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Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Fall 2006 Progress Update

Preprint

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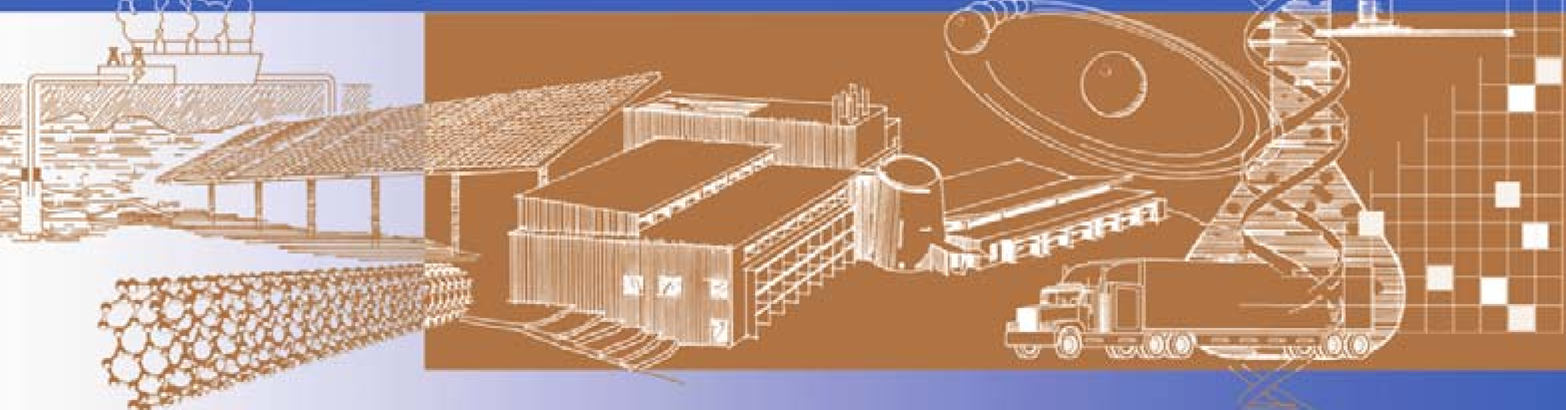

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CONTROLLED HYDROGEN FLEET AND INFRASTRUCTURE DEMONSTRATION AND VALIDATION PROJECT: FALL 2006 PROGRESS UPDATE[1]

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Abstract

The U.S. Department of Energy (DOE) initiated the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project through a competitive solicitation process in 2003. The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. Four industry teams have signed cooperative agreements with DOE and are supporting plans for more than 130 fuel cell vehicles and 20 hydrogen refueling stations over the 5-year project duration. This paper provides a status update covering the progress accomplished by the demonstration and validation project over the last six months; the first composite data products from the project were published in March 2006. The composite data products aggregate individual performance into a range that protects the intellectual property of the companies involved, while publicizing the progress the hydrogen and fuel cell industry is making as a whole relative to the program objectives and timeline. Updates to previously published composite data products, such as on-road fuel economy and vehicle/infrastructure safety, will be presented along with new composite data products, such as fuel cell stack efficiency and refueling behavior. Comparison of progress toward DOE technical targets will be made through these composite data products, and future project activities and analysis will also be discussed.

Keywords: fuel cell vehicles, FC stack, vehicle performance, hydrogen infrastructure, energy efficiency

1 Introduction

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

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Significant resources from private industry and government are being devoted to overcoming these barriers.

DOE is working with industry to develop these technologies through its Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. This multi-faceted program simultaneously addresses hydrogen production, storage, delivery, conversion (fuel cells), technology validation, deployment (education), safety, and codes and standards. Many key technical barriers, such as hydrogen storage and fuel cell durability, have been identified and are being addressed. Additional challenges may become apparent through integrated, real-world application of these technologies. Prior to this project, the number of fuel cell vehicles in service has been small, and vehicle operation has focused primarily in California, limiting the quantity and geographic diversity of data collected. To address vehicle and refueling infrastructure issues simultaneously, DOE is conducting a large-scale "learning demonstration" involving automotive manufacturers and fuel providers. This learning demonstration, titled the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," is Phase 1 of the HFCIT Program's technology validation effort, spanning from 2004-2009.

In April 2003, DOE initiated a competitive solicitation for proposals for this project, and four cooperative agreements between DOE and industry partners were awarded in fiscal year 2004. These four teams will ultimately support more than 130 fuel cell vehicles, which will be validated on-road, as well as about 20 hydrogen refueling stations. Sixty-three first-generation vehicles have already entered into service with customers, and several new hydrogen refueling stations have opened, with more vehicles and stations planned. Estimated government investment in this 5-year project will be about $170 million; with cost-share from industry, total projected expenditures are over $350 million.

2 Project Objectives and Targets

One of the HFCIT Program's key objectives is to conduct parallel learning demonstrations of hydrogen infrastructure and fuel cell vehicles to permit industry to assess progress towards technology readiness. We will accomplish this objective through validating the vehicle and infrastructure as a complete integrated system. The quantity and breadth of data collected and analyzed will enable evaluation of technology status versus DOE program targets, as well as refocusing of DOE-funded research and development as appropriate. The ability to refocus research and development as an integrated part of DOE's program makes this project unique.

Table 1. Project Performance Targets

Key Hydrogen Learning Demonstration Targets		
Performance Measure	**2009***	**2015****
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station (untaxed)	$3/gge	$2-3/gge
* To verify progress toward 2015 targets ** Subsequent projects to validate 2015 target		

This project has specific performance targets for 2009 that will be used to evaluate progress toward the 2015 targets. The targets listed in Table 1 address key barriers to successful market entry. Fuel cell stack durability is critical to customer acceptance of fuel cell vehicles. Although 2,000-hour durability in 2009 is considered acceptable to validate progress, a 5,000-hour lifetime (equivalent to approximately 100,000 miles) is estimated as a requirement for market acceptance. Vehicle range is also an important consumer expectation. Although many factors contributed to the failure of all-electric vehicles to gain market acceptance despite California government mandates, limited vehicle driving range is widely accepted as a significant contributor. Finally, hydrogen production cost is a key metric because consumers are much less likely to purchase an alternative fuel vehicle if the fuel is significantly more expensive than gasoline.

3 Industry Partners

The DOE solicitation required each team to include both an automotive original equipment manufacturer (OEM) and an energy provider, and that the OEM or energy provider be the team lead. Automotive OEMs are leading three of the teams, and an energy provider is the leader of the fourth. Figure 1 shows the teaming arrangement of the four teams along with their fuel cell vehicles. The major companies making up the four teams are as follows:

- Chevron and Hyundia-Kia
- DaimlerChrysler and BP
- Ford Motor Company and BP
- General Motors and Shell

Figure 1. OEM & fuel supplier teams, along with representative vehicles

4 Five Geographic Regions Test Climate Compatibility

Vehicle and infrastructure validation is taking place in five different geographic regions. Operating vehicles in a variety of climates is important because each climate presents a different technical challenge for fuel cells. Cold climates permit evaluation of a fuel cell vehicle's ability to start and operate in sub-freezing temperatures—a key threshold for a fuel cell system that requires humidification and produces water during operation. Hot environments permit evaluation of the system's ability to reject heat while keeping the fuel cell stack membranes adequately humidified. Fuel cell systems operate at lower temperatures than internal combustion engines (ICEs), making heat rejection more challenging and typically requiring a larger coolant radiator. All the regions include moderate conditions during the year, which should permit us to compare performance of a large number of vehicles under similar environmental conditions. Figure 2 shows the project stations (colored symbols) in the context of the other stations already in place (white symbols) in the five geographic regions in which this project is focused.

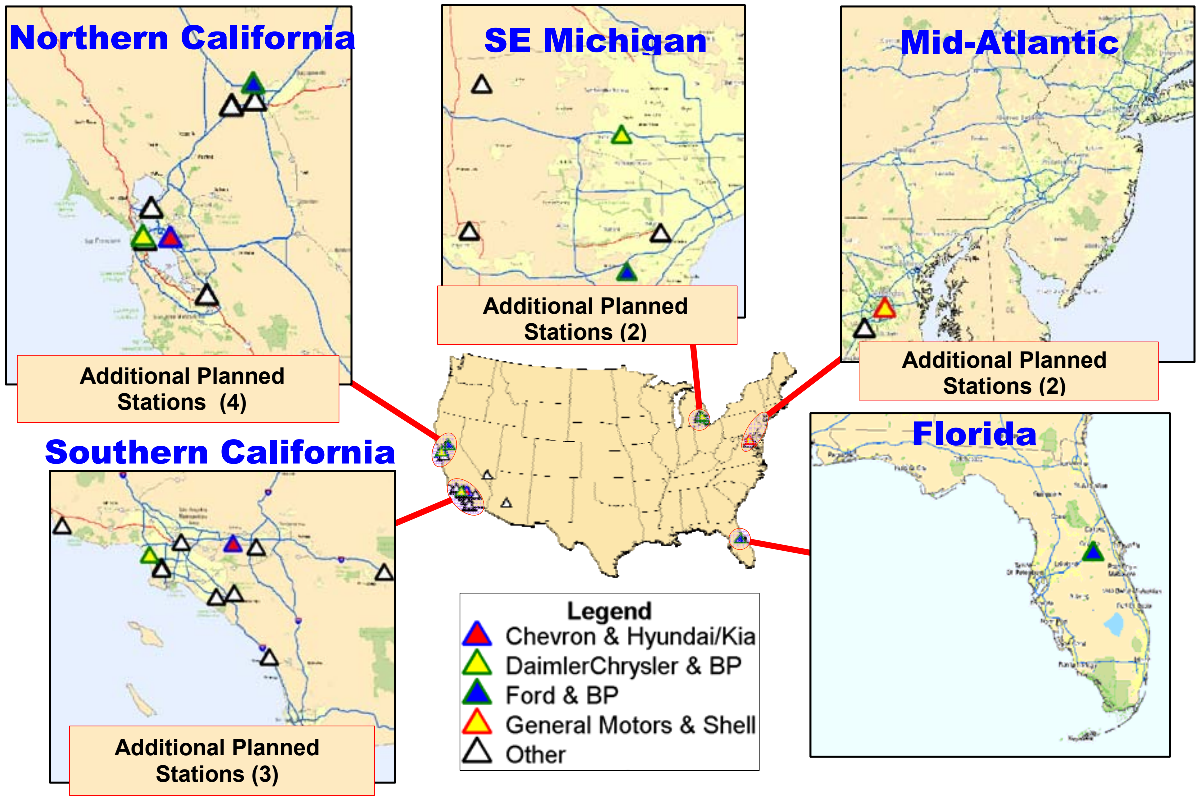

Figure 2. Online H_2 refueling infrastructure in five regions of Learning Demo

5 Analysis Tools and Methodology

5.1 Handling Large Amounts of Protected Data

Because most of the data to be collected are highly confidential and represent the result of several hundred million dollars of development effort from each company, considerable attention is given to data security. Figure 3 provides an overview of the data collection and analysis process for this project. Raw data and reports from partner companies are delivered to the Hydrogen Secure Data Center (HSDC), located at the National Renewable Energy Laboratory (NREL) in Golden, Colorado. Access to the HSDC is strictly controlled and limited to a handful of individuals within NREL and DOE. Detailed analyses and reports are generated within the HSDC, the results of which are available only to the limited number of individuals authorized to enter the HSDC. The only public data products permitted to leave the HSDC are termed “composite data products” and are agreed upon in advance with each partner company. These data products contain no confidential information and display only aggregate data from the partners. For instance, the composite data products will contain ranges of performance values, and the performance of individual companies is not distinguishable. Additional composite data products will be developed, approved for release, and then published as the project progresses. Additionally, detailed data products are created for individual companies so that they can share in the benefits of NREL having performed unique analysis on their data. Meetings have been held with each of the four teams to share these results, and the companies have found these results extremely valuable.

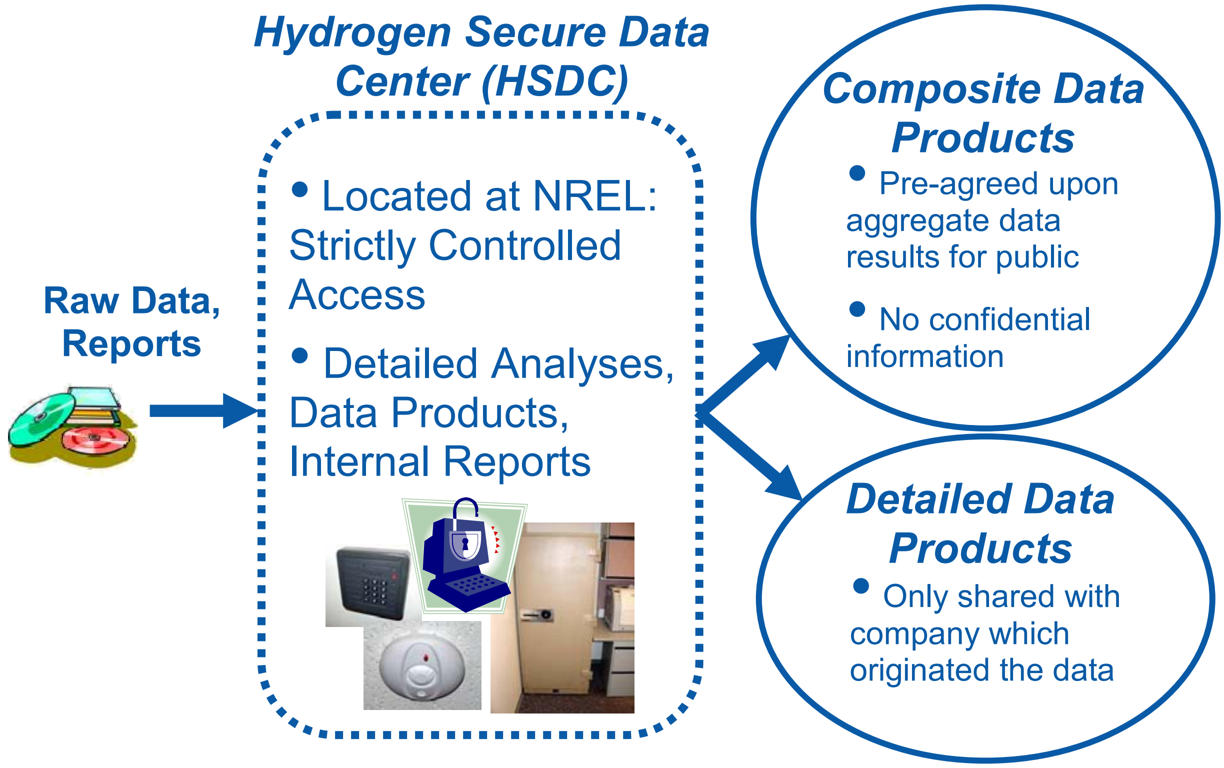

Figure 3. Data collection and analysis process overview

5.2 Advanced Data Analysis Tool Developed for This Project

With 63 fuel cell vehicles currently in the validation fleet, all of which are providing second-by-second data from every single trip, a large quantity of data is quickly being amassed in NREL's HSDC. As shown in Figure 4, the high rate of data accumulation began in the spring of 2005. Through June 2006 the HSDC had received data for over 43,000 individual vehicle trips, adding up to 19 GB of on-road data.

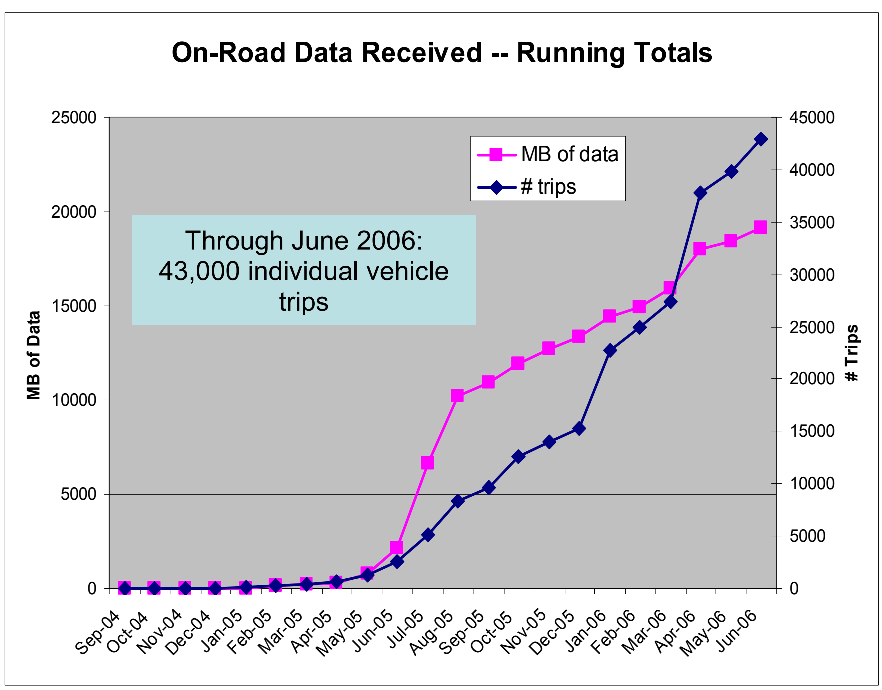

Figure 4. Cumulative number of vehicle trips and size of data received at the HSDC

While the sheer volume of data received may suggest that it couldn't possibly all be analyzed in detail, NREL has created advanced analysis tools to automate the processing of the data and analyze every single trip that each vehicle drives. Figure 5 shows screen images of NREL's analysis tool—the NREL Fleet Analysis Toolkit (NREL FAT). Programmed entirely in MATLAB, this tool automates the analysis of new monthly data through just three mouse-clicks. All of the analysis results can also be viewed as automatically generated figures within the graphical user interface (GUI).

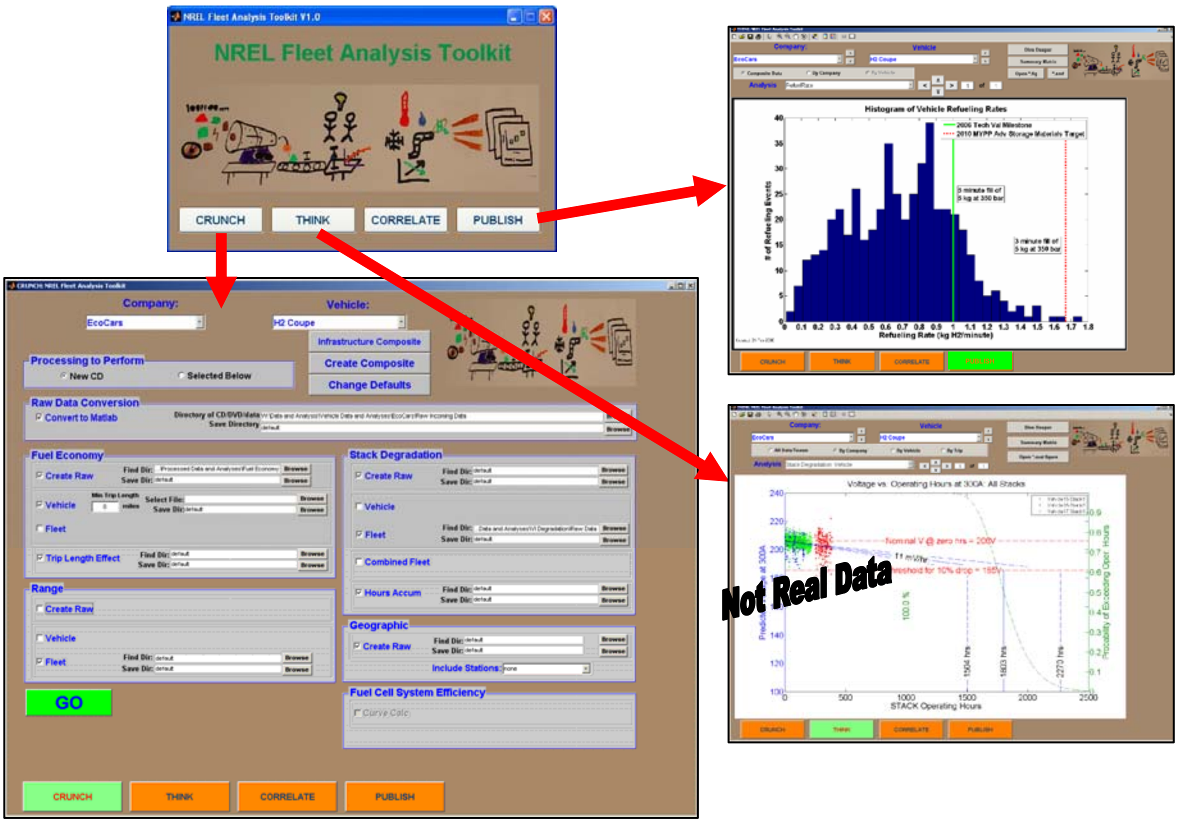

Figure 5. Screen images of NREL's Fleet Analysis Toolkit

6 Vehicle Composite Data Product Results

6.1 Fuel Cell System Efficiency

Along with fuel feedstock diversity and zero tailpipe emissions, high efficiency is one of the key reasons that hydrogen powered fuel cell vehicles are being pursued. DOE has a target of 60% fuel cell system efficiency at ~25% of system net power. The Learning Demonstration project evaluated the efficiency of the fuel cell systems from each of the four teams through controlled steady-state vehicle chassis dynamometer testing. To achieve a sweep of many relatively constant net power output points from the fuel cell system installed in the vehicle, the vehicle was typically driven at a number of steady-state speeds, sometimes with a simulated road grade added to increase the power load for this system.

Hydrogen fuel use was measured from calibrated sensors using several different approved techniques, depending on the particular vehicle and test facility. These methods include integration of the gross fuel cell (FC) electrical current output (adjusted for any purge), measuring on-board tank temperature and pressure, measuring off-board tank temperature and pressure, or measuring hydrogen mass flow directly. The efficiency of the fuel cell system was then calculated as output/input, or "net FC system energy out" over the "lower heating value (LHV) of the input fuel energy." The net power output from the FC system was calculated by taking the gross power output minus the FC system auxiliaries (such as compressors, fans, pumps, etc.) per the draft SAE J2617 test procedure. The range of results is shown in Figure 6. It was found that the efficiency ranged between 52.5% and 58.1%, very close to the DOE target of 60%. It is anticipated that in the second generation FC stacks that will be demonstrated in the second half of this project, the 60% target will be met by one or more of the industry teams. In the future, these controlled dynamometer tests will also be used to look at changes in the performance of FC systems as they age, since the tests are repeated every six months.

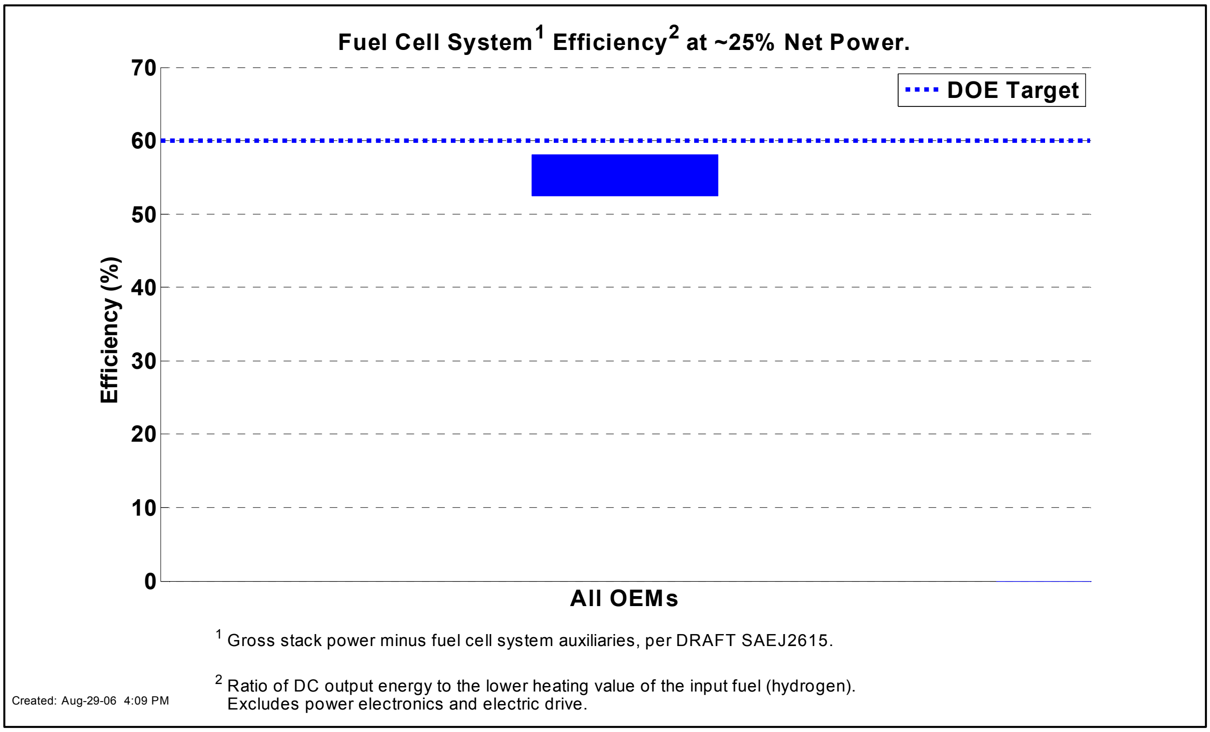

Figure 6. Range of measured fuel cell system efficiency at ~25% net power from all four teams

6.2 Vehicle Fuel Economy and Range

In addition to the steady-state tests on the vehicle chassis dynamometer (dyno) to obtain the fuel cell system efficiency points, city and highway drive cycle tests were performed according to the Draft SAE J2572 procedures for fuel cell vehicles to obtain vehicle fuel economy. Figure 7 shows the results from these tests. The raw dyno results from all four teams are shown on the left, the adjusted “window sticker” fuel economy is shown in the center, and on-road fuel economy is shown on the right. Each range represents one data point per manufacturer, and the on-road results exclude trips <1 mile since the vehicles experienced an unusually high number of short or idle trips during vehicle launch into the fleets. Note that the dyno results are the initial baseline results from spring 2006 [1], while the on-road results have been updated with 6-months more data. The on-road fuel economy ranges from 30.7 miles/kg H_2 to 45.2 miles/kg.

Using the dyno fuel economy and the amount of usable hydrogen on-board each vehicle, the theoretical maximum range of each vehicle can be calculated. This spread of ranges from the four teams is shown in Figure 8. For conventional vehicles, most consumers are not familiar with raw dyno test results. Instead, they are familiar with the adjusted “window sticker” fuel economy they see when they buy their vehicles, and even more familiar with their actual on-road fuel economy since many vehicles now track it electronically and display that information to the driver. Therefore, to show this real-world impact of on-road fuel economy on driving range, we took the ratio of the window-sticker fuel economy to the dyno fuel economy, and the ratio of on-road fuel economy to dyno fuel economy, which also provides the ratio of the driving range for each team.

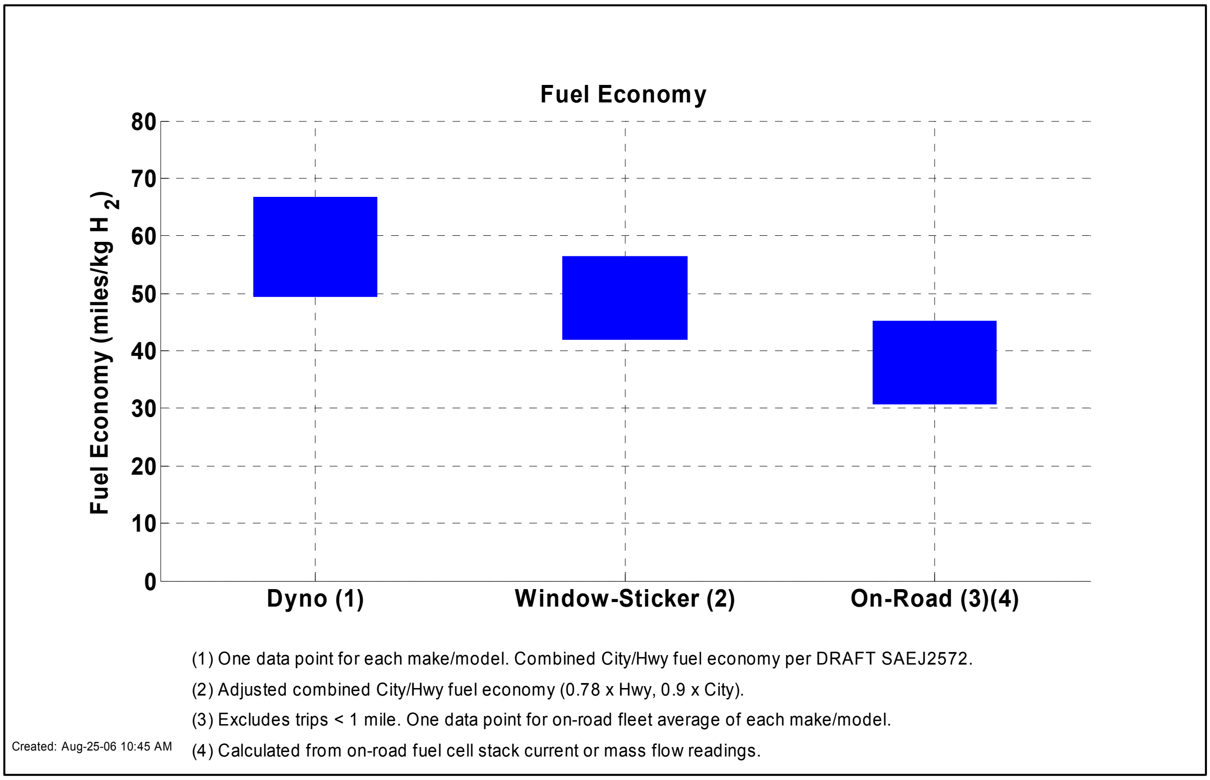

Figure 7. On-road and dyno fuel economy from all four teams

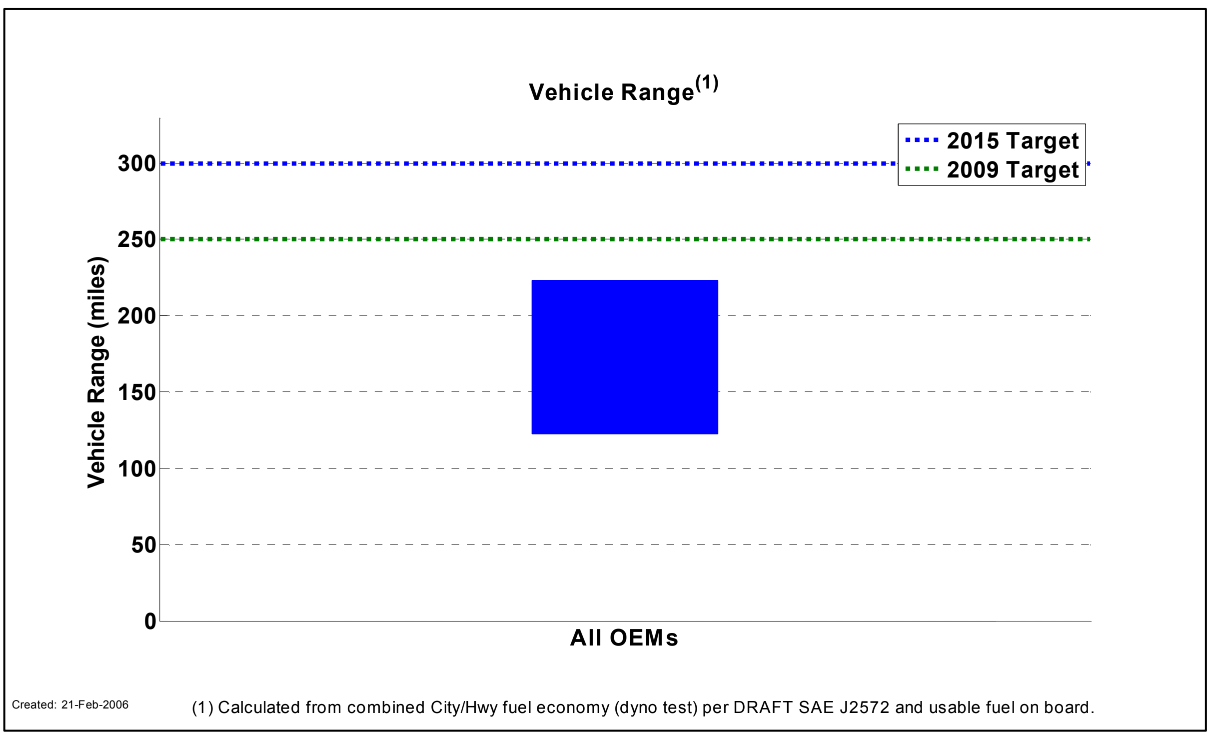

Figure 8. Vehicle range calculated from dyno fuel economy and usable hydrogen

Figure 9 shows the spread of these vehicle range ratios, showing that, from this Learning Demonstration so far, the average fleet on-road driving ranges (if all usable on-board fuel was consumed) varied between around 63% - 75% of the theoretical dyno range. This result is significant because it helps explain (in part) why the vehicles are being refueled after driving relatively short distances as compared to their theoretical dyno range.

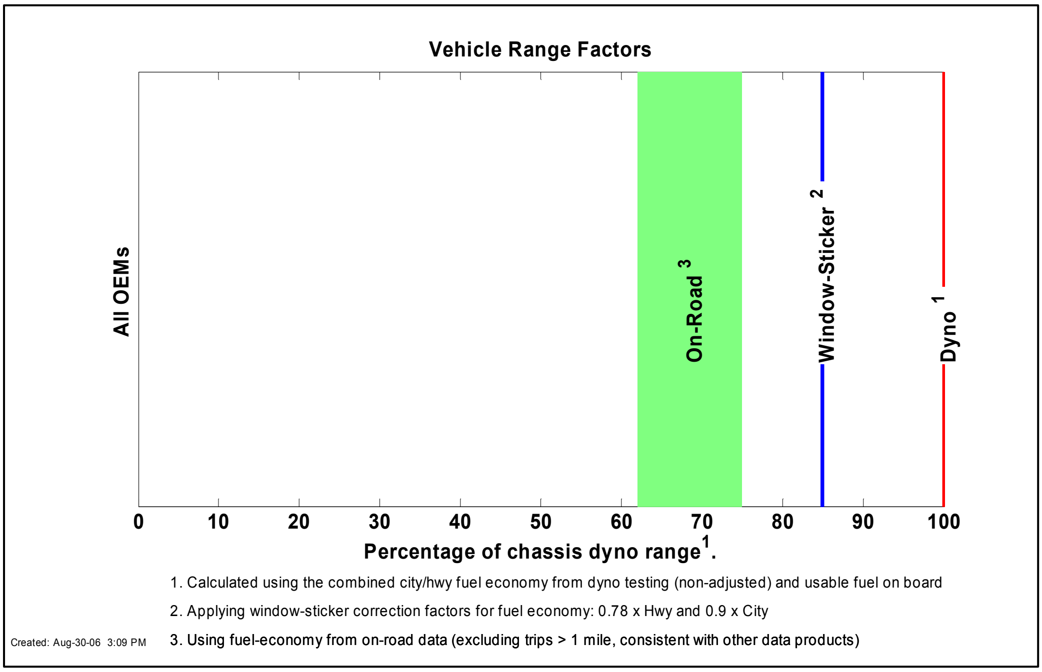

Figure 9. Reduced effective range of vehicles due to actual on-road fuel economy

Figure 10 shows a normalized histogram (blue bars) of how far (as a percentage of dyno range) vehicles were driven before being refueled. The dashed green curve is the cumulative percentage of refuelings that were performed below a given percentage of dyno range. This result indicates that roughly 50% of the refuelings were done at <35% of the dyno range and 95% of the refuelings were done at <65% of the dyno range. So while reduced on-road fuel economy explains some of the short distance between refuelings, it cannot account for most of them. The two main reasons suspected for this reduced effective driving range are: limited hydrogen infrastructure and lack of comfort of the drivers draining their fuel to "empty" with this limited infrastructure. Future analyses will further explore this dynamic between infrastructure coverage, range, and driving patterns.

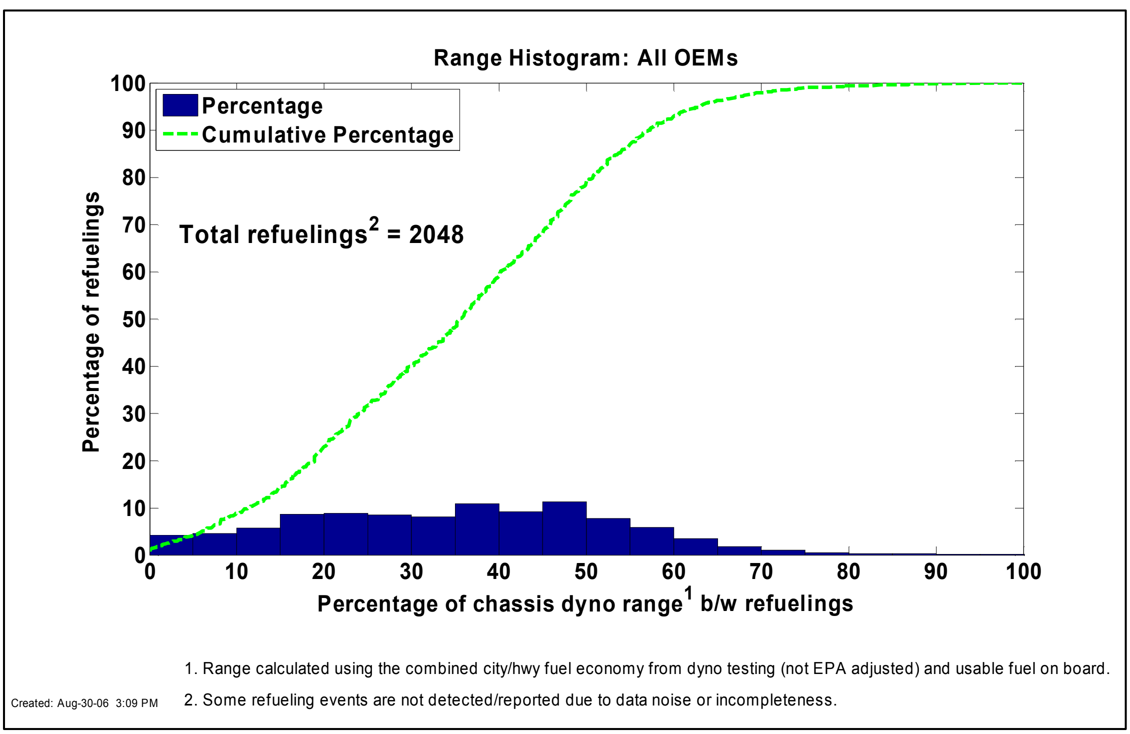

Figure 10. A large percentage of vehicle refueling is being performed at a significantly

6.3 Overall Progress in Vehicle Rollout

Data has been flowing to NREL's HSDC room for five quarters. As seen in Figure 11, the 63 vehicles currently deployed represent roughly half of the total vehicles that will be validated from this project. The majority of these vehicles are using 350 bar pressurized hydrogen tanks.

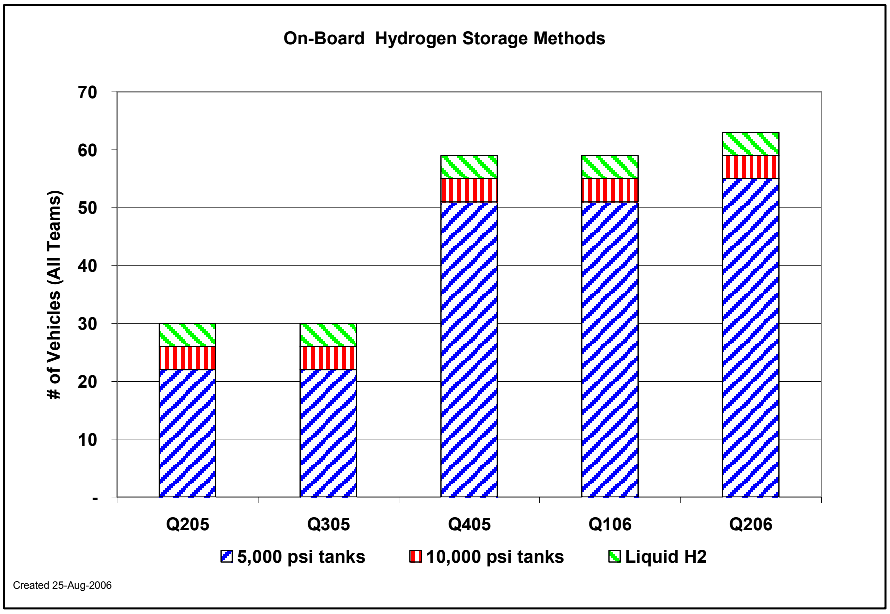

Figure 11. Number of vehicles by quarter using various on-board storage technologies

Additionally, from Figure 12 it can be seen that the majority of the vehicles have accumulated between 100-300 hours of operation and 3000-7500 miles. The rate of vehicle usage continues to increase, making the data set much deeper and allowing additional analyses to be performed.

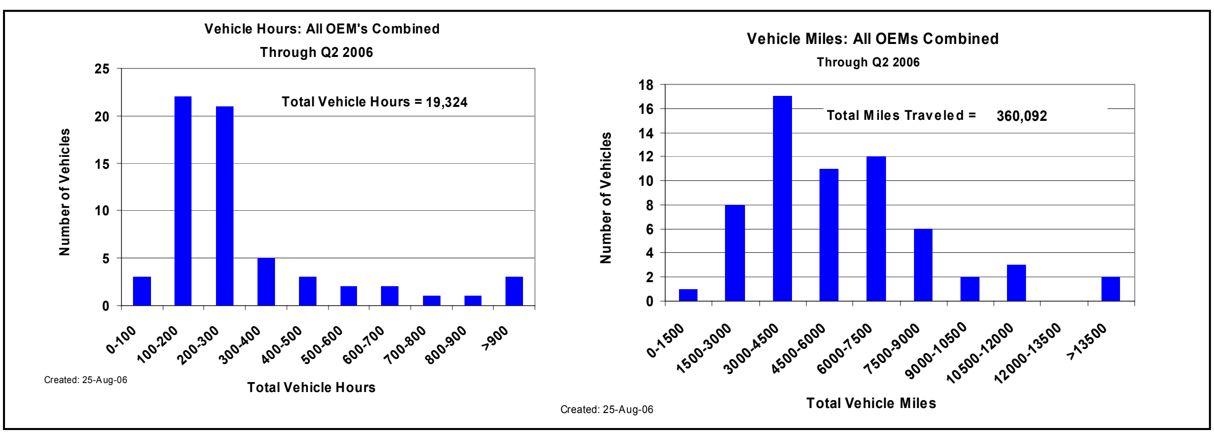

Figure 12. Histograms of operating hours and miles traveled

6.4 Vehicle Safety Incidents

Safety is an important part of this project—not only to protect human safety today, but also to learn important lessons about how to make and operate safe vehicles and infrastructure before they are rolled out to the public in a larger scale in the future. All safety incidents, near-misses, and non-events are reported to the HSDC and then combined into a chart (Figure 13) that shows the number of events by quarter. While there were only three reported events in the first three quarters, there were six minor hydrogen leaks reported in the first quarter of 2006. The root of these minor problems has been identified and fixed; no safety events were reported in the following quarter. The Learning Demonstration is living up to its name by providing an opportunity to identify any problems in a controlled environment, learn from them, and produce safer vehicles, refueling procedures, and equipment for the future.

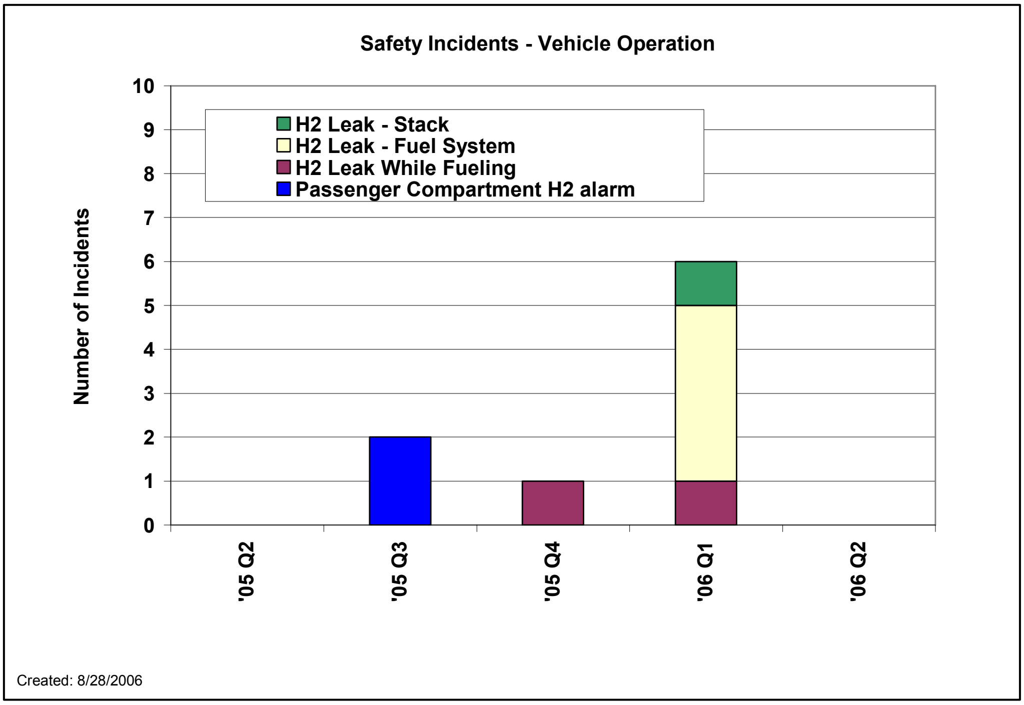

Figure 13. Number of vehicle safety events by quarter

6.5 Hydrogen Refueling Rate Histograms

Valuable data are gathered on the interaction between the vehicles and the hydrogen infrastructure. The data are reported to the HSDC on every single refueling event, either from the refueling station data or from on-board vehicle data. DOE has a 2006 target of a five-minute fill of 5 kg at 350 bar, which results in an effective target of 1 kg/min. Future targets, focused on advanced storage materials, seek a 1.67 kg/min rate in 2010. Based on over 2000 refueling events analyzed, shown in Figure 14, the average refueling rate observed was 0.69 kg/min, with a median of 0.72 kg/min. 18% of the refueling events exceeded the DOE target of 1 kg/min.

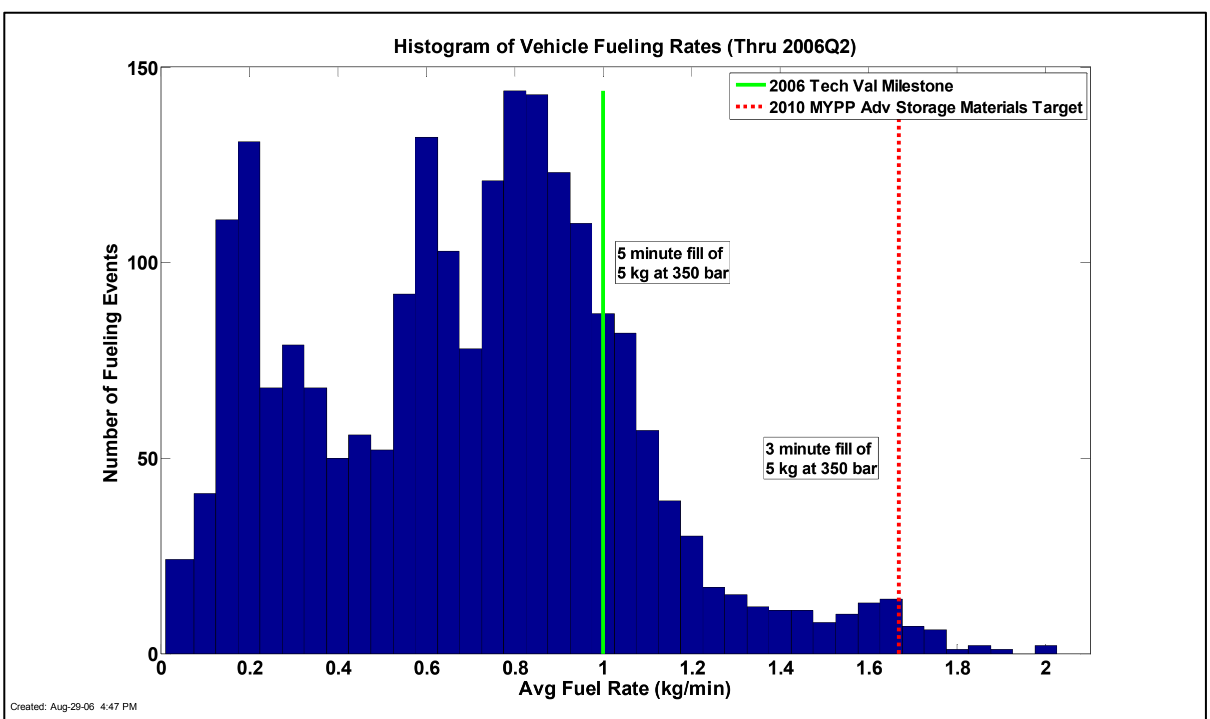

Figure 14. Vehicle refueling rate histogram

Notice that the distribution appears to be tri-modal, with peaks occurring at 0.2 kg/min, 0.6 kg/min, and 0.85 kg/min. This is due to a mixture of different types of stations (mobile vs. permanent) and communication and non-communication fills. It also includes some stations that have refueling protocols that impose limits on the refueling rate.

7 Conclusions

The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project has now completed five quarters of operation with the data being delivered to NREL's Hydrogen Secure Data Center for analysis. This includes 63 vehicles and 9 project stations. Aggregate results, called composite data products, have been developed to report on project progress. On fuel cell system efficiency, the four teams ranged from 52.5% to 58.1% efficiency, very close to DOE's target of 60%. On the metric of vehicle driving range, current storage technologies only allow between 122 and 223 miles for these four vehicles, but actual on-road driving range between refuelings is found to be shorter than the theoretical range due to lower on-road fuel economy, limited infrastructure, and driver comfort with running out of fuel. There is a wide distribution of refueling rates, but 18% of the refueling events demonstrated a refueling rate higher than DOE's 1 kg/min target in 2006. Fuel cell stack durability will be one of the next composite data products created in 2006, with a comparison made to DOE's 2006 target of 1000 hours.

References

[1] Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., Hooker, D., "Hydrogen Fleet & Infrastructure Demonstration and Validation Project: Progress Update," NHA Annual Hydrogen Meeting and Exposition, Long Beach, CA, March 2006.

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Mr. Wipke has worked at NREL in the area of advanced vehicles for 13 years. The first decade of that time was spent researching hybrid electric vehicles through on-road data collection, analysis, and computer modeling using ADVISOR, NREL's advanced vehicle simulator. In 2003, ADVISOR was licensed to AVL for commercialization and Mr. Wipke moved to the hydrogen group at NREL to work on the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project and lead the Hydrogen Technology Validation Team. He holds a masters degree in mechanical engineering from Stanford University.

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