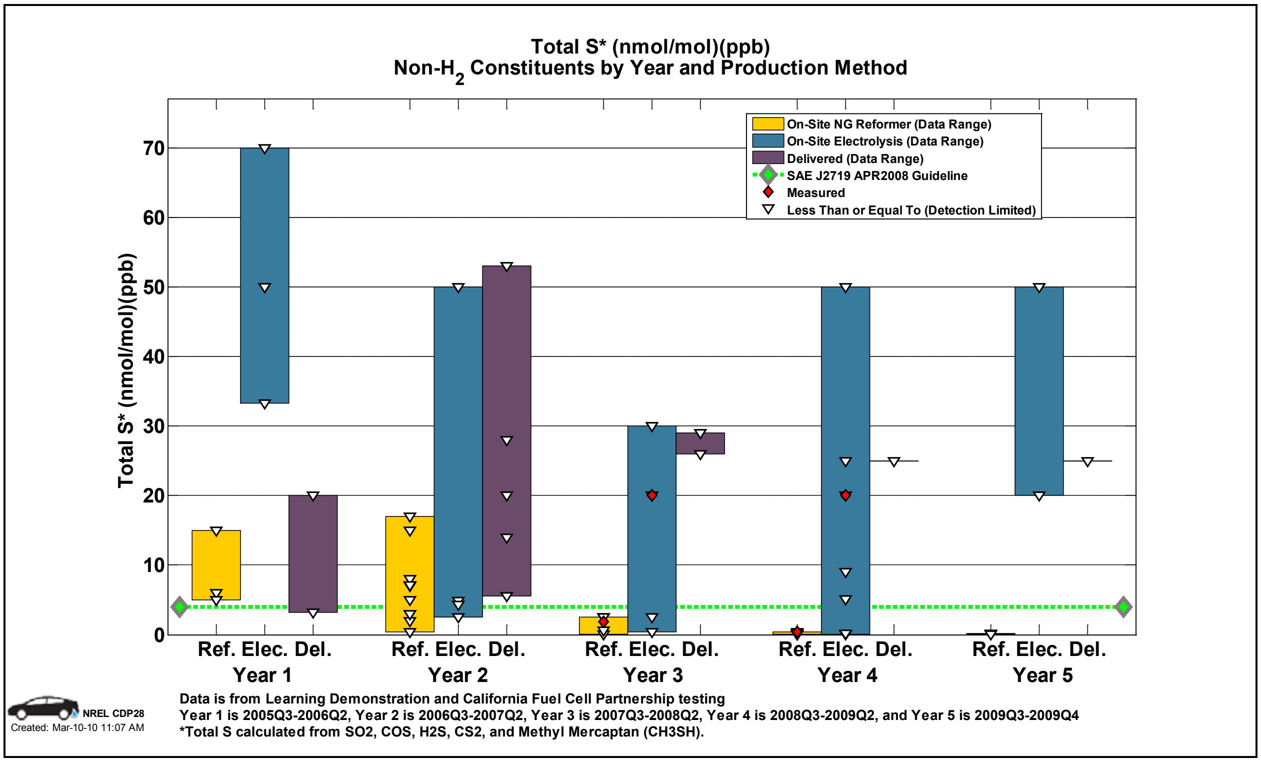



**Figure 81: Hydrogen fuel constituents – sulfur (CDP28)**

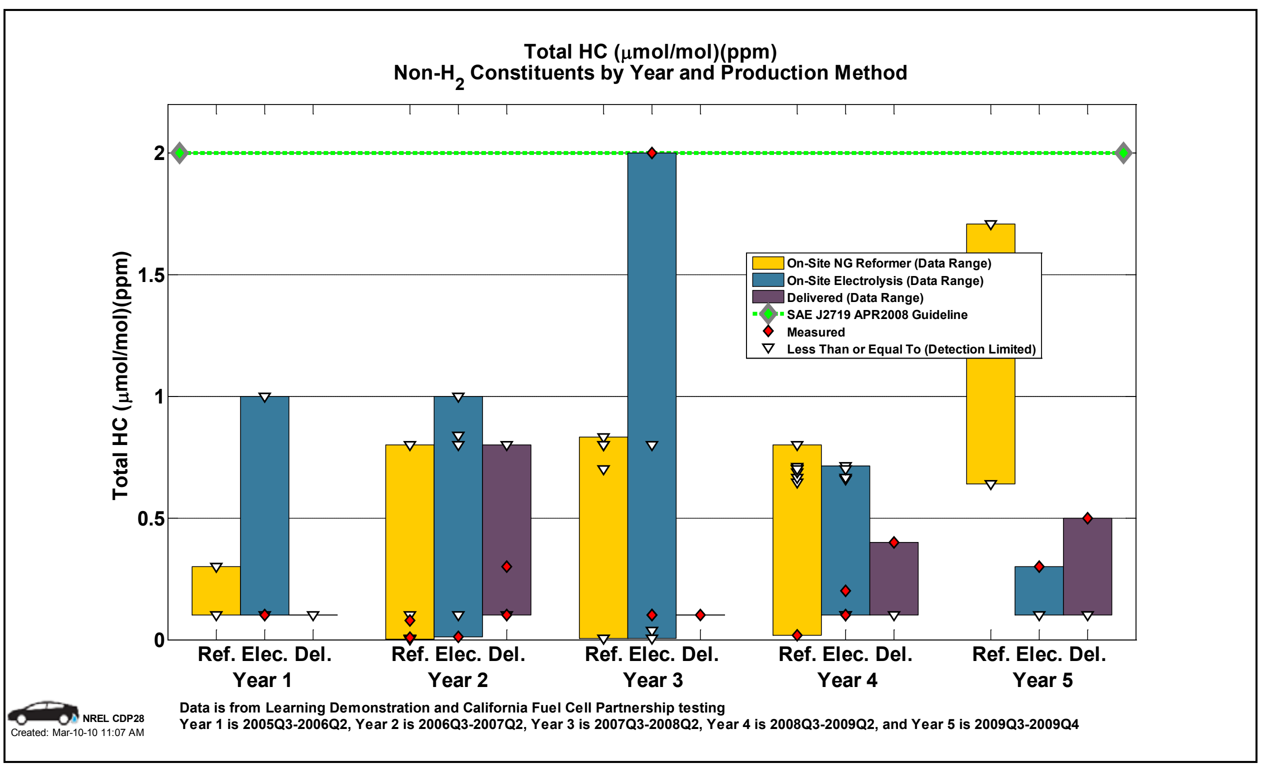



**Figure 82: Hydrogen fuel constituents – total hydrocarbons (CDP28)**

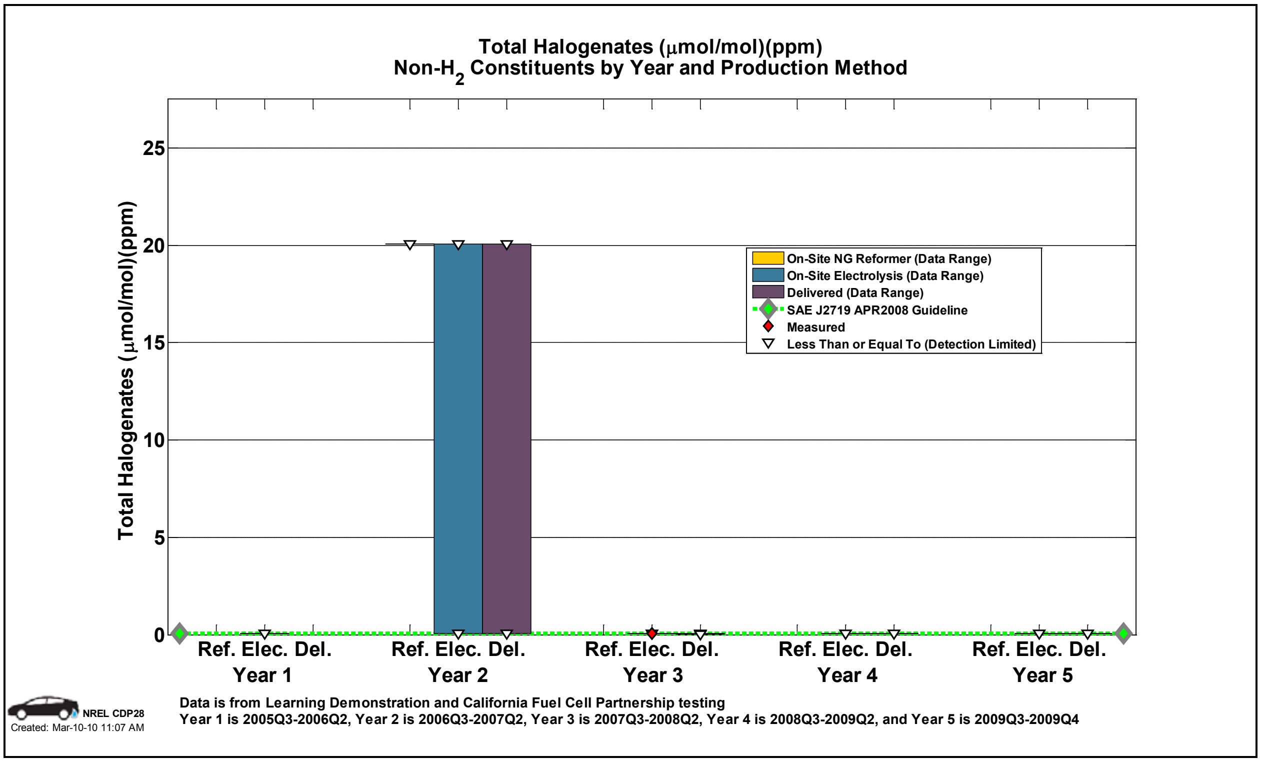



**Figure 83: Hydrogen fuel constituents – total halogenates (CDP28)**

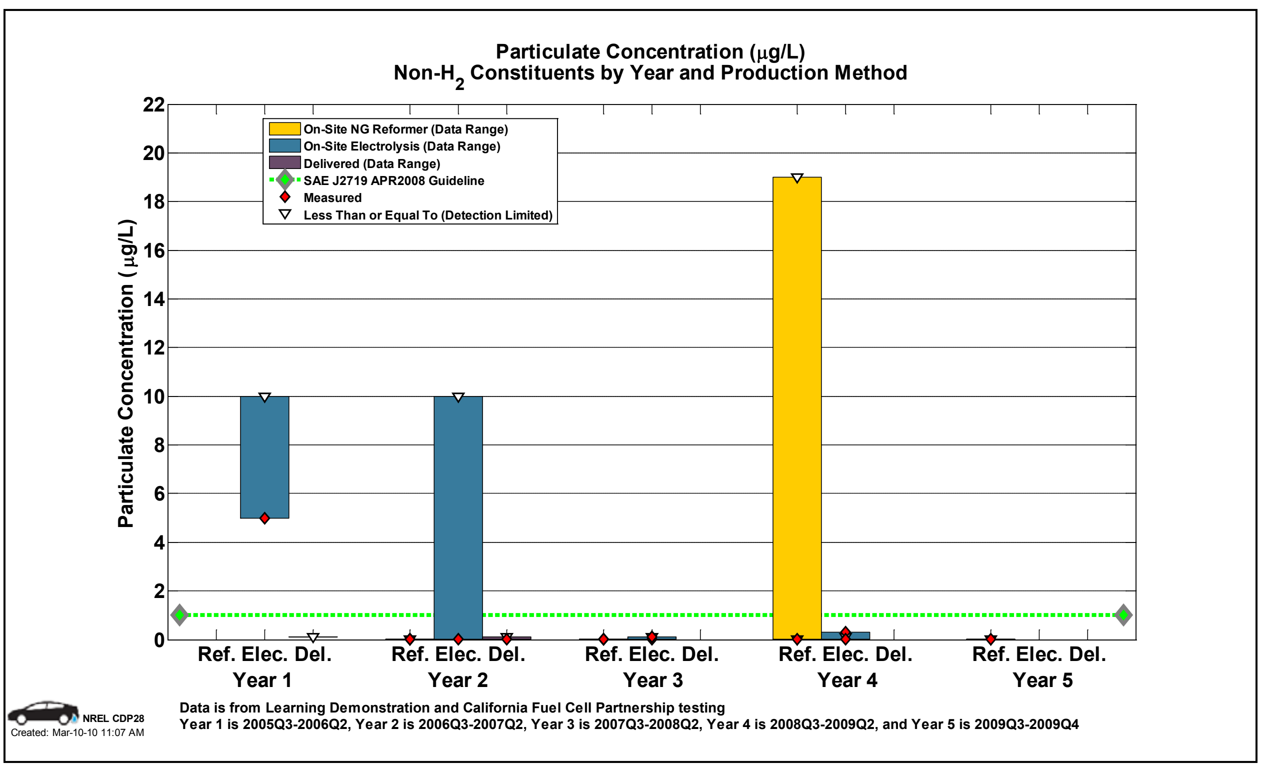



**Figure 84: Hydrogen fuel constituents – particulate concentration (CDP28)**

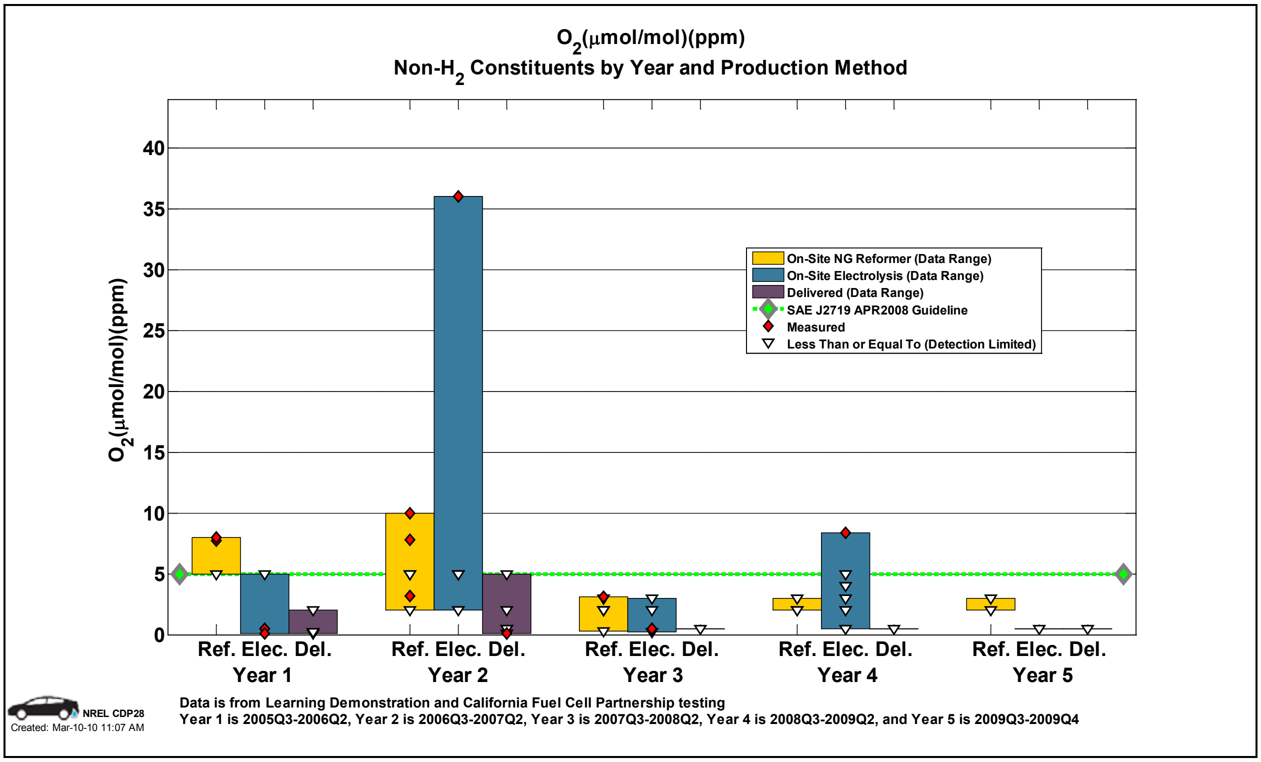



**Figure 85: Hydrogen fuel constituents – oxygen (CDP28)**

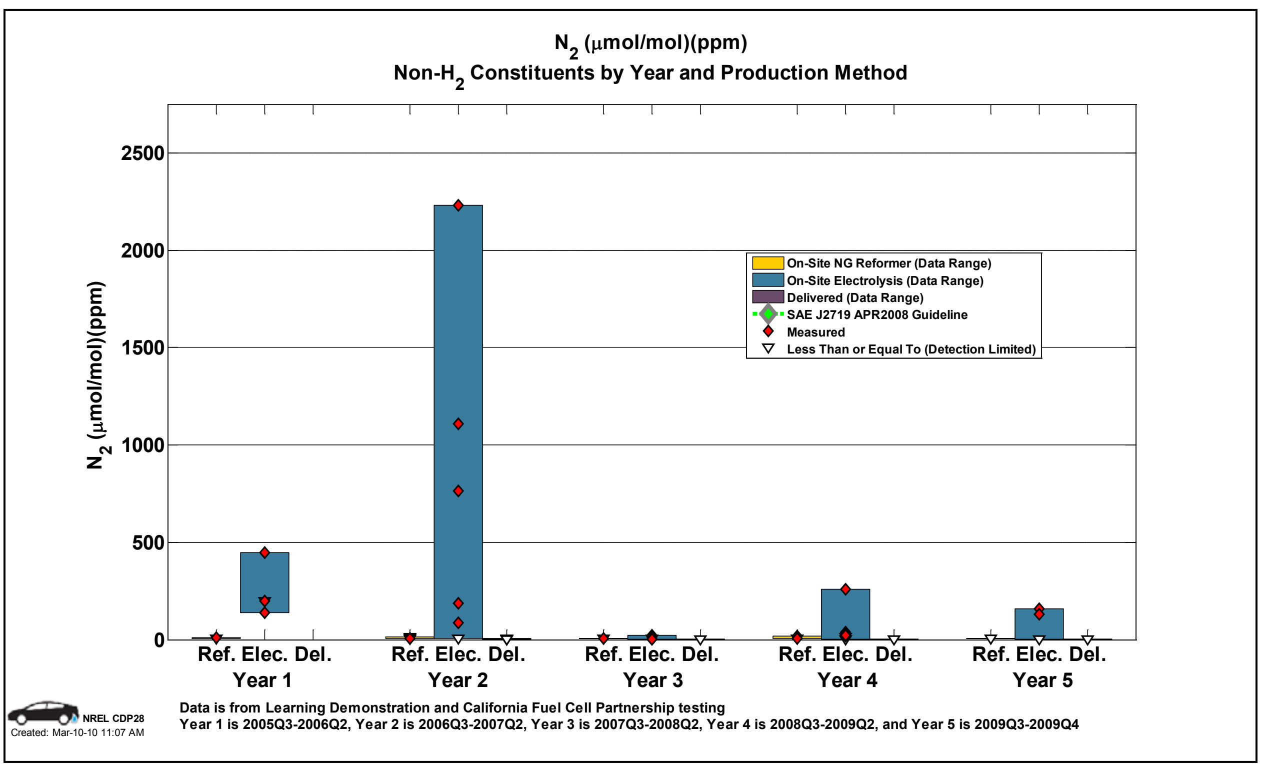



**Figure 86: Hydrogen fuel constituents – nitrogen (CDP28)**

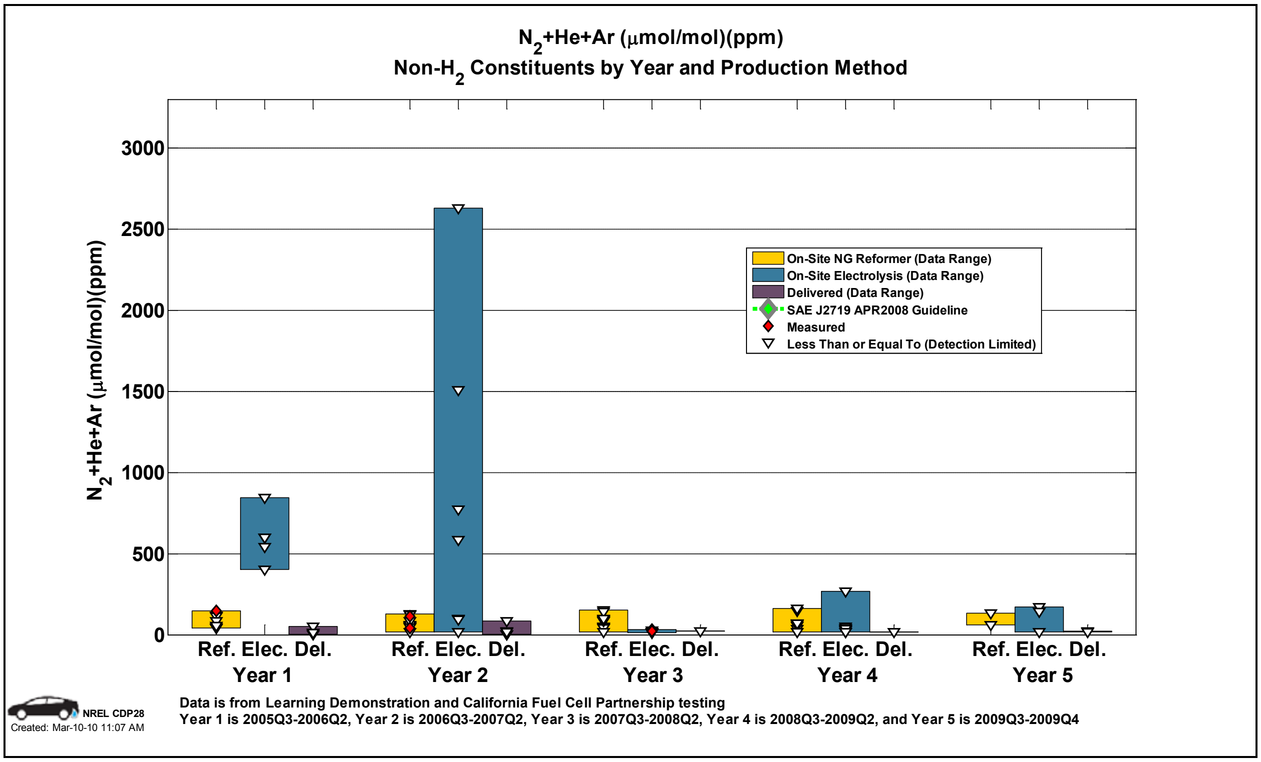



**Figure 87: Hydrogen fuel constituents – nitrogen + helium + argon (CDP28)**

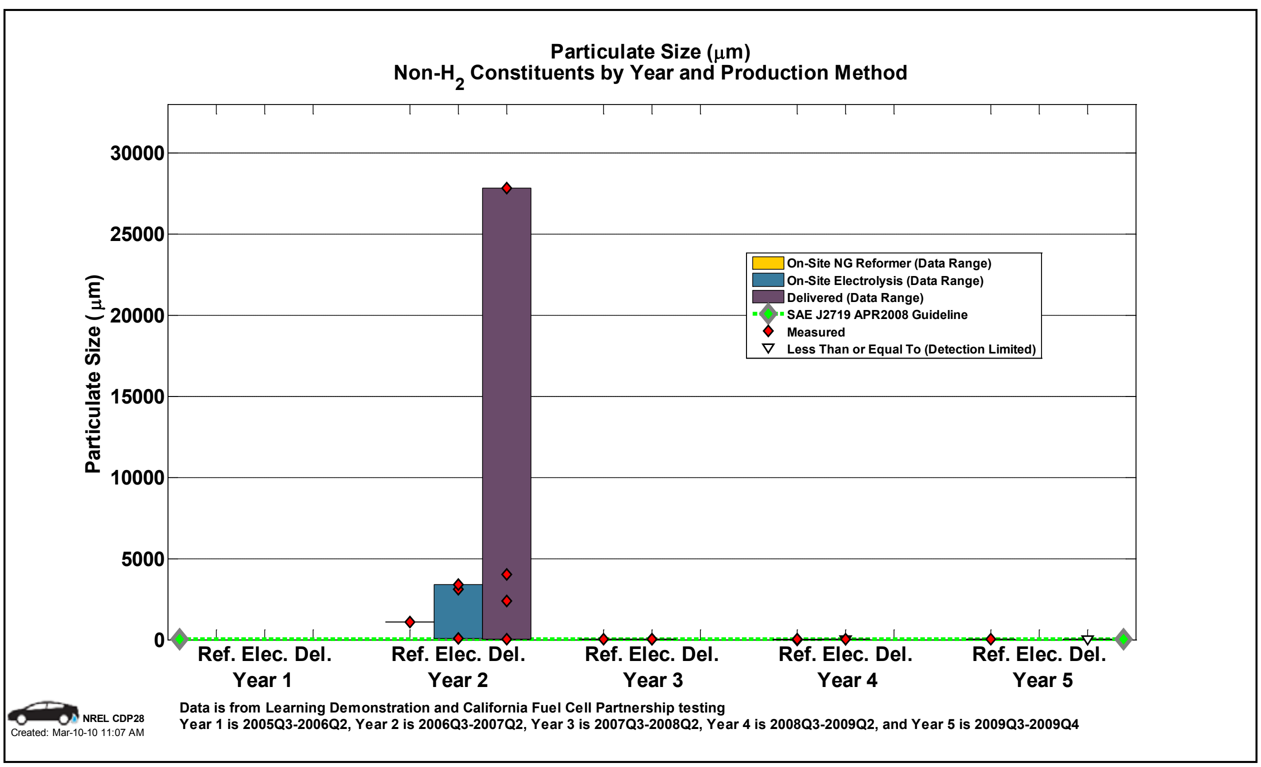



**Figure 88: Hydrogen fuel constituents – particulate size (CDP28)**

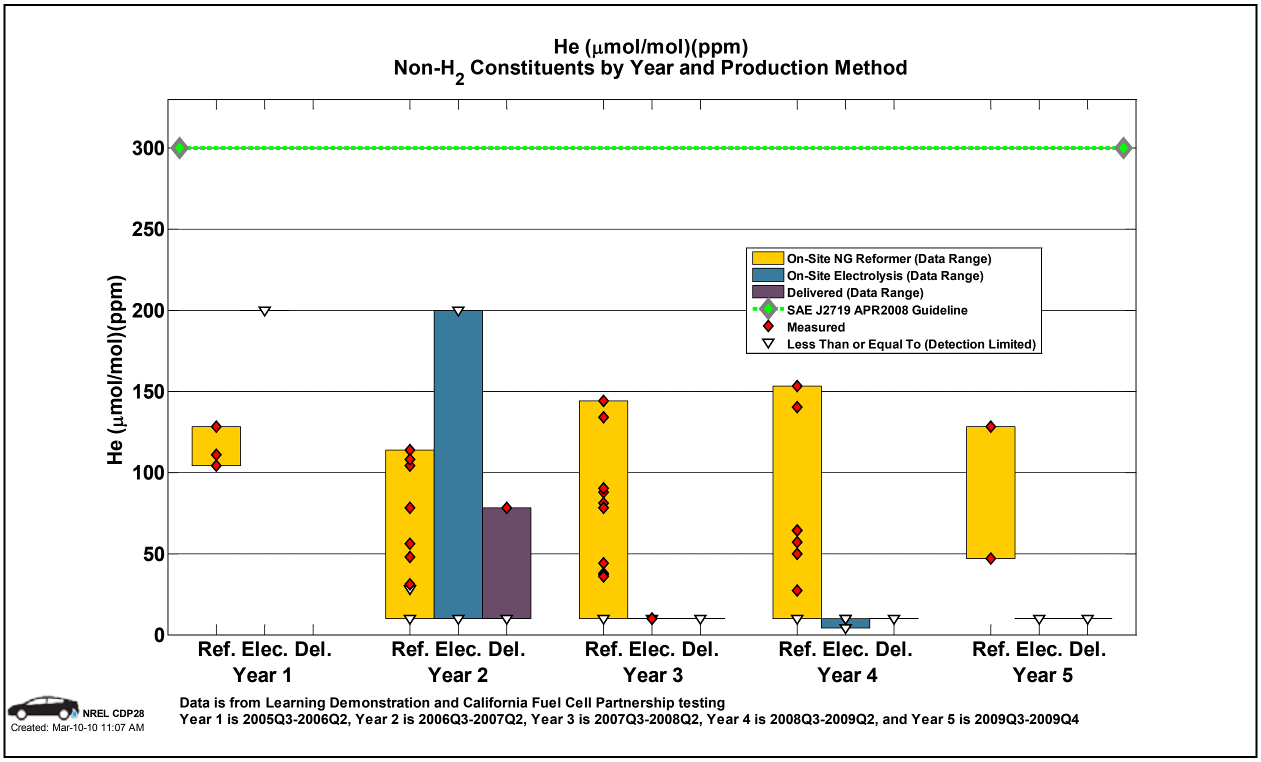



**Figure 89: Hydrogen fuel constituents – helium (CDP28)**

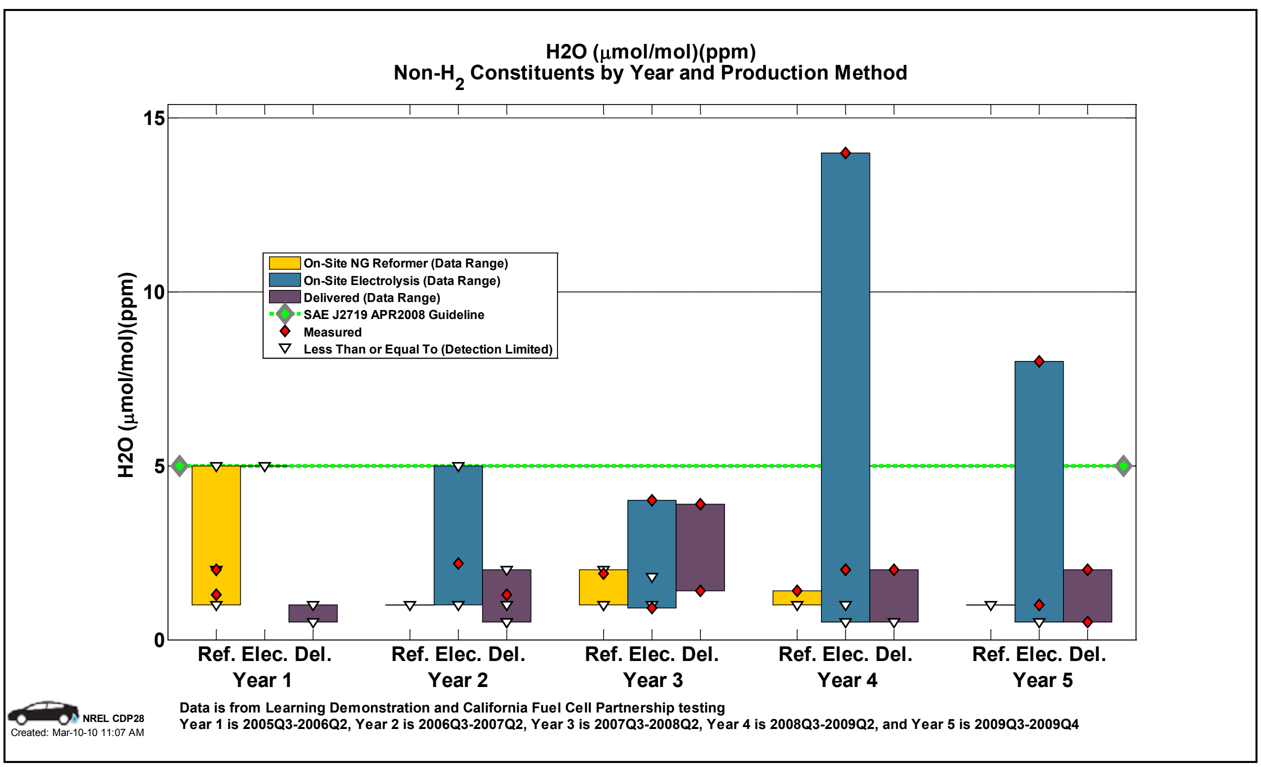



**Figure 90: Hydrogen fuel constituents – water (CDP28)**

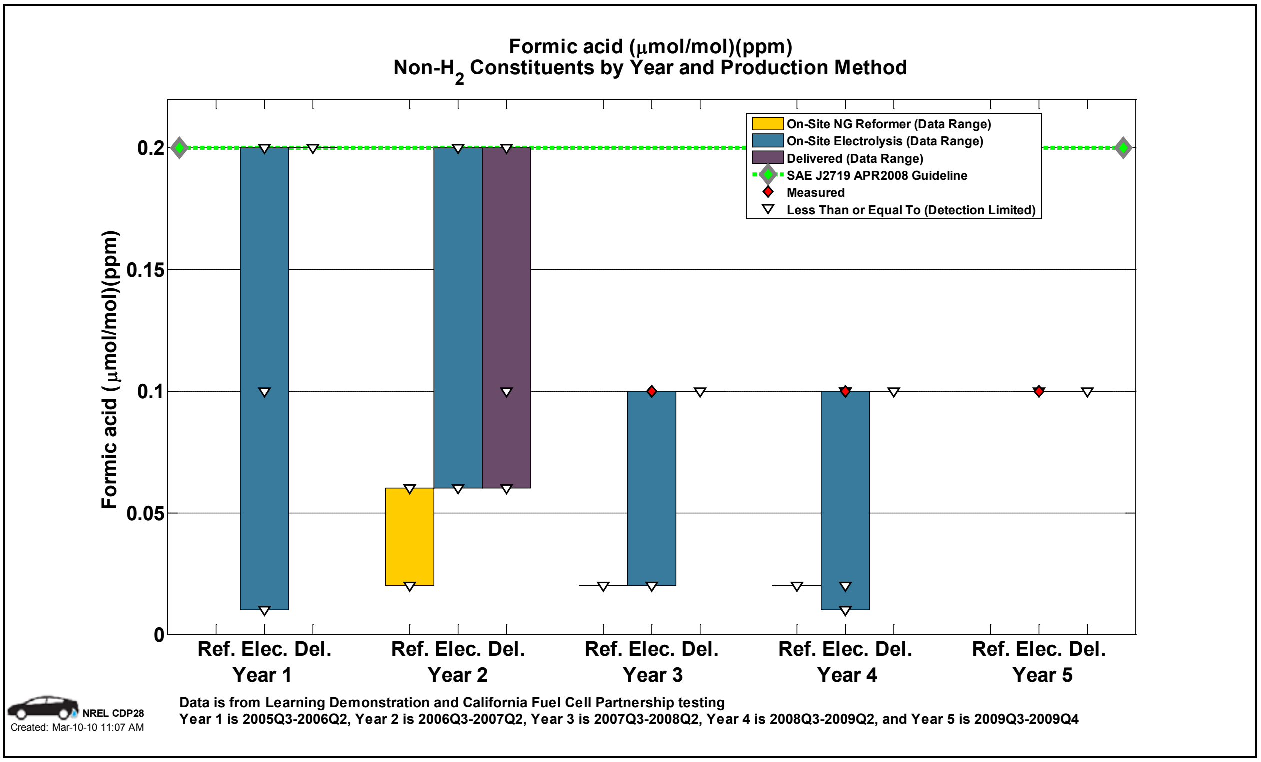



**Figure 91: Hydrogen fuel constituents – formic acid (CDP28)**

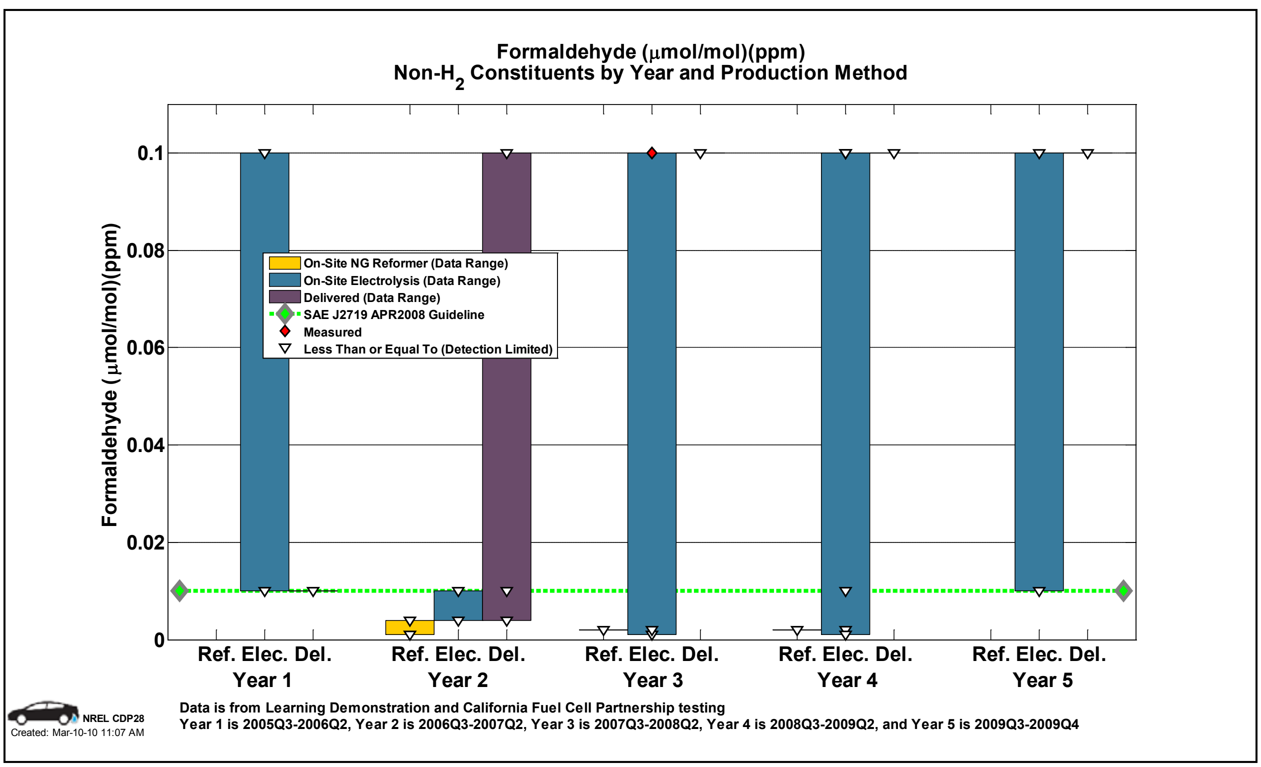



**Figure 92: Hydrogen fuel constituents – formaldehyde (CDP28)**

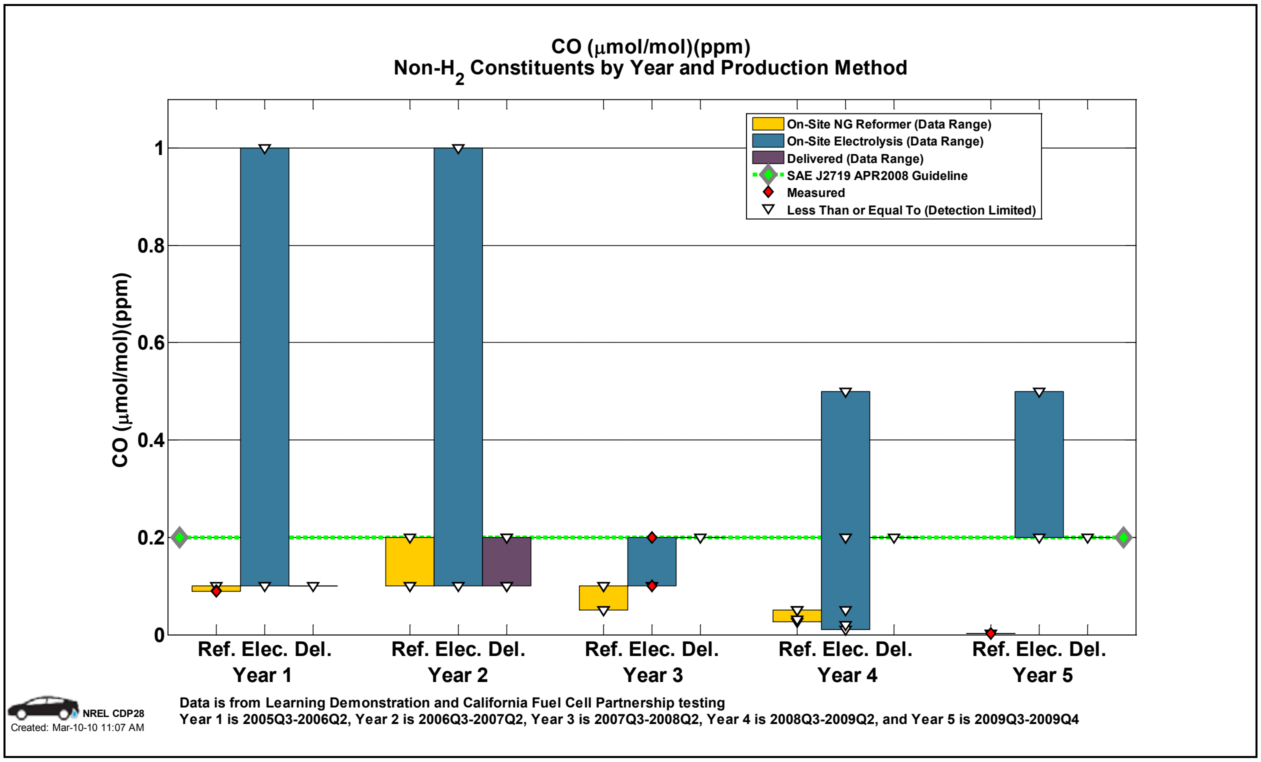



**Figure 93: Hydrogen fuel constituents – CO (CDP28)**

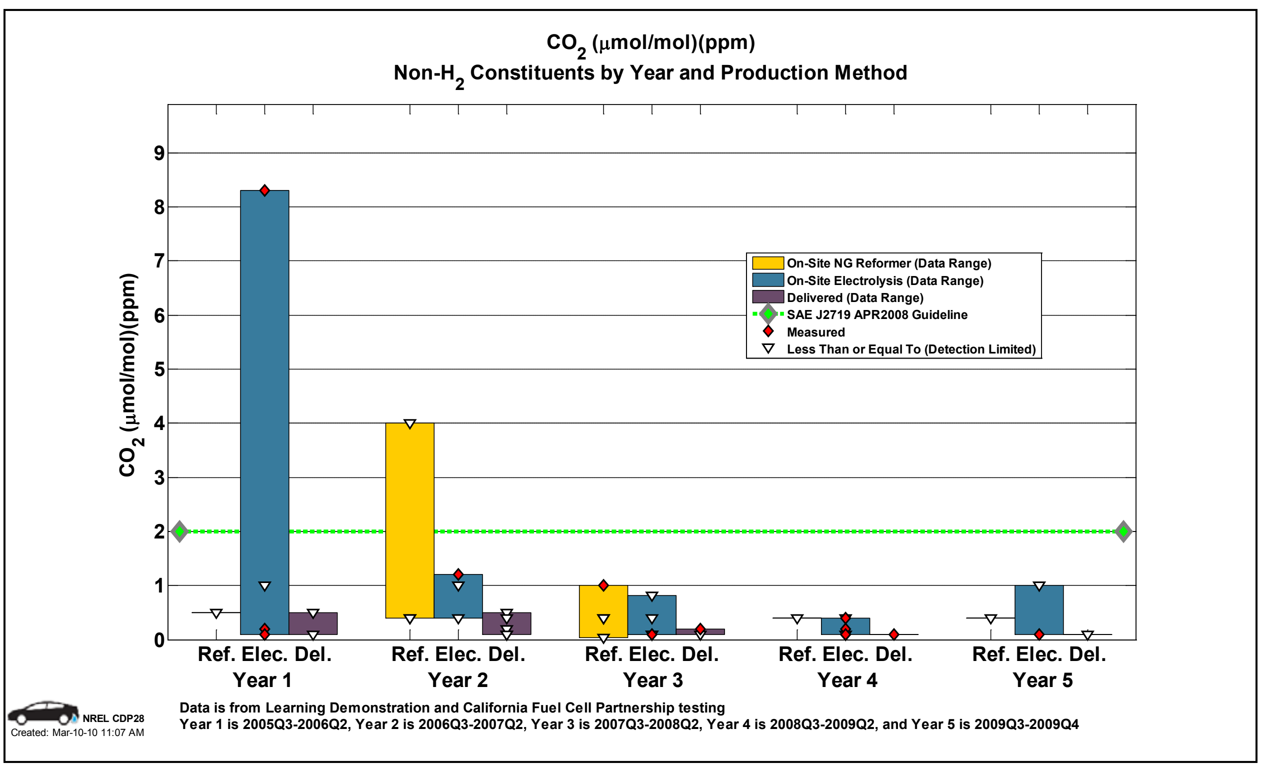



**Figure 94: Hydrogen fuel constituents – $CO_2$ (CDP28)**

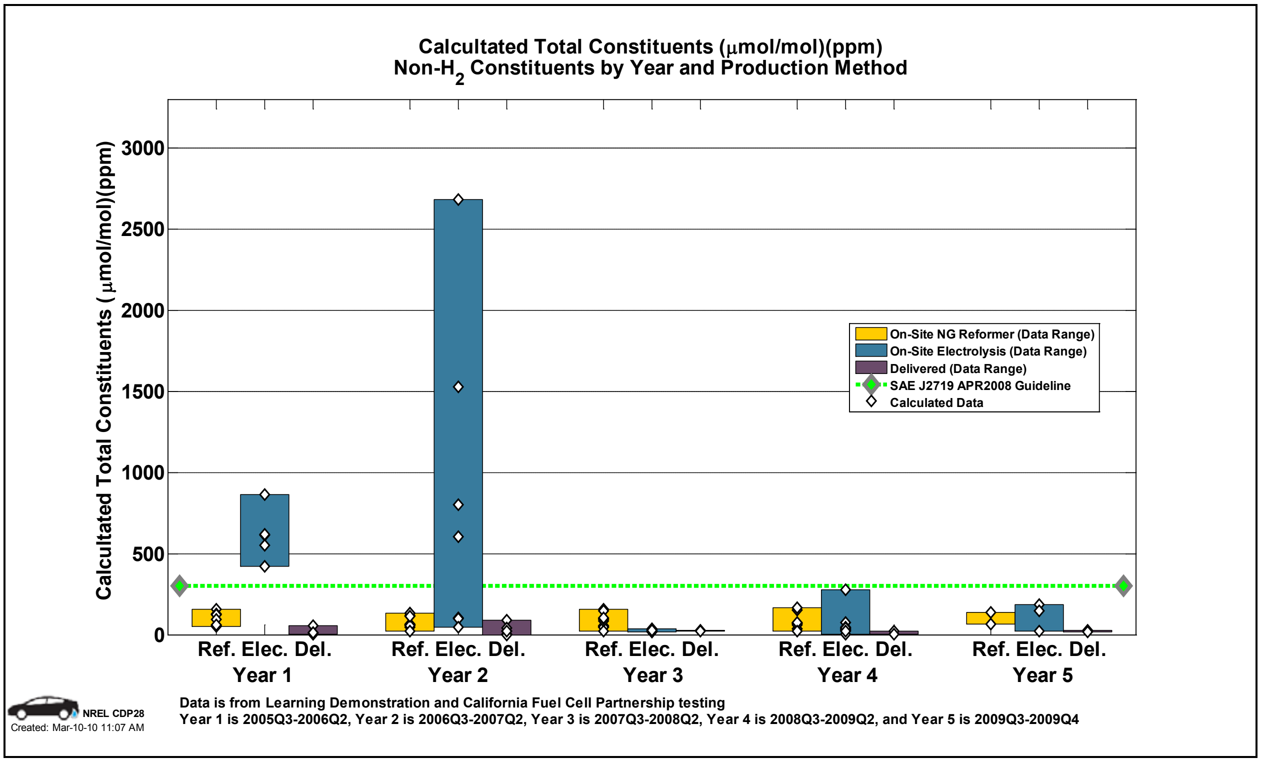



**Figure 95: Hydrogen fuel constituents – total (CDP28)**

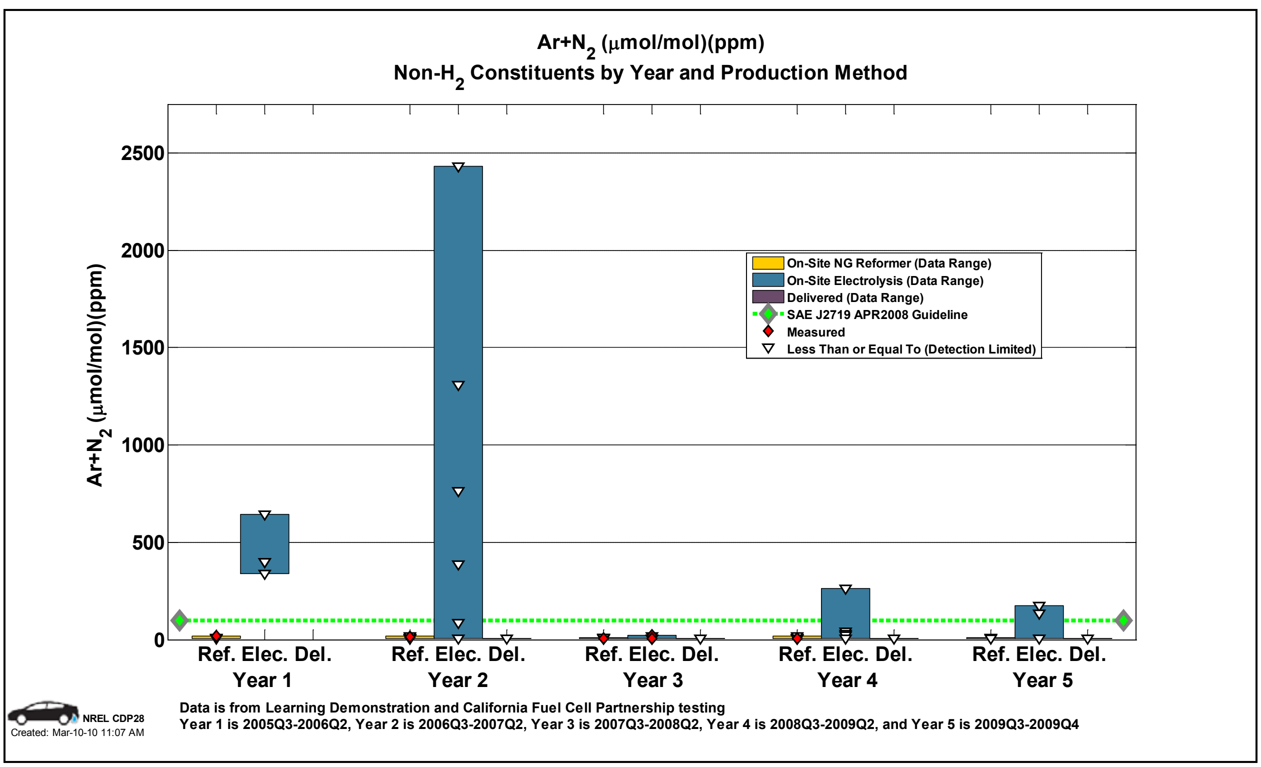



**Figure 96: Hydrogen fuel constituents – argon + nitrogen (CDP28)**

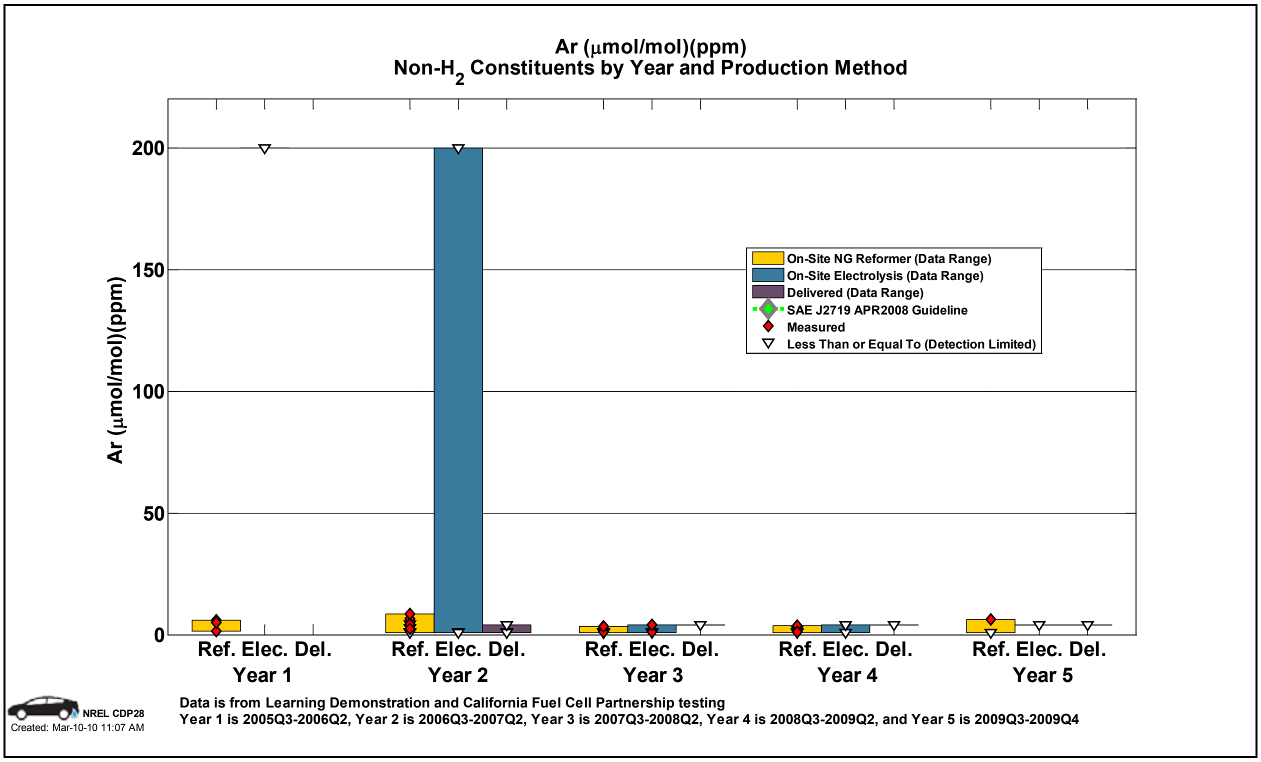



**Figure 97: Hydrogen fuel constituents – argon (CDP28)**

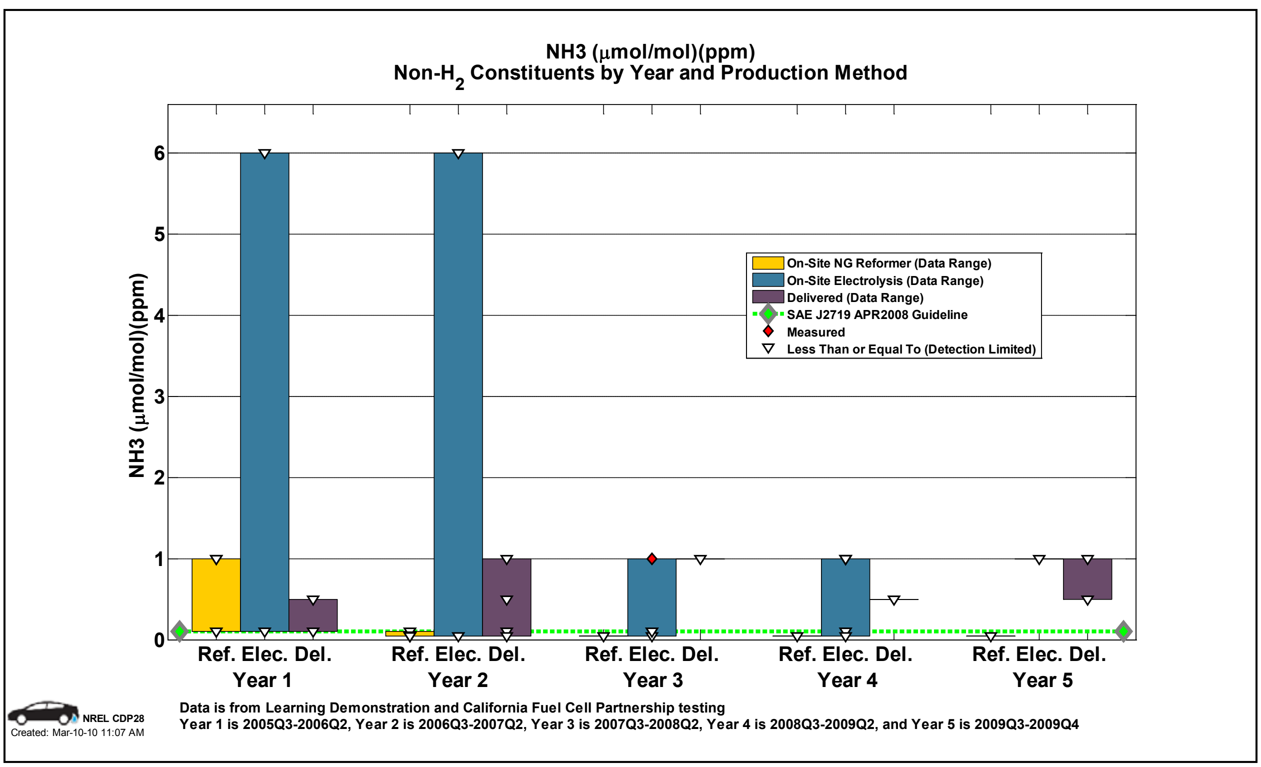



**Figure 98: Hydrogen fuel constituents – ammonia (CDP28)**

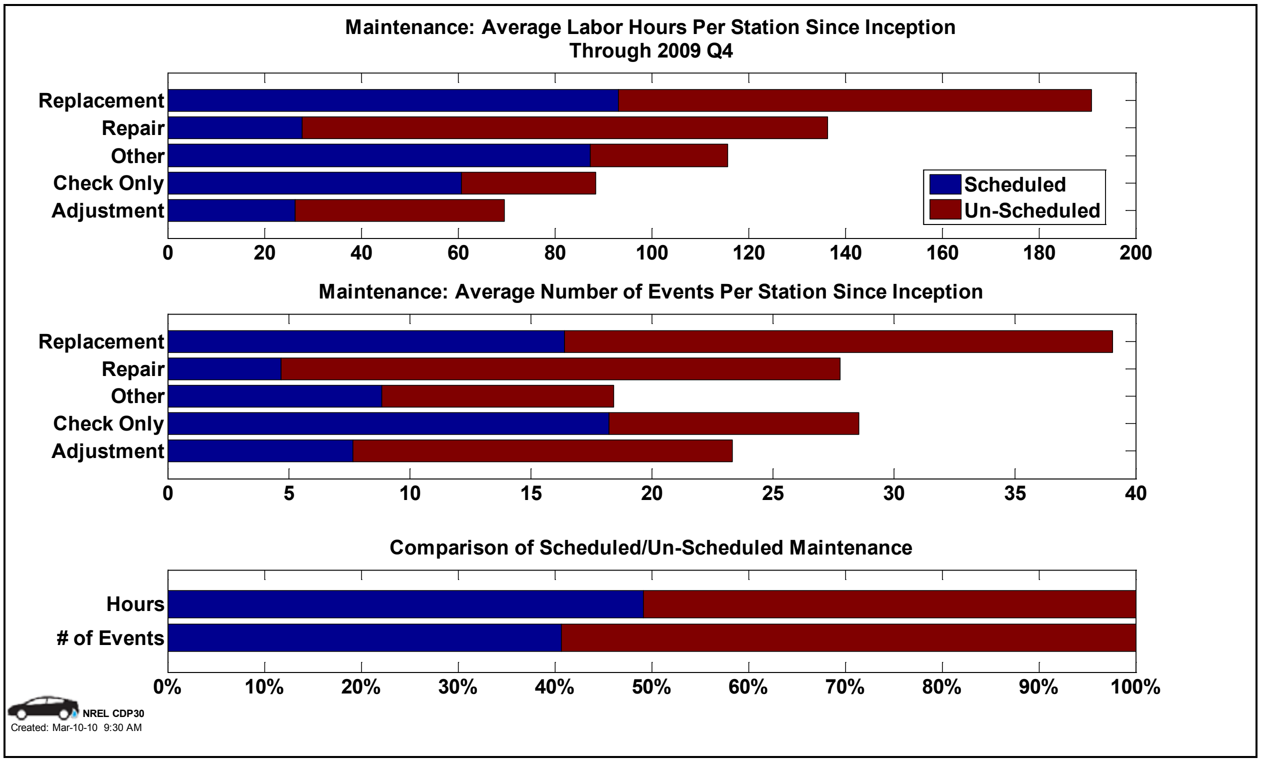



Figure 99: Infrastructure maintenance (CDP30)

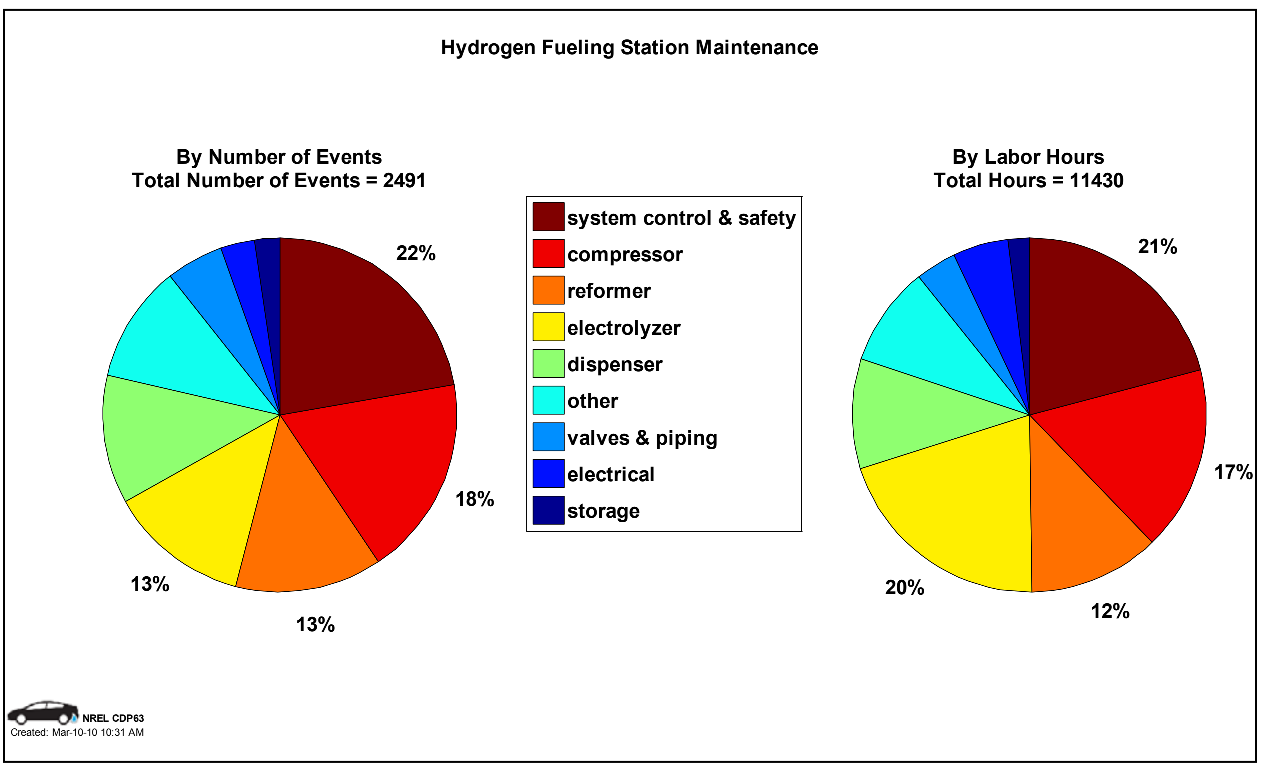



Figure 100: Hydrogen fueling station maintenance by system (CDP63)

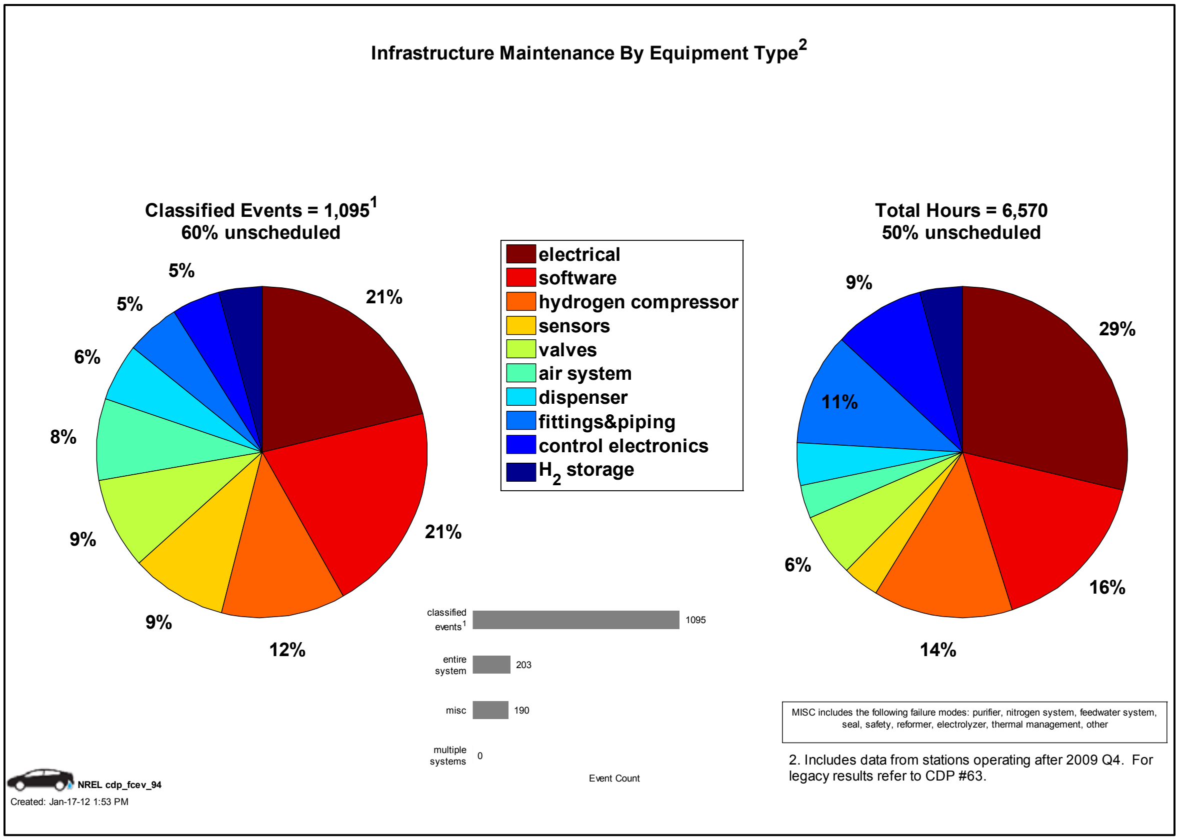



**Figure 101: Infrastructure maintenance by category after 2009Q4 (CDP94)**

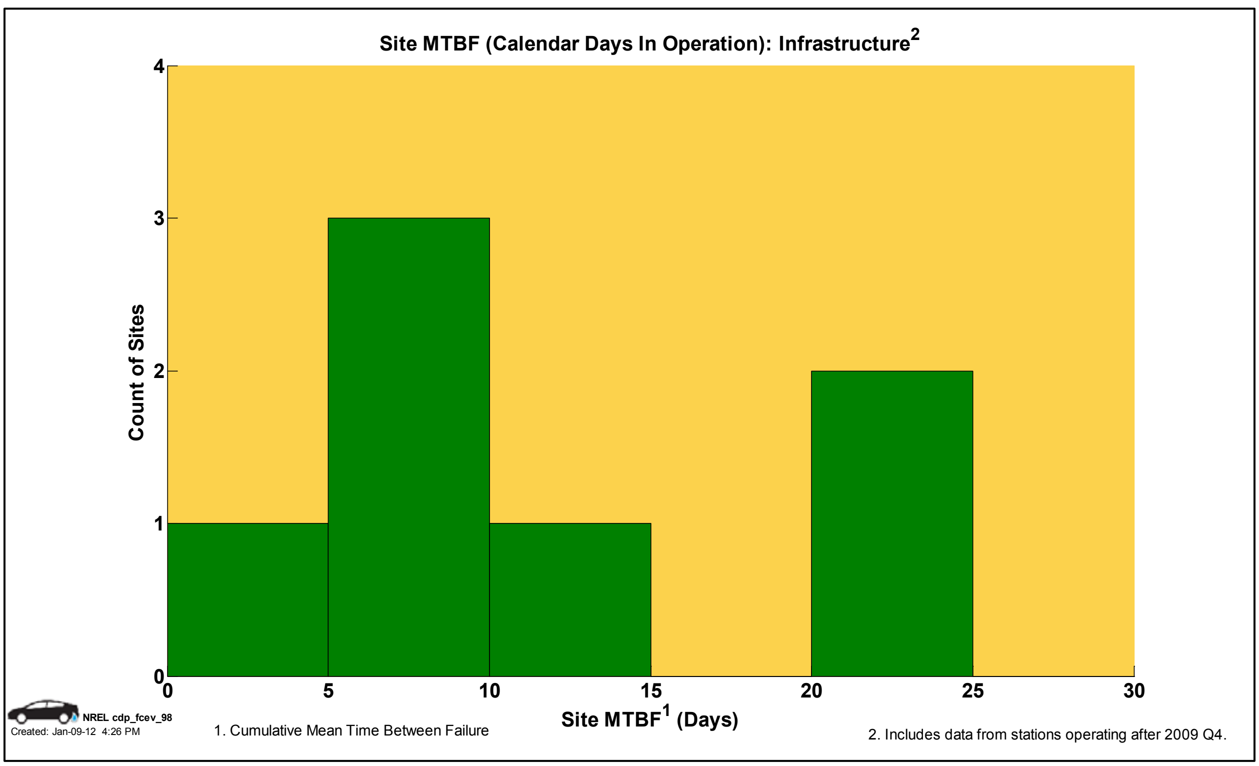



**Figure 102: Infrastructure, based on calendar days of operation after 2009Q4 (CDP98)**

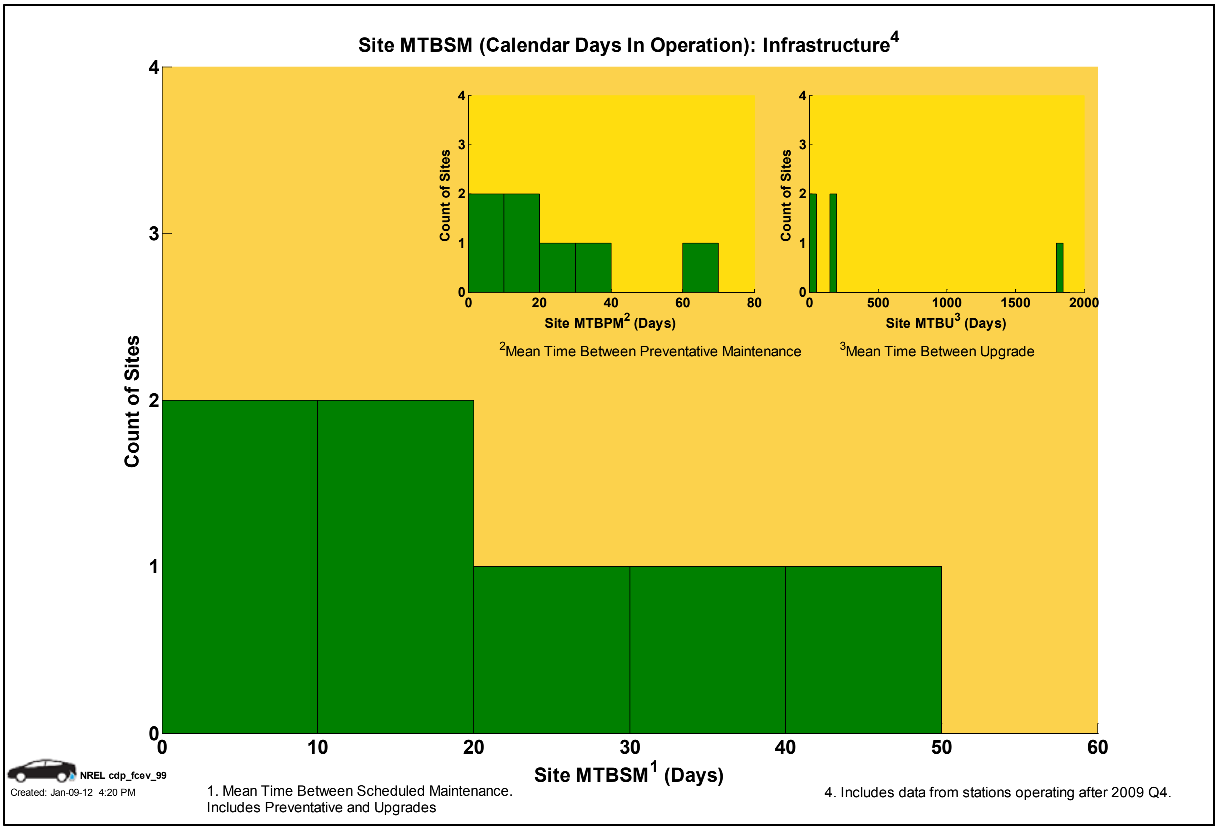



**Figure 103: Infrastructure mean time between scheduled maintenance after 2009Q4 (CDP99)**

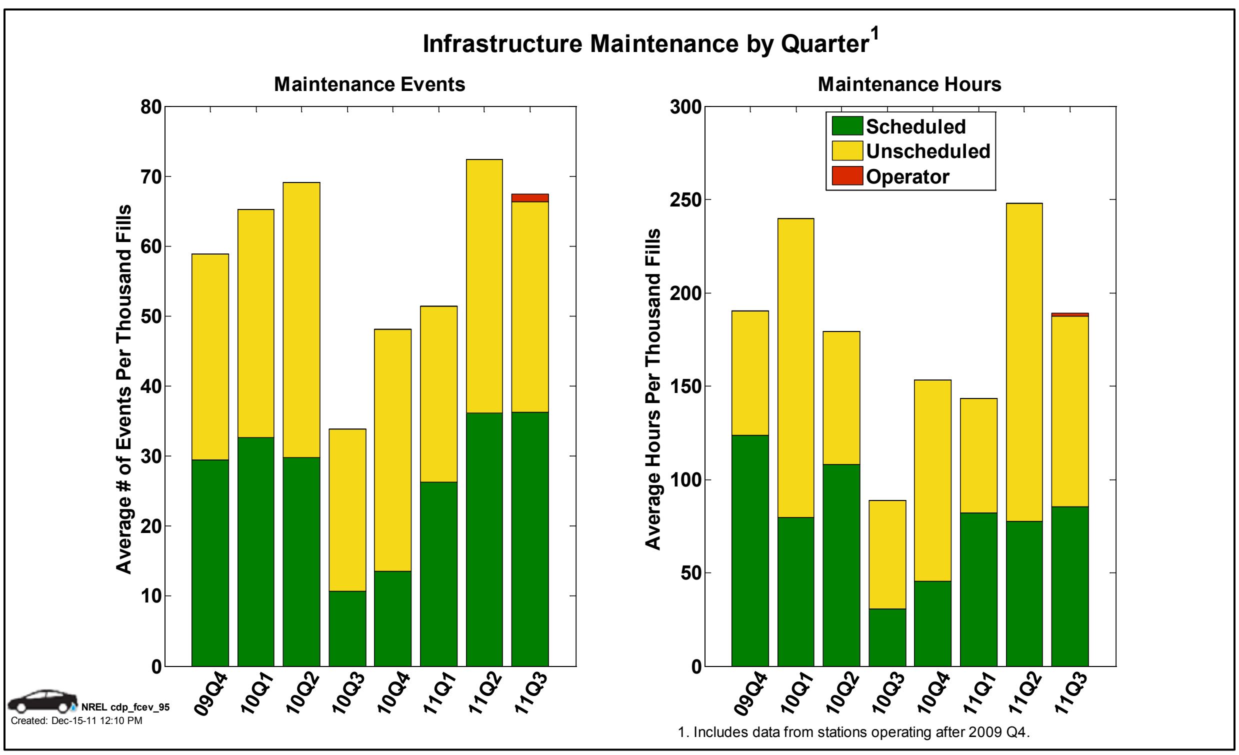



**Figure 104: Infrastructure maintenance by quarter after 2009Q4 (CDP95)**

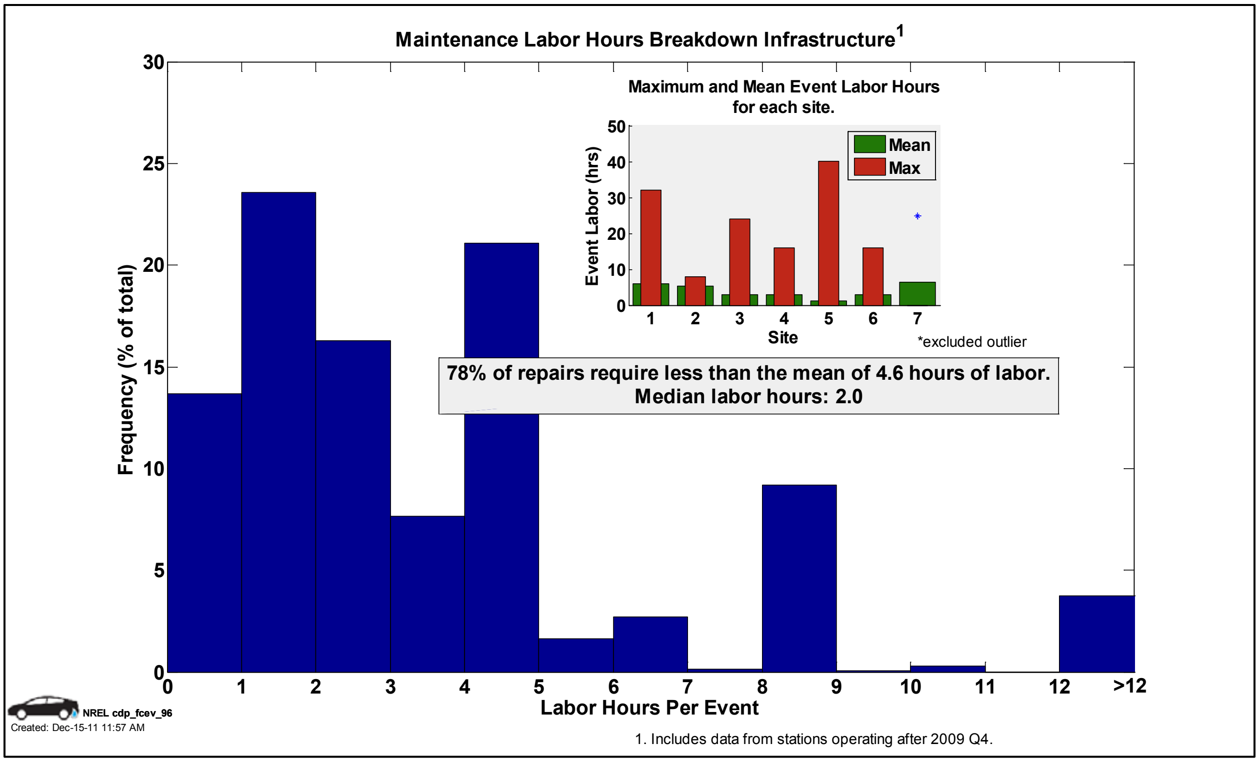



**Figure 105: Infrastructure labor hours after 2009Q4 (CDP96)**

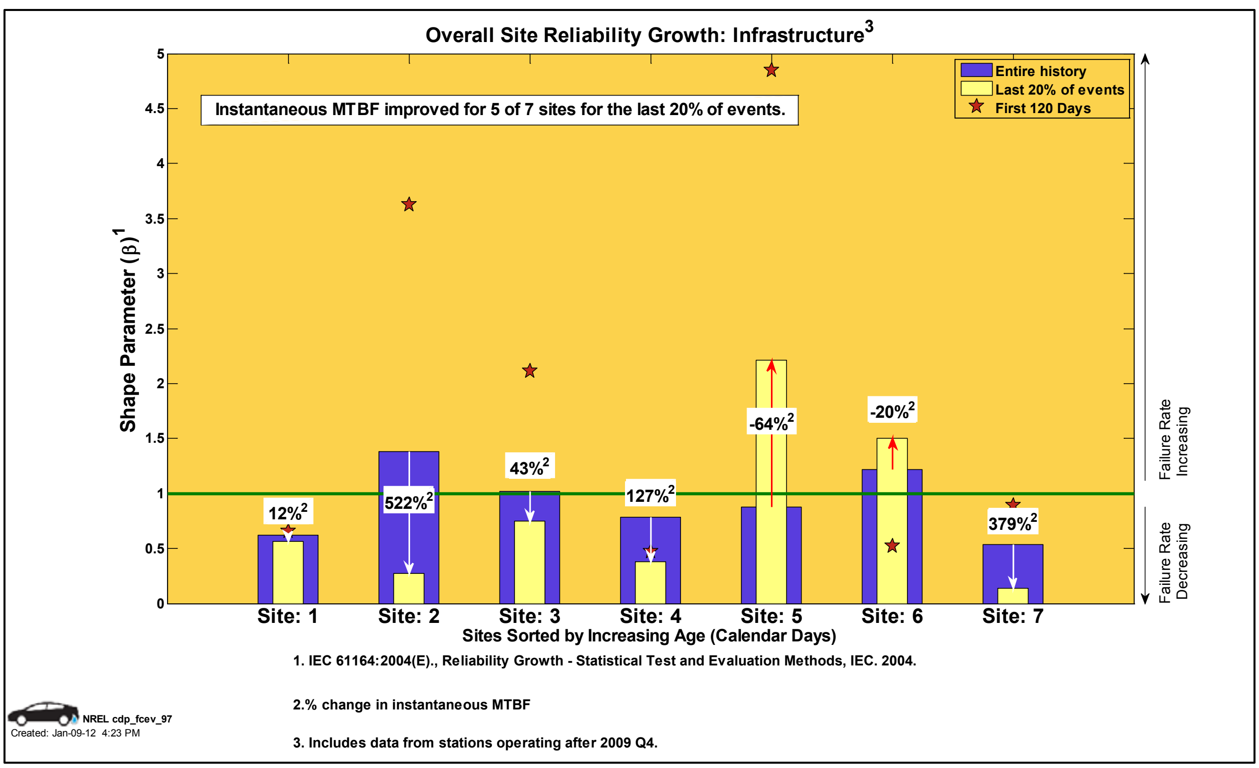



**Figure 106: Infrastructure reliability growth after 2009Q4 CDP97)**

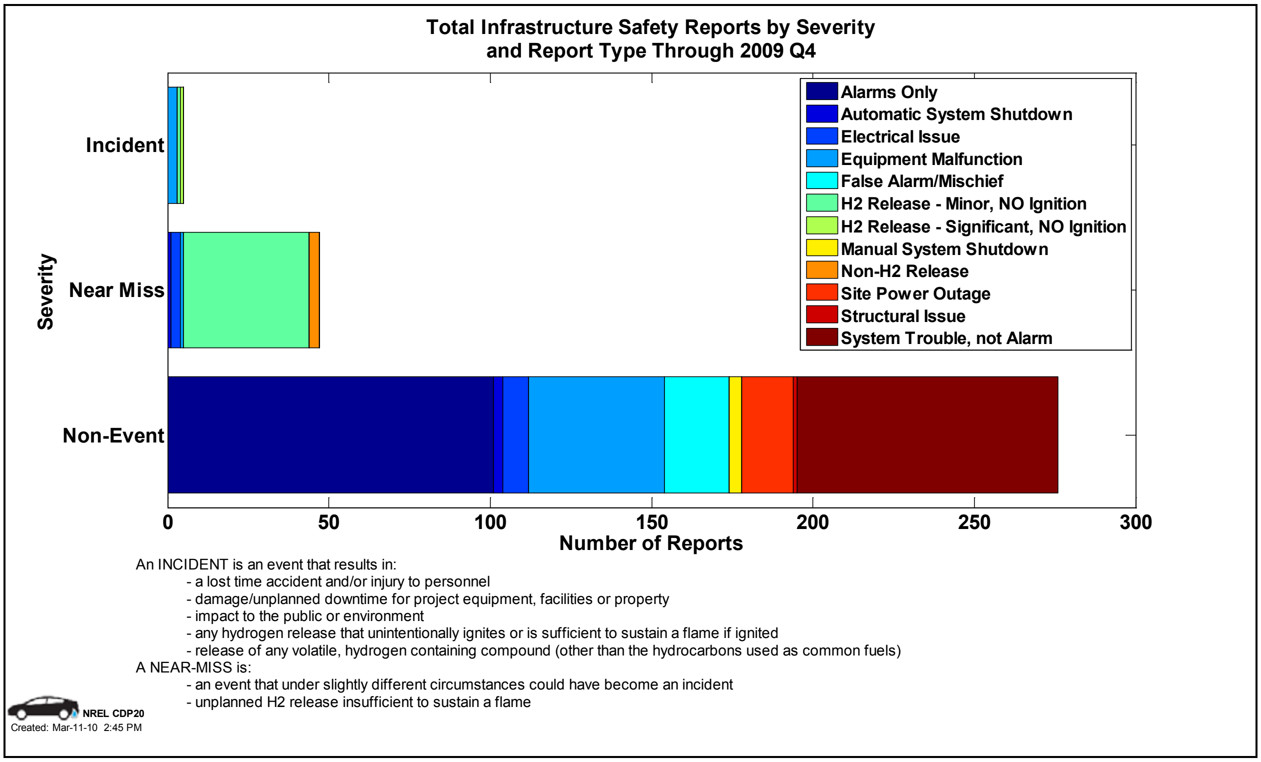



**Figure 107: Safety reports – infrastructure (CDP20)**

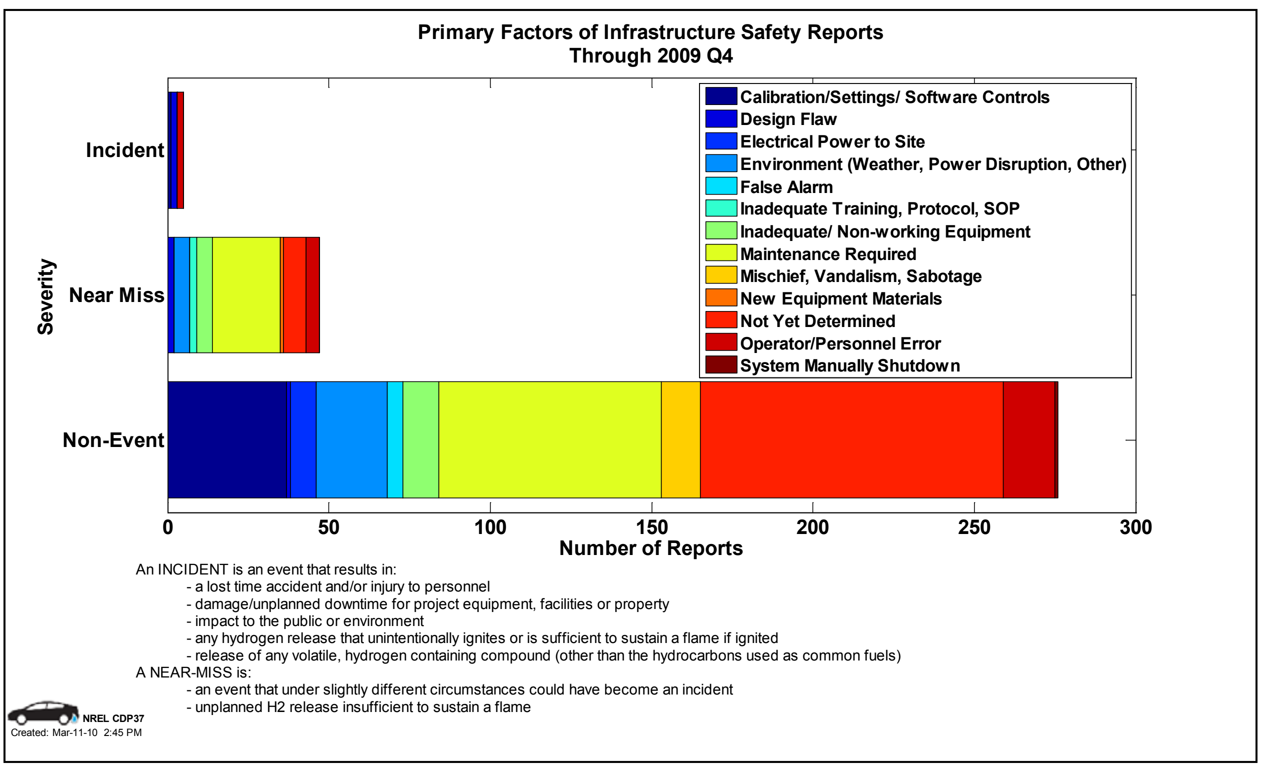



**Figure 108: Primary factors of infrastructure reports (CDP37)**

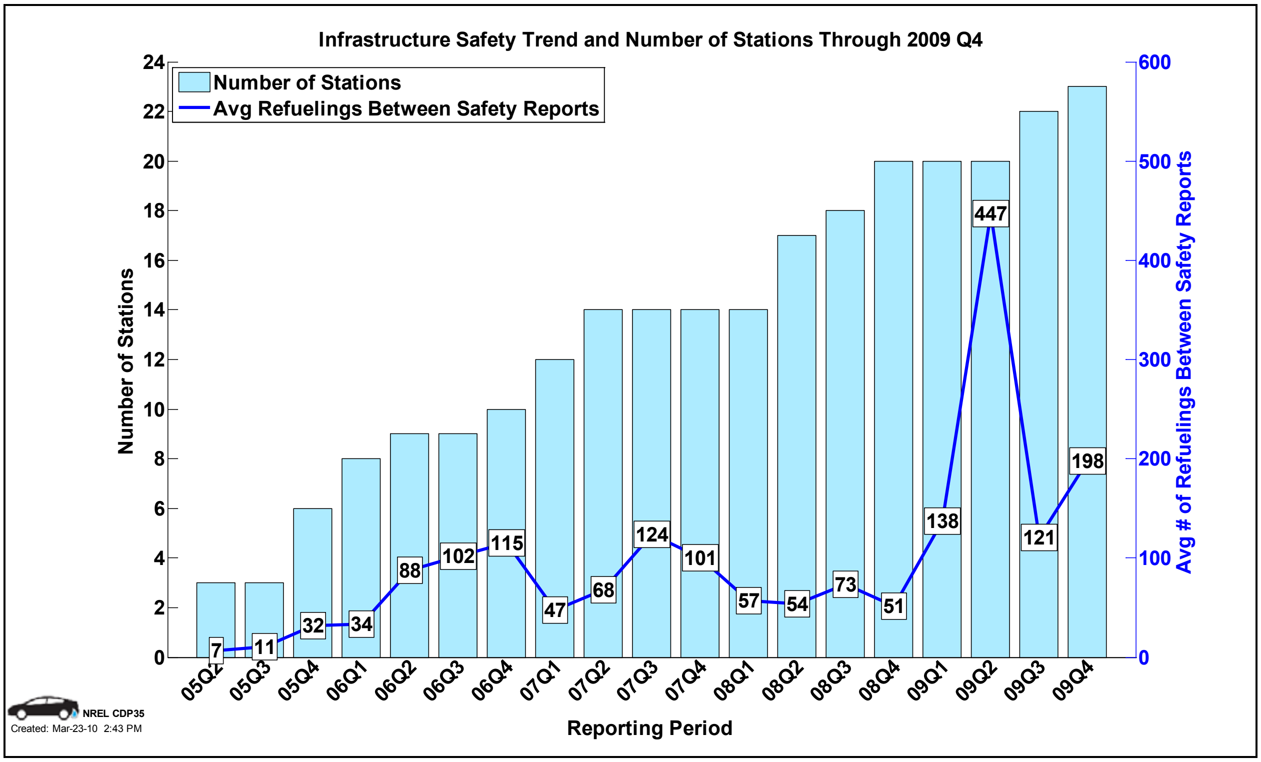



**Figure 109: Average refuelings between infrastructure safety reports (CDP35)**

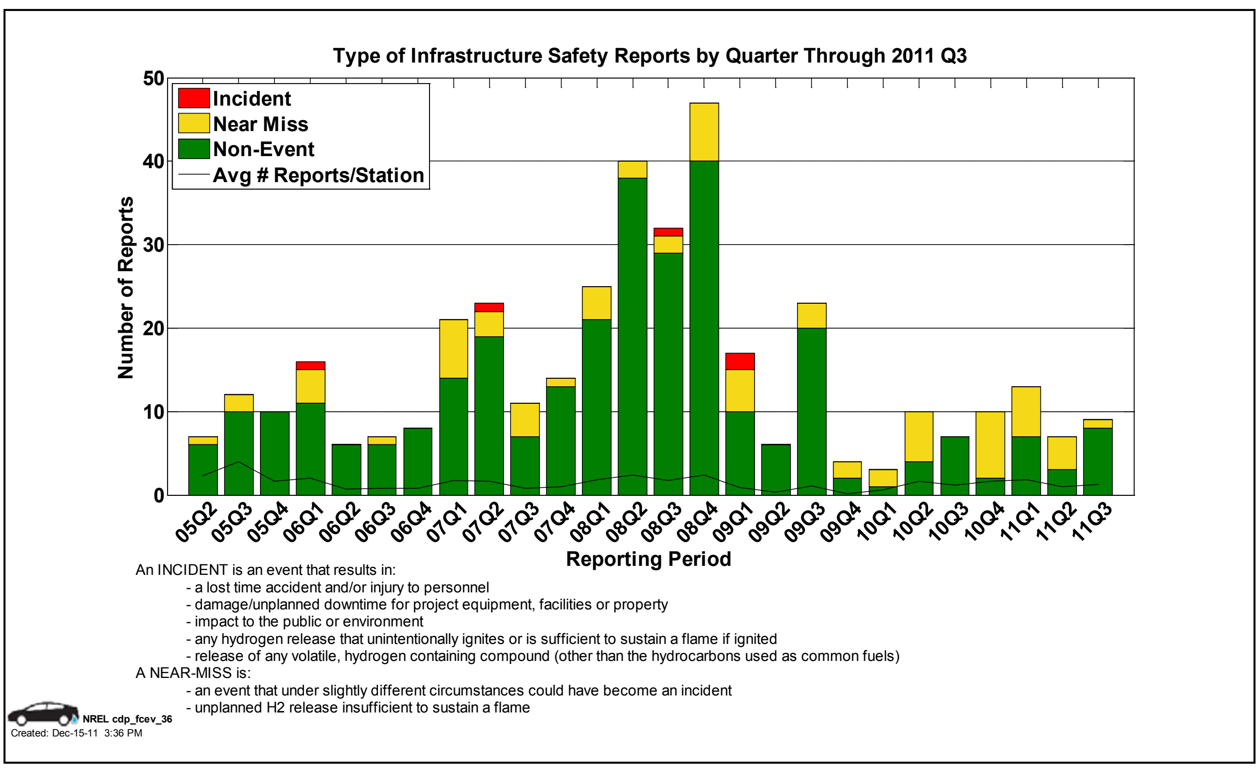



**Figure 110: Type of infrastructure safety report by quarter (CDP36)**

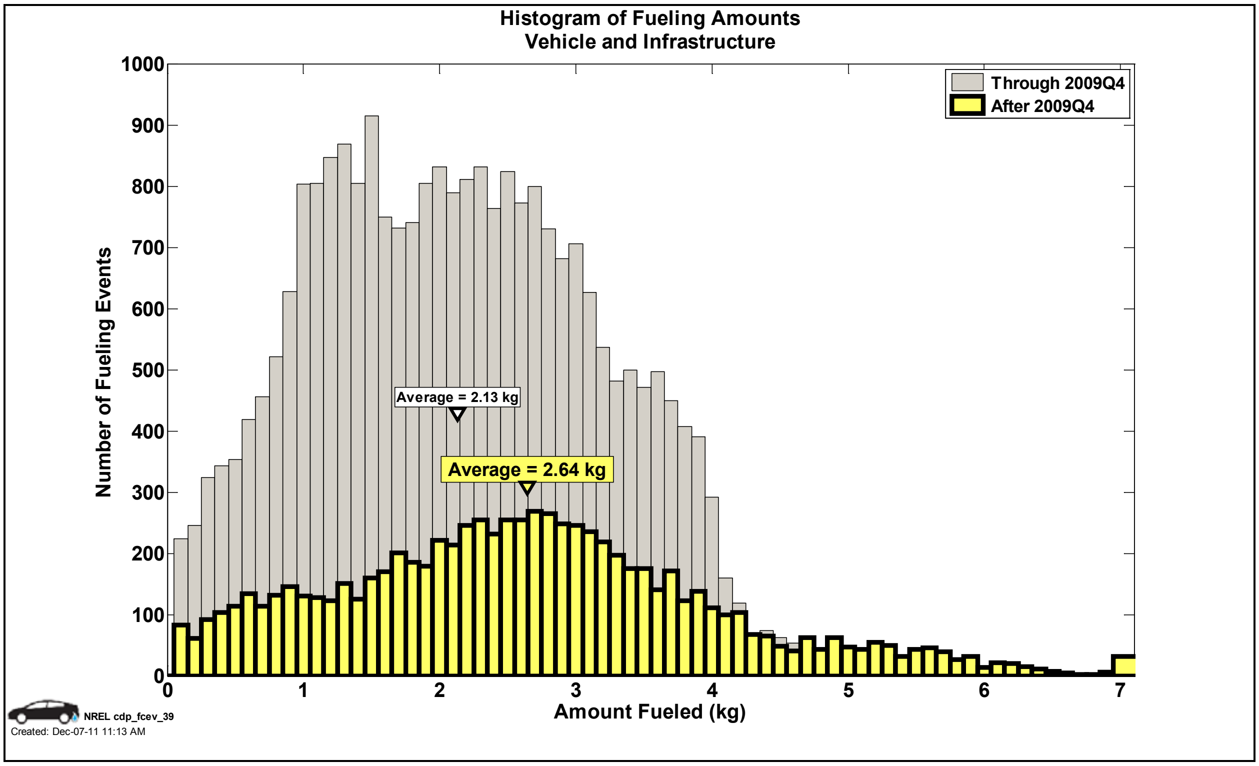



Figure 111: Fueling amounts (CDP39)

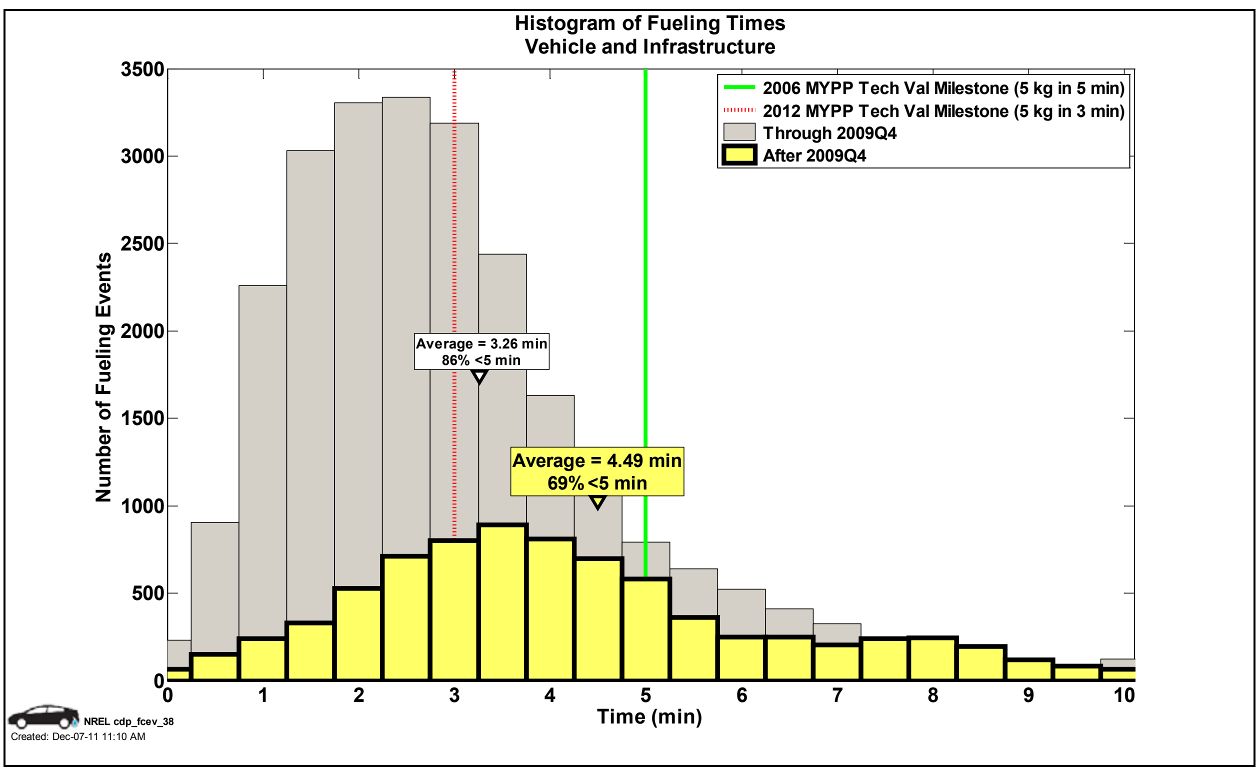



Figure 112: Fueling times (CDP38)

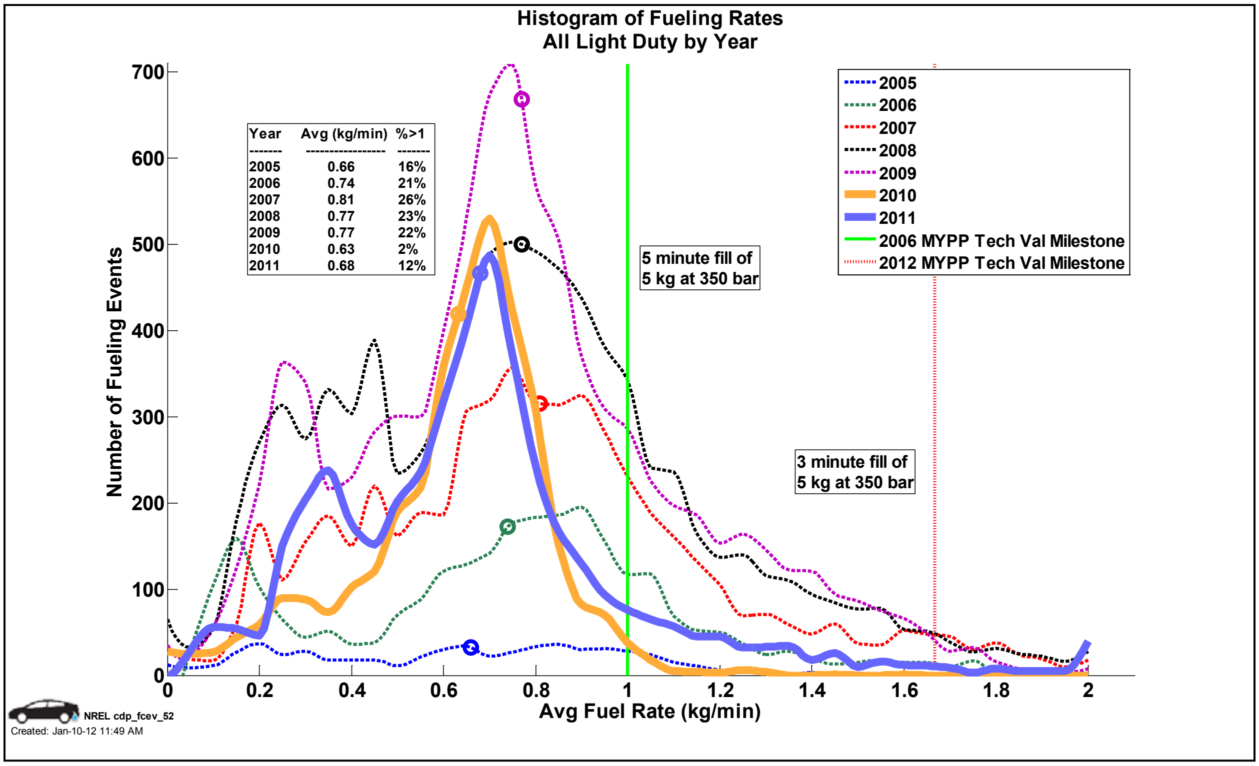



**Figure 113: Fueling rates by year (CDP52)**

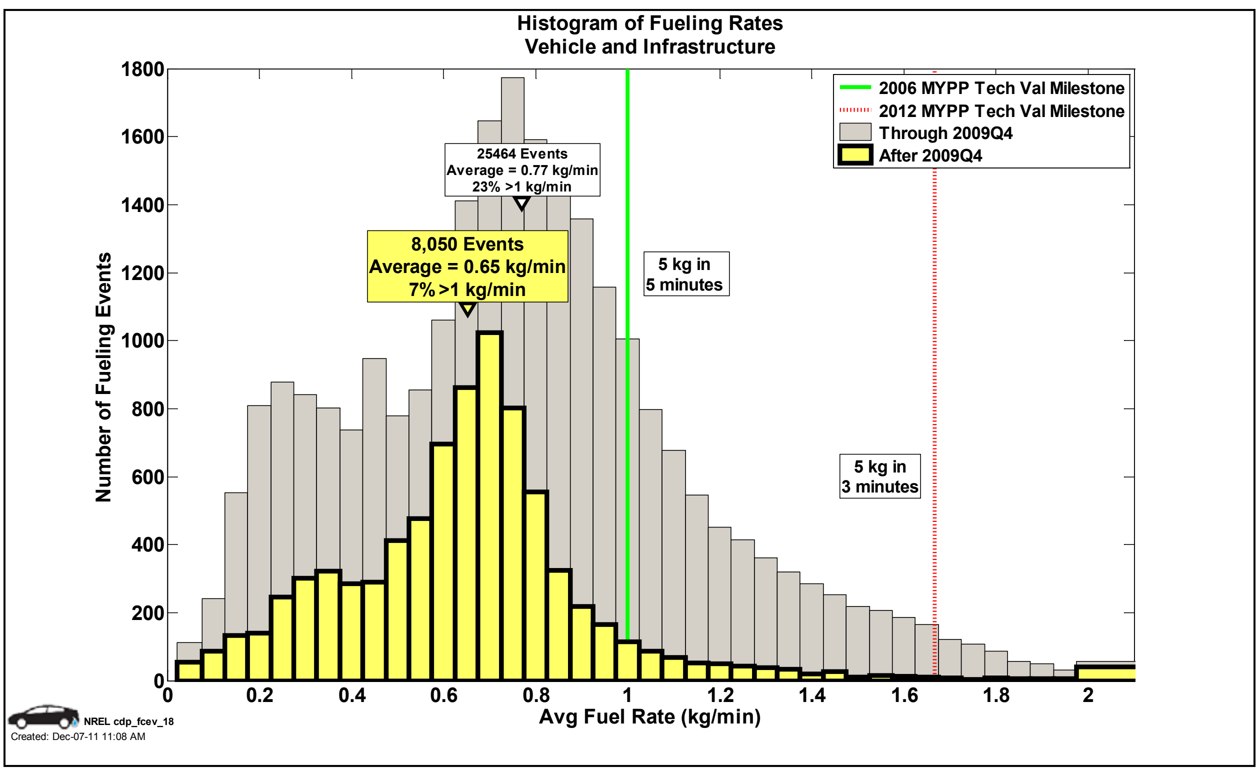



**Figure 114: Fueling rates (CDP18)**

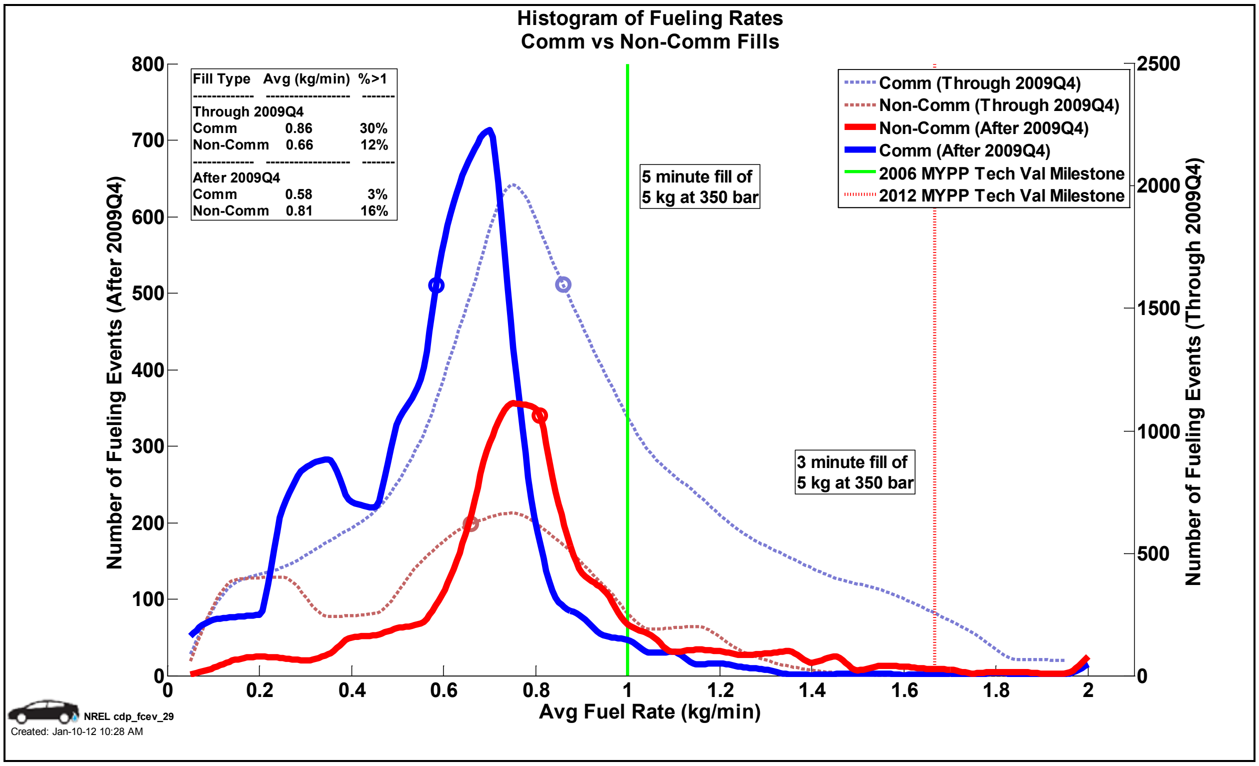



**Figure 115: Fueling rates – communication and non-communication fills (CDP29)**

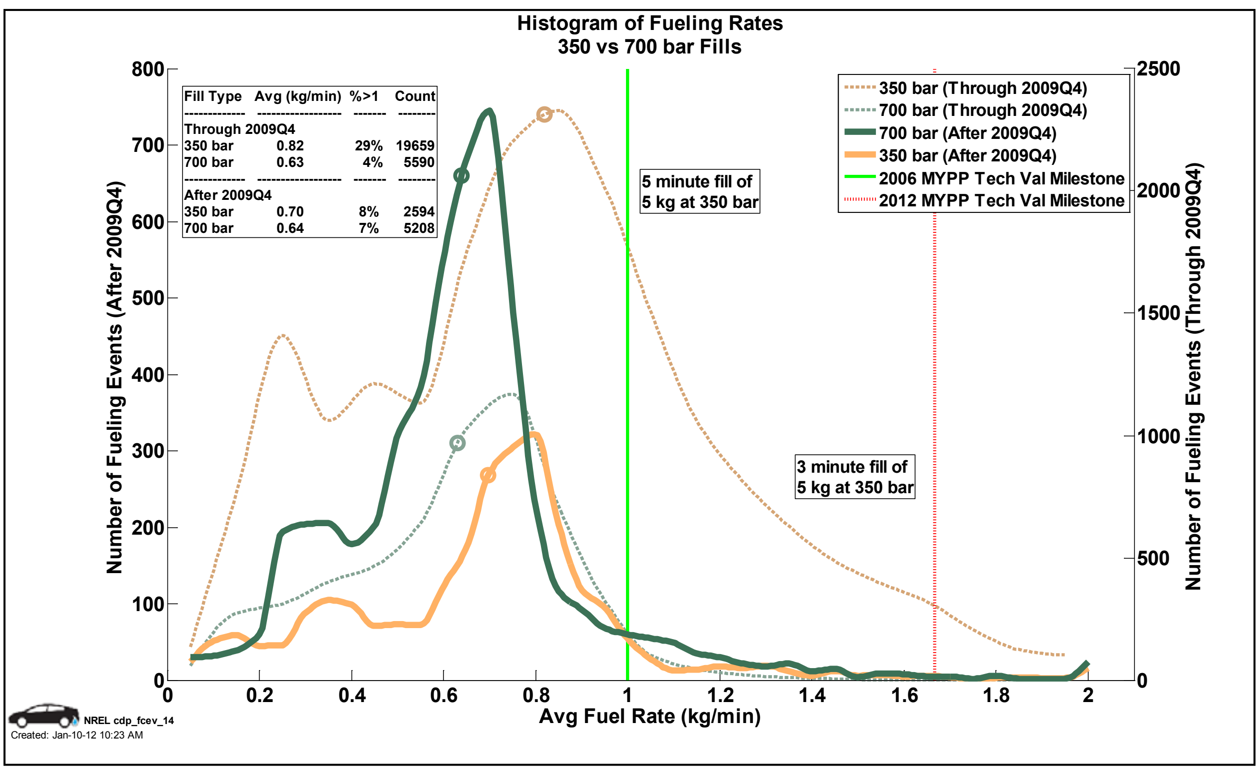



**Figure 116: Fueling rates – 350 and 700 bar (CDP14)**

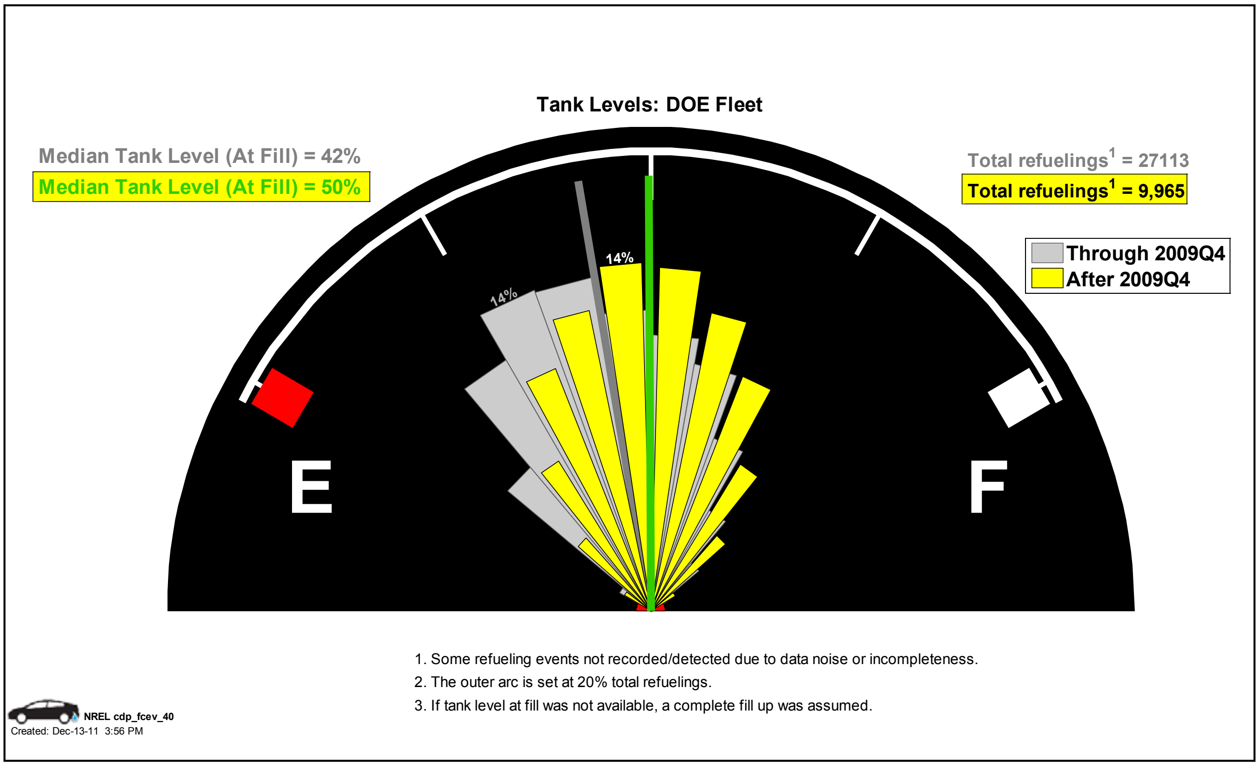



**Figure 117: Hydrogen tank level at fueling (CDP40)**

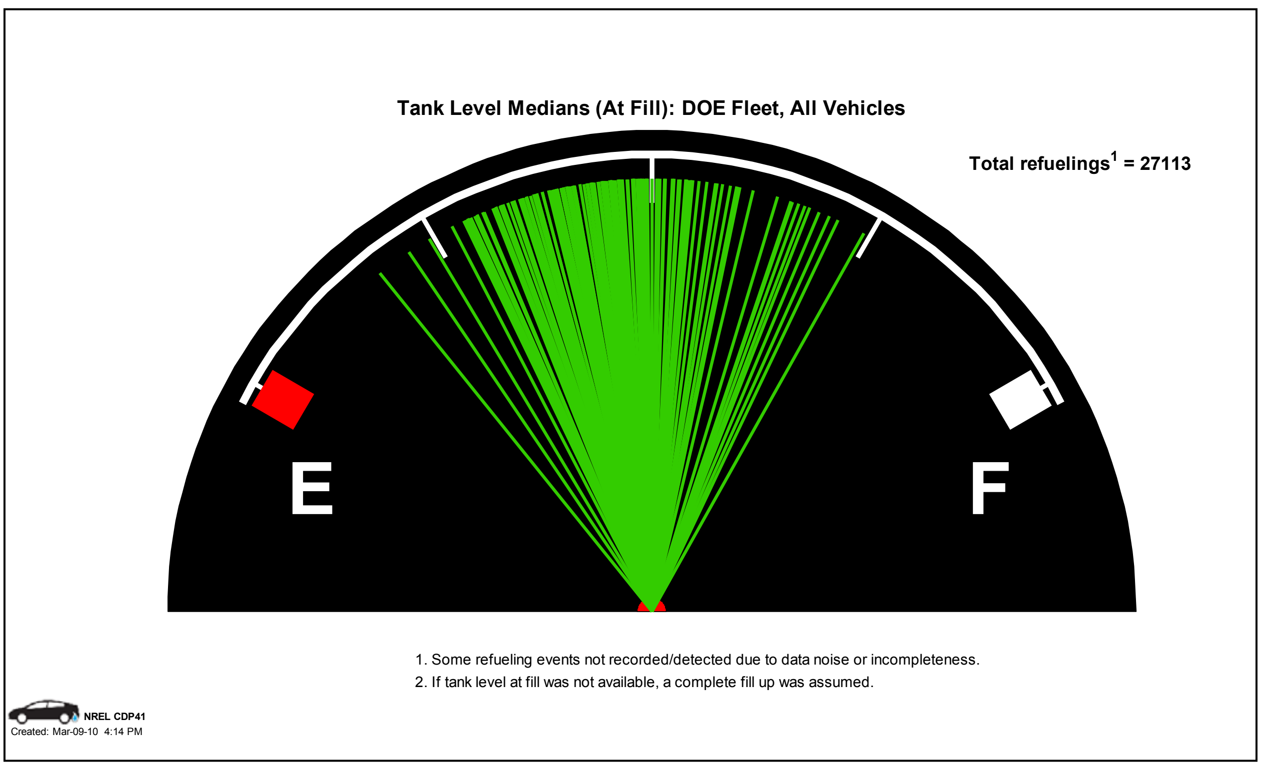



**Figure 118: Fueling tank levels – medians (CDP41)**

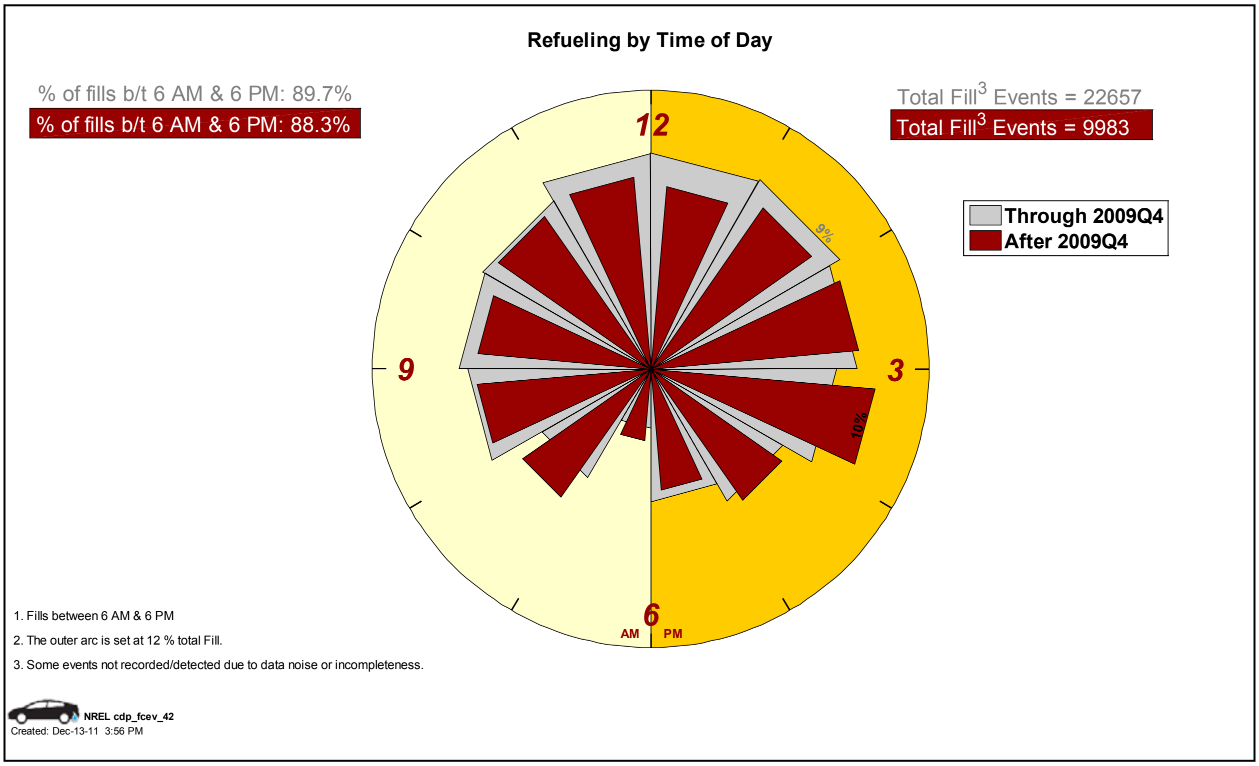



**Figure 119: Fueling by time of day (CDP42)**

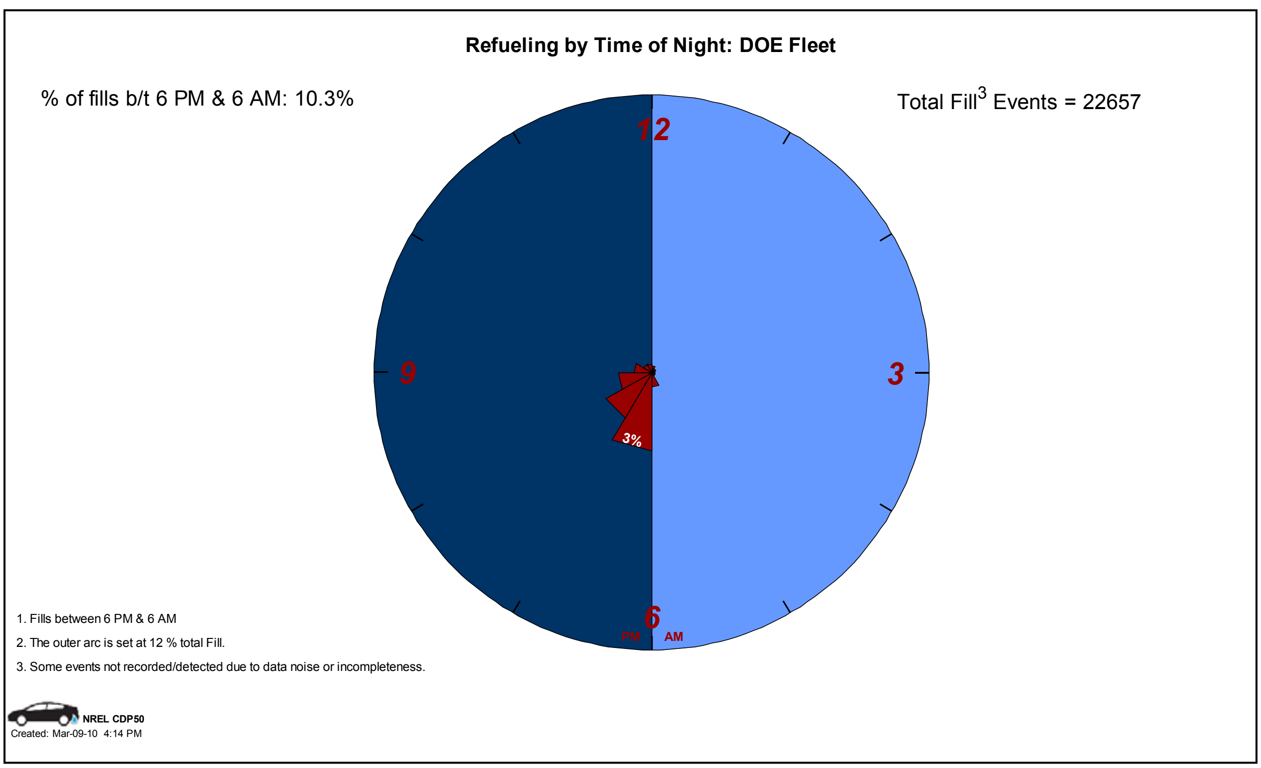



**Figure 120: Fueling by time of night (CDP50)**

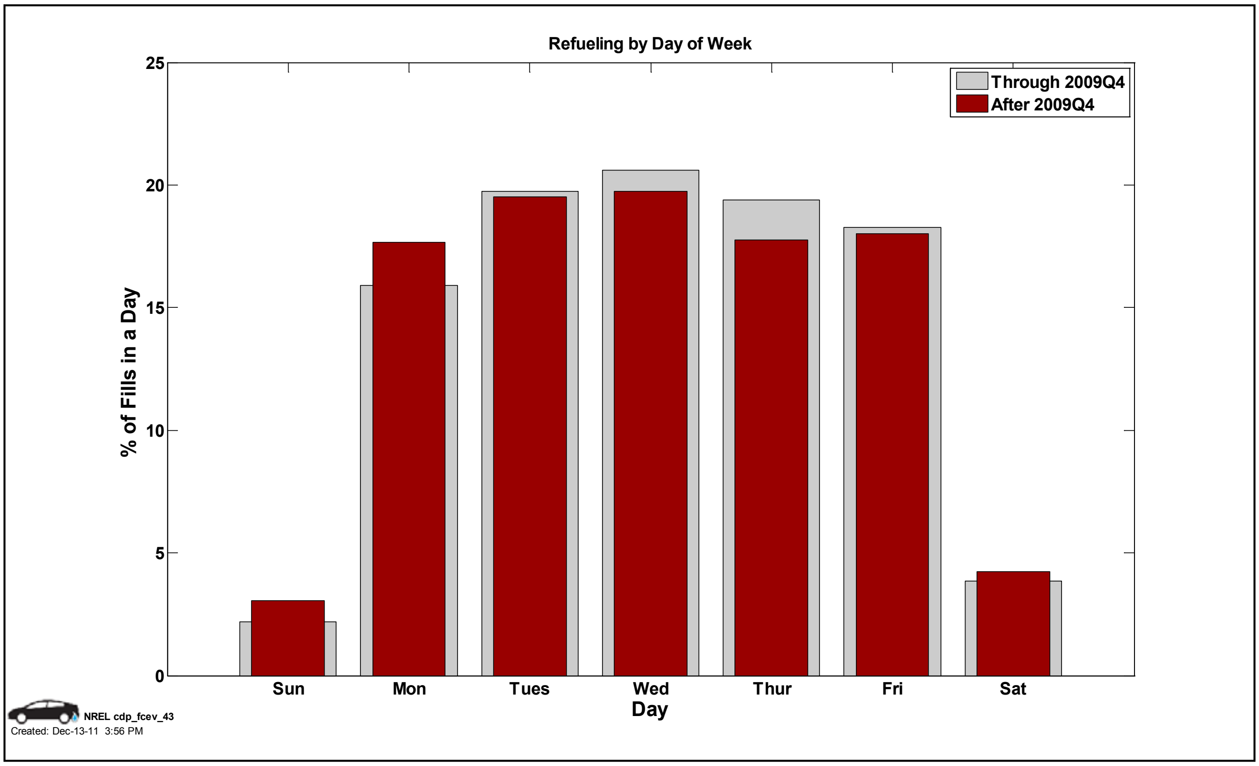



**Figure 121: Fueling by day of week (CDP43)**

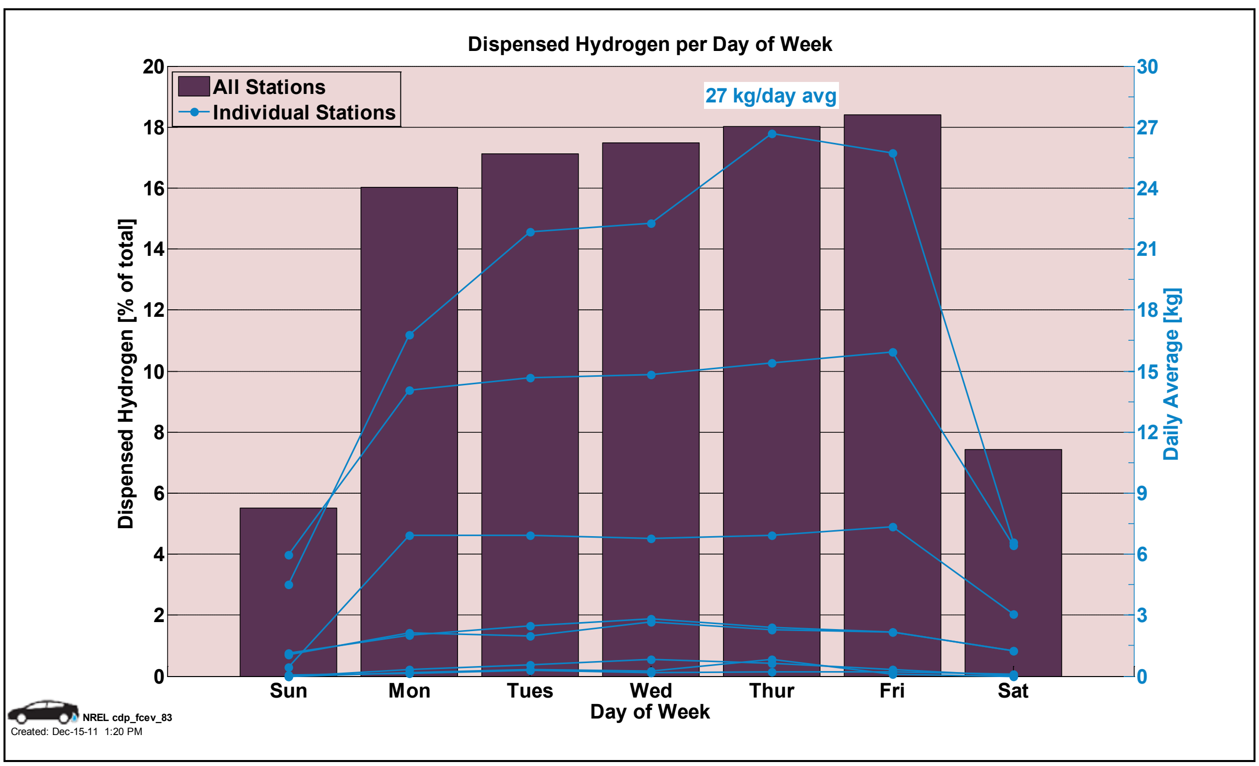



**Figure 122: Hydrogen dispensed by day of week and station (CDP83)**

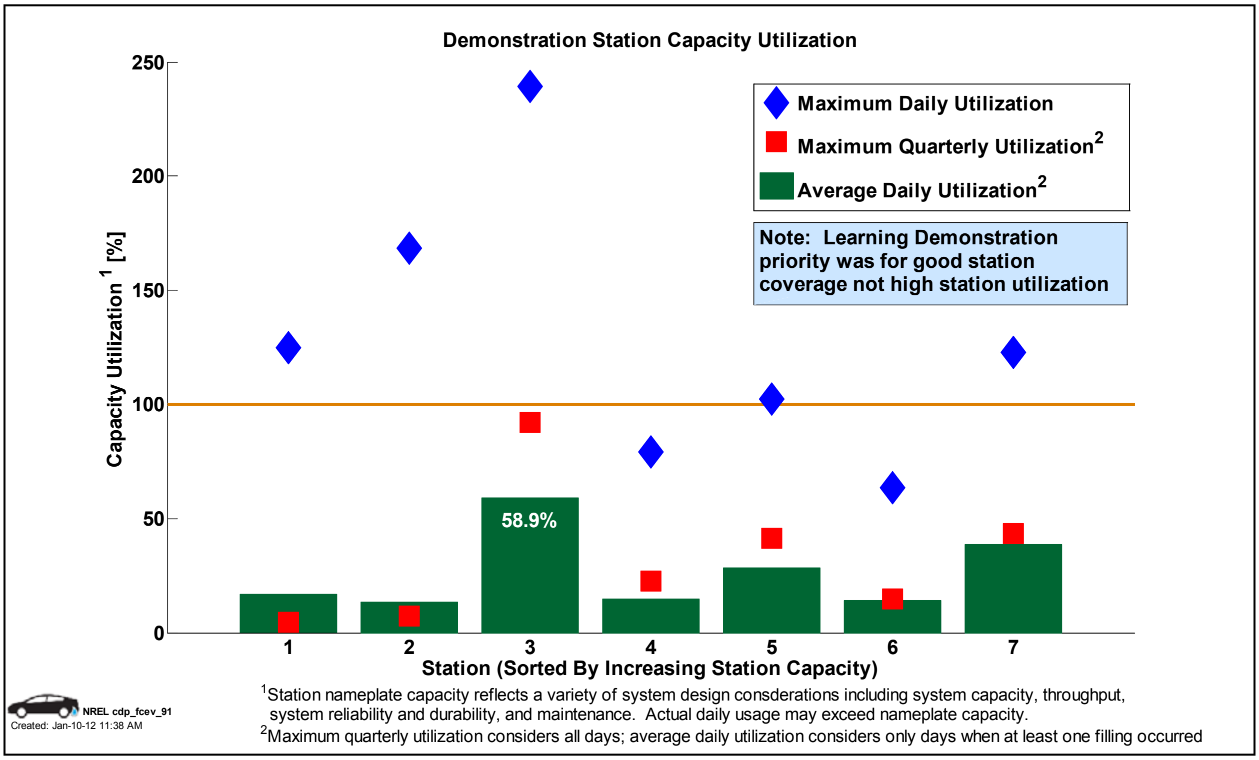



**Figure 123: Demonstration station capacity utilization (CDP91)**

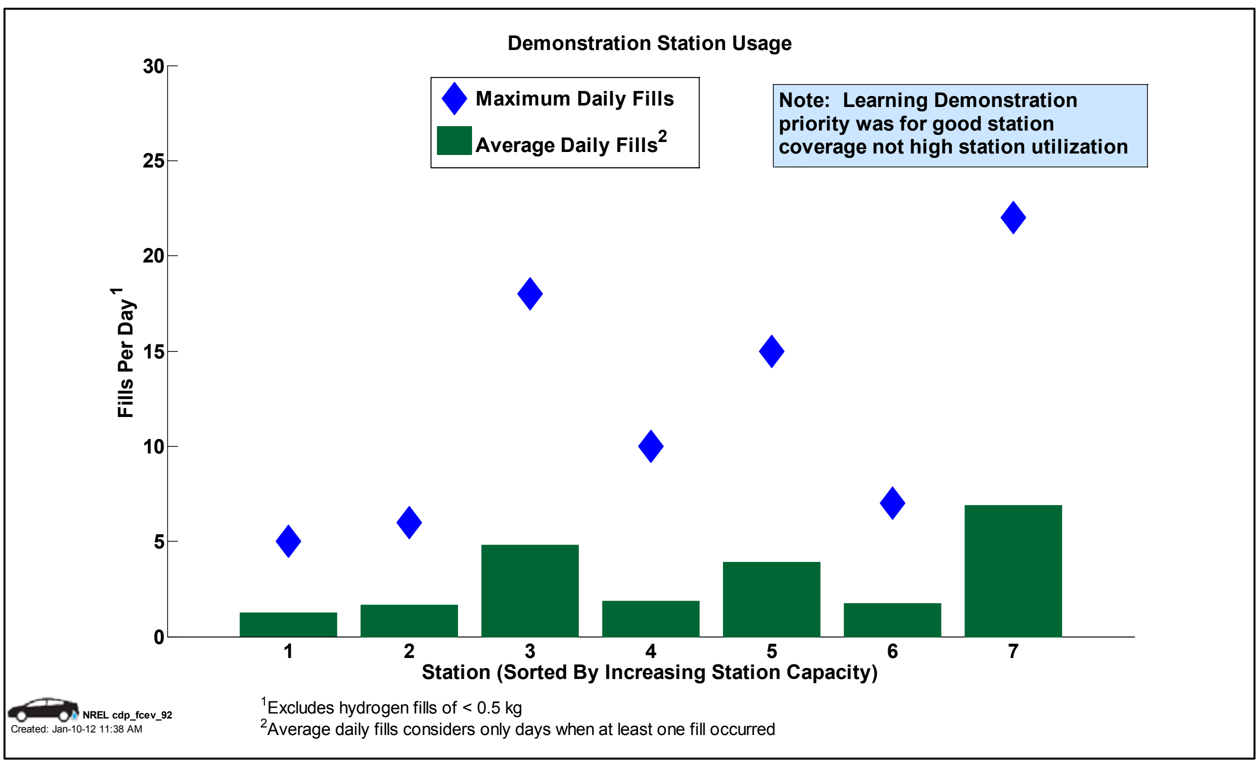



**Figure 124: Demonstration station usage (fills per day) (CDP92)**

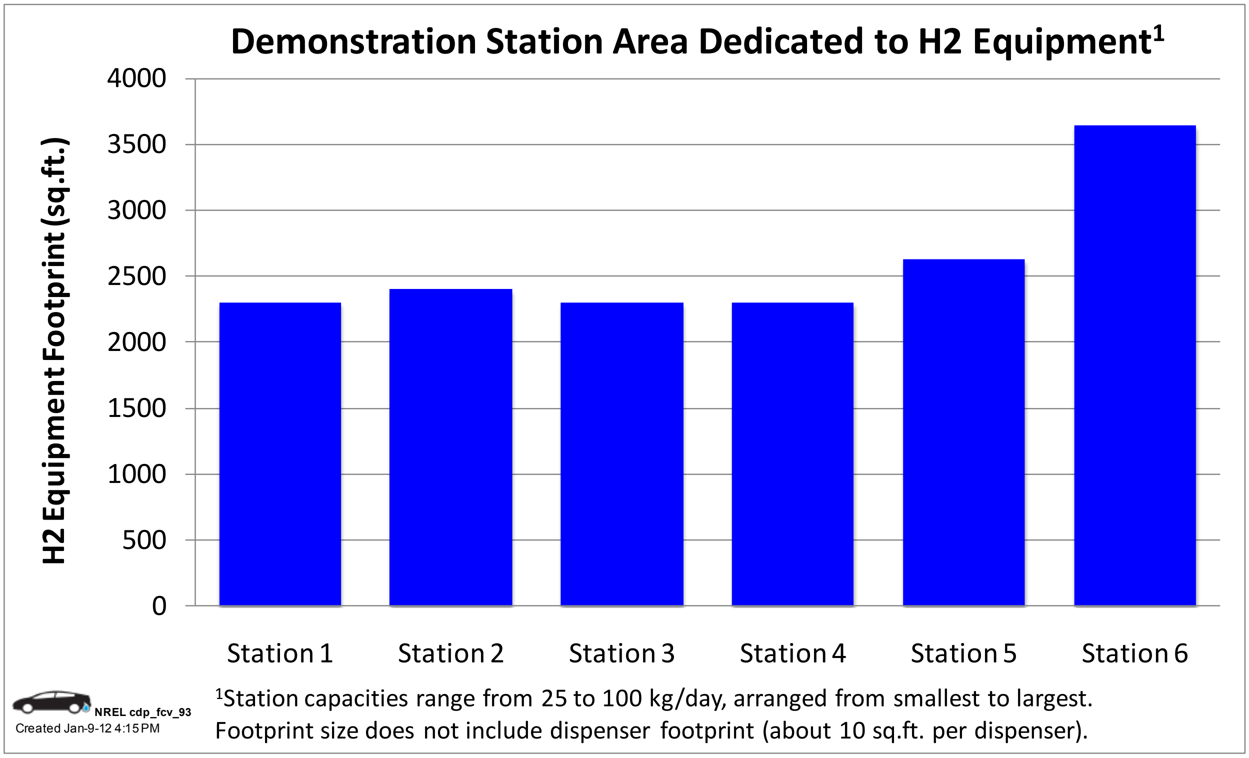



**Figure 125: Demonstration hydrogen station equipment footprint (CDP93)**

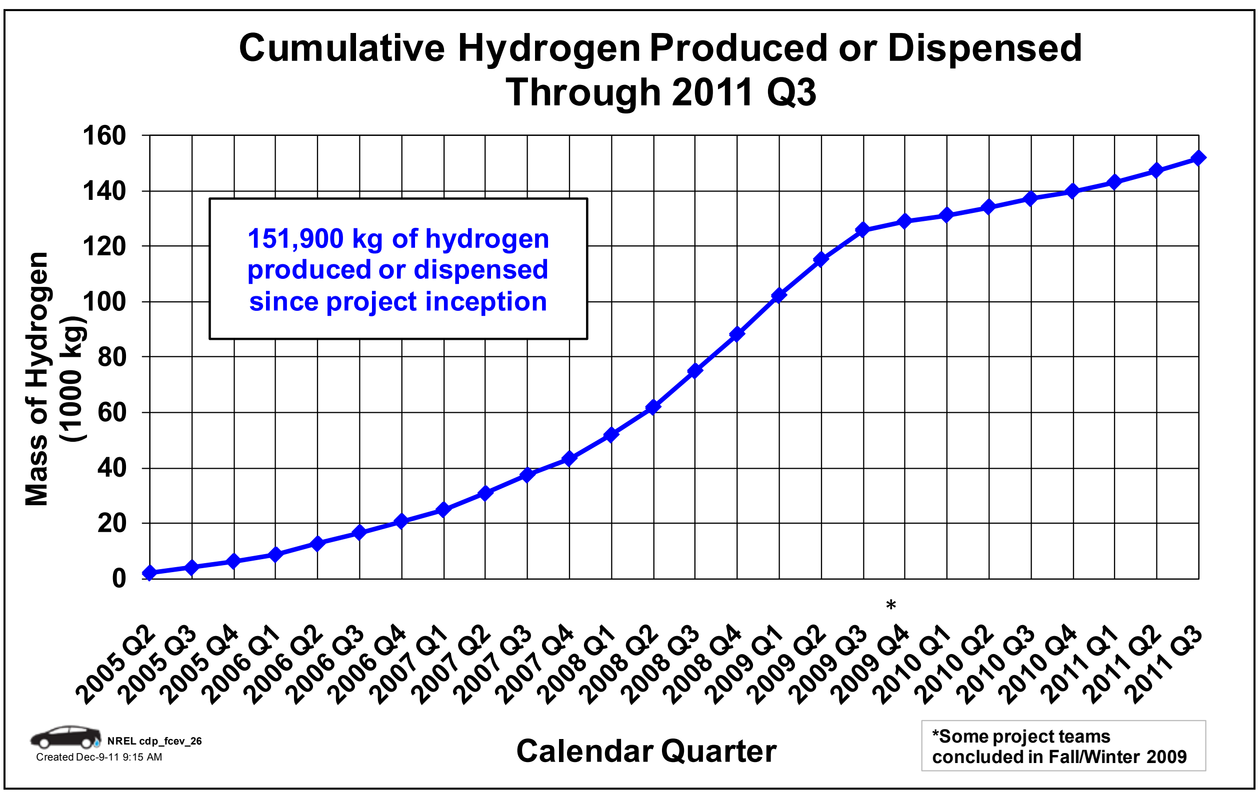



**Figure 126: Cumulative hydrogen produced or dispensed (CDP26)**