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Fuel Cell Vehicle Learning Demonstration: Spring 2008 Results

Preprint

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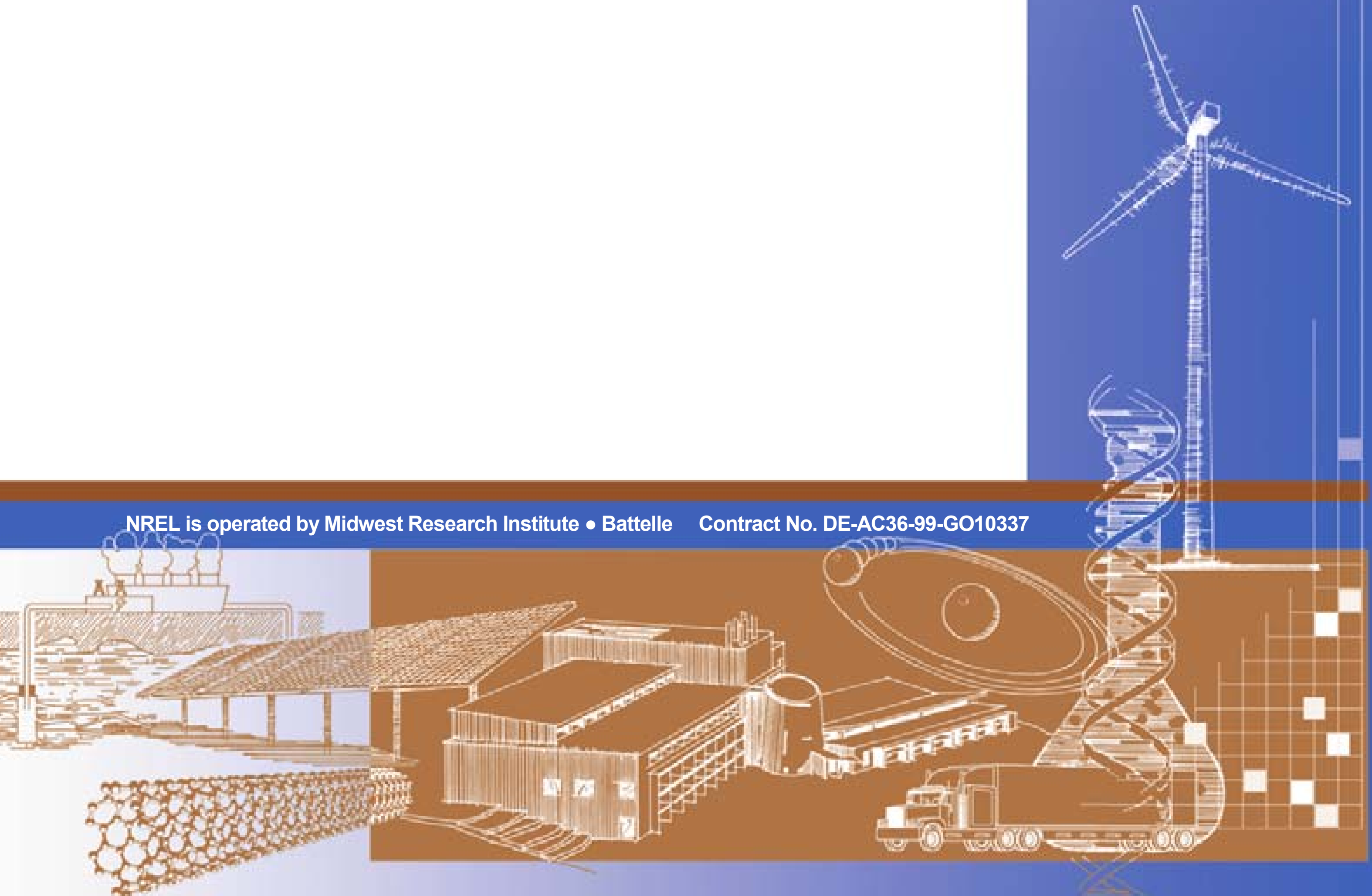
Presented at the NHA Annual Hydrogen Conference 2008
Sacramento, California
March 30–April 3, 2008

Conference Paper
NREL/CP-560-43055
April 2008



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FUEL CELL VEHICLE LEARNING DEMONSTRATION: SPRING 2008 RESULTS[1]

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Abstract

The "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," also known as the Fuel Cell Vehicle and Infrastructure Learning Demonstration, is a five-year U.S. Department of Energy (DOE) project started in 2004. The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. The DOE's National Renewable Energy Laboratory (NREL) has now analyzed data from almost three years of the five-year project. During this time, 92 vehicles have been deployed, 14 project refueling stations were placed in use, and no fundamental safety issues have been identified. We've analyzed data from over 200,000 individual vehicle trips covering 1,100,000 miles traveled and over 40,000 kg hydrogen produced or dispensed.

Public analytical results for this project are in the form of composite data products, which aggregate individual performance into a range that protects the intellectual property and the identity of each company, while still publishing overall status and progress. One of the key metrics from the project is fuel cell durability. We analyze all of the field data from the fuel cell vehicles, and make degradation projections based on a theoretical 10% drop in voltage at high current. With additional hours of operation accumulated on the stacks, the four-team average projection is now 1,200 hours with some individual stacks accumulating more than 1,000 hours. In the next six months we will work to improve the accuracy of the voltage degradation projections by adding a non-linear fit (or a two-step linear fit) to avoid potentially overestimating the projected time that could occur as the accumulated hours continues to grow.

To understand what is causing the stacks to gradually degrade, NREL continues to characterize how each stack is used and performs multivariate analysis on this dataset to examine dominant variables affecting stack voltage degradation rate. Results to date indicate that extracting trends across all four teams is probably not possible due to technical differences among the teams' hardware, but that

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individual results should be useful to the teams individually and for feeding back trends into the research and development program.

We’ve analyzed fuel cell system efficiency at ¼-power and compared it to the DOE target of 60%; system efficiency results from the four teams ranged from 52.5% to 58.1%. Using data on communication vs. non-communication fills we found that communication fills demonstrated a higher rate of fill than non-communication fills and the slowest of the non-communication fill rates (0.2 kg/min) are being phased out. We also examined refueling and driving behavior, and found the Learning Demonstration fleet to be representative of national statistics with the exception of fewer late afternoon and weekend trips, an abundance of short trips, and a shorter average distance traveled per day. Finally, we’ve now published a total of 47 composite data products and made them directly accessible to the public from our Hydrogen Technology Validation Web site.

Keywords: fuel cell vehicle, stack voltage degradation, hydrogen infrastructure, analysis, refueling.

1. Introduction

Hydrogen fuel cell vehicles (FCVs) are being developed and tested for their potential as commercially viable and highly efficient zero-tailpipe-emission vehicles. Using hydrogen fuel and high-efficiency fuel cell vehicles provides environmental and fuel feedstock diversity benefits to the United States. Hydrogen 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. Significant resources from private industry and government are being devoted to overcoming these barriers.

The U.S. Department of Energy (DOE) is working with industry partners 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), market transformation, safety, and codes and standards. DOE has previously identified many key technical barriers, such as hydrogen storage and fuel cell durability. These barriers are being addressed through additional research. Other challenges may become apparent through integrated, real-world application of these technologies. Prior to this project, the number FCVs in service was small, and vehicle operation was focused primarily in California. The result was limited quantity and geographic diversity of the 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 a cornerstone of the HFCIT Program's technology validation effort, spanning from 2004 to 2009.

2. Project Objectives and Targets

This project's objective is to conduct parallel learning demonstrations of hydrogen infrastructure and FCVs to allow the government and industry to assess progress towards technology readiness. We are identifying the current status of the technology and tracking its evolution over the five-year project duration. In particular, we are tracking differences between the first- and second-generation FCVs. The DOE's National Renewable Energy Laboratory (NREL) works to provide DOE and industry with maximum value from the data produced by this "learning demonstration." We seek to understand the progress toward the technical targets and provide that information to the HFCIT research and development (R&D) activities. This information will allow the program to move more quickly toward cost-effective, reliable hydrogen FCVs and supporting refueling infrastructure. The ability to feed results back into to the research and development as an integrated part of DOE's program makes this project unique compared to typical demonstration projects.

Fuel cell stack durability is critical to customer acceptance of fuel cell vehicles, and will be discussed in this paper. 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 to be a requirement for market acceptance. Vehicle range is also an important consumer expectation. Although many factors contributed to the failure of battery-electric vehicles to gain market acceptance despite California government mandates, limited vehicle driving range and long charging times were widely accepted as significant contributors. 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. Auto Industry and Refueling Infrastructure Partners

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

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

Figure 1 shows the teaming arrangement of the four teams along with their first-generation fuel cell vehicles. In addition to data from the four Learning Demonstration teams, data from another DOE project called the California Hydrogen Infrastructure Project (CHIP) is also analyzed and included in the infrastructure results to further broaden the available data set. Figure 2 shows examples of the four types of hydrogen refueling stations analyzed at NREL.

Figure 1: Photographs of the Four Teams' First-Generation Vehicles with Small Inset Photos Showing the Second-Generation Vehicles

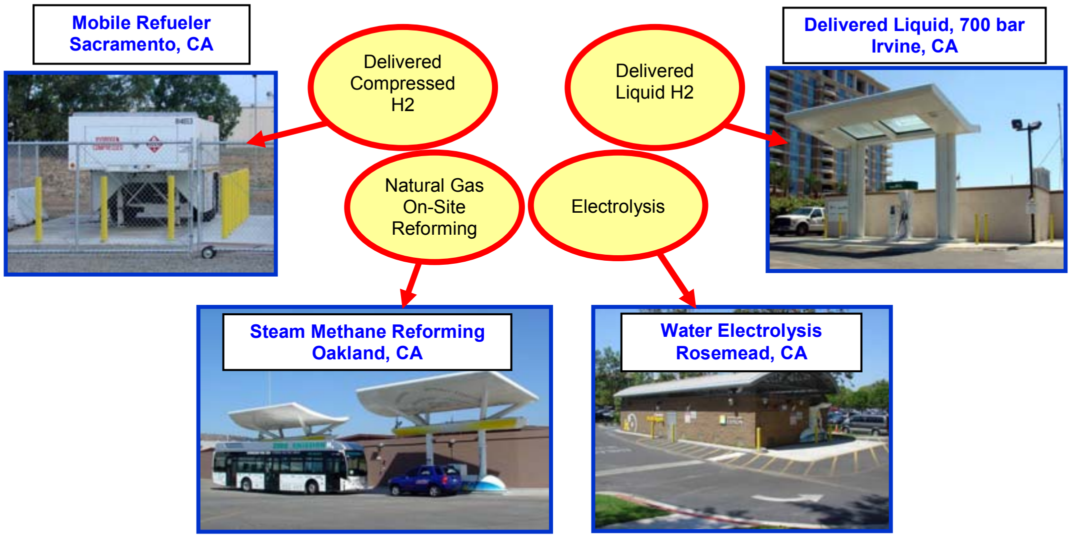


Figure 2: Four Examples of Hydrogen Production and Refueling Facilities

4. Data Analysis Approach and Tools

NREL's approach to accomplishing the Learning Demonstrations' objectives is structured around a highly collaborative relationship with each of the four industry teams. We are receiving raw technical data on both the hydrogen vehicles and refueling infrastructure that allows us to perform unique and valuable analyses across all four teams. Our primary objectives are to feed the current technical challenges and opportunities back into the HFCIT R&D Program and assess the current status and progress toward targets.

To protect the commercial value of these data for each company, we established the Hydrogen Secure Data Center (HSDC) to house the data and perform our analyses. To ensure value is fed back to the hydrogen community, we publish composite data products (CDPs) twice a year at technical conferences and in journals [1-2]. These data products report on the progress of the technology and the project, focusing on the most significant results. Additional CDPs are conceived as additional trends and results of interest are identified. We also provide detailed analytical results from each individual company's data back to them to maximize the industry benefit from NREL's analysis work and obtain feedback on our methodologies. These individual results are not made available to the public.

To process such a large data set (second-by-second data from over 200,000 vehicle trips), we have created a specialized analysis tool at NREL called the Fleet Analysis Tool (FAT). This tool enables us to convert the data into a common format, perform all of the predefined analyses, and then study the results graphically. The tool is unique in that it lets us quickly compare data from within a team (stack to stack) or between teams. It also is the mechanism by which we create our CDPs, which pull individual results from each team into aggregate results.

5. Composite Data Products – Public Results

The most recent set of CDPs is called the "Spring 2008" results, and includes a total of 47 results. Due to the large number of results now available from this project, not all of them can be discussed in conference papers or presentations. Therefore, we discuss all of the results in detail in semi-annual NREL technical publications called Progress Reports. This paper will cover some highlights from the recent results. An expanded version of these results can be found in the Spring 2008 Progress Report, which is available on our Web site (www.nrel.gov/hydrogen/proj_learning_demo.html).

5.1 Fuel Cell Operation and Impact on Efficiency

Results published from this project in 2006 showed that the range of fuel cell net system efficiency at ¼ power from the four Learning Demonstration teams ranged from 52.5% to 58.1%, which is very close to DOE's target of 60%. Recent analysis has focused on examining the regions of most frequent operation and their overall impact on energy usage. Since a fuel cell system's peak efficiency is normally at low powers (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. As reported in the last progress report, a significant amount of time is being spent at low fuel cell system power. In fact, the teams' average amount of time spent at <5% of peak power was over 50%. However, for overall vehicle fuel efficiency, the amount of energy spent at various power levels and the efficiency at those power levels is the critical metric. We found that much of the fuel cell energy (about 40%) is expended at fuel cell power levels between 20% and 50% of peak power (Figure 3). This matches up very well with the peak fuel cell system efficiency points (at ~25% power) previously discussed. Only about 20% of the energy is expended at powers <15% of peak power, indicating that low power efficiency is not as important as the percentage of time spent there would imply.

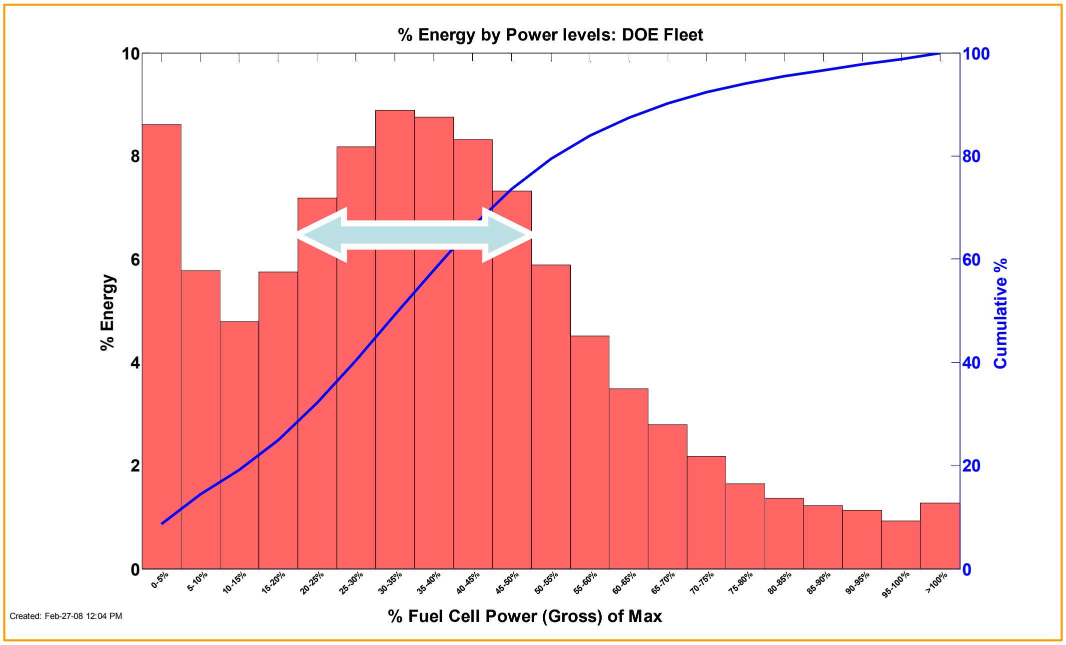


Figure 3: Fuel Cell System Energy within Power Levels

5.2 The Impact of Short Trips

Recently there has been much public attention on the potential for plug-in hybrid-electric vehicles (PHEVs) to improve the United States' oil-dependency situation without waiting for fuel cell vehicles to be commercialized. The Learning Demonstration vehicle data were evaluated to see how these early fuel cell vehicles were being used (mostly in fleet operation) and what impact these real duty cycles would have on plug-in vehicles and potentially future plug-in versions of these fuel cell vehicles. We first looked at the amount of energy consumed by all Learning Demonstration vehicle trips (Figure 4) and found that almost 40% of the trips required less than 0.5 kWh of energy to be produced by the fuel cell system. This indicates that a battery would not have to be very large to handle several plug-in FCV trips for the Learning Demonstration vehicles, provided that 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 PHEVs will primarily be recharged slowly during off-peak/night times, then these data need to be analyzed with both the daily miles traveled and the amount of time between trips in mind.

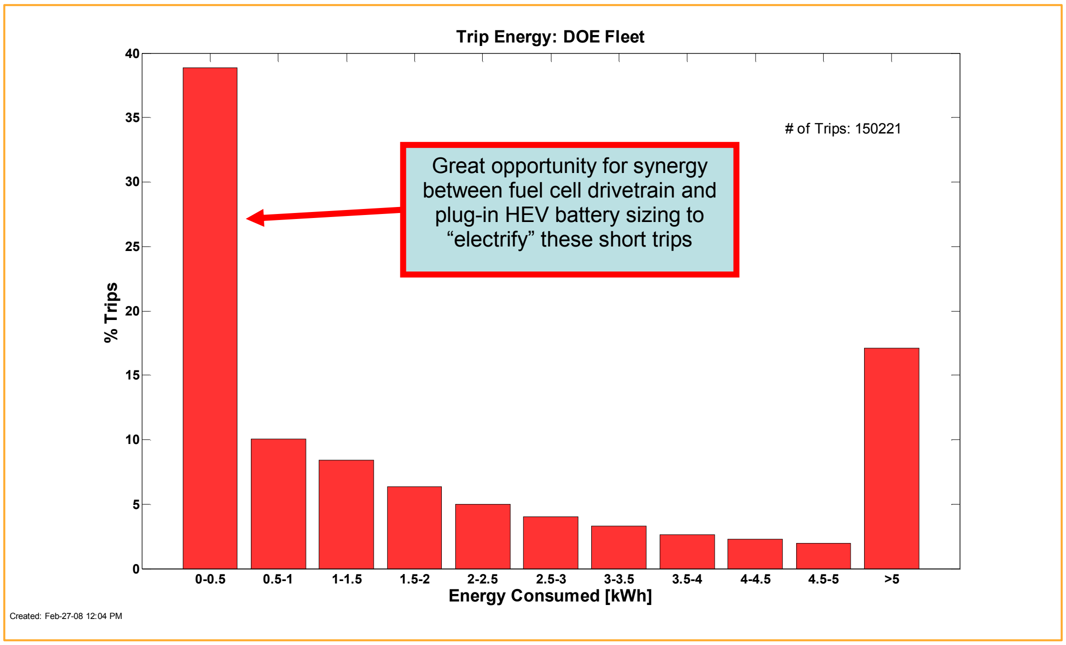
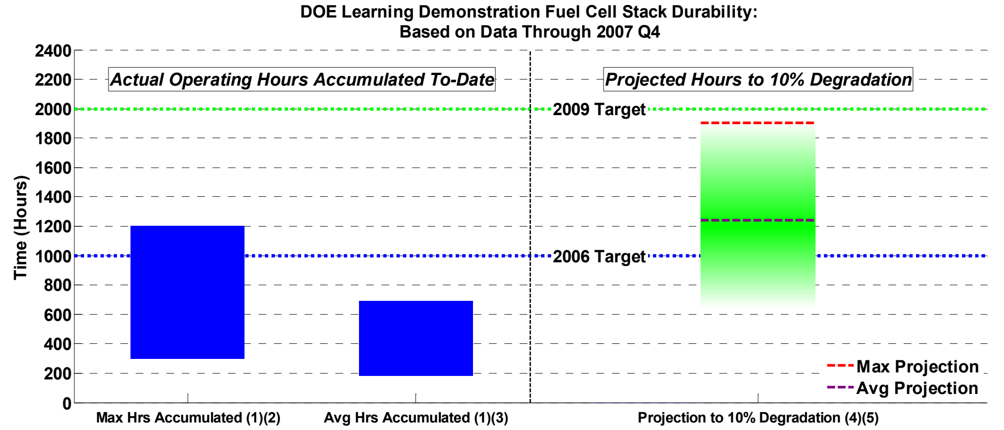


Figure 4: Histogram of Fuel Cell System Output Energy

We also performed these additional analyses and found that an effective 20-mile electric range would electrify about ½ of the Learning Demonstration fleet's daily miles traveled. However, this would satisfy only about ¼ of the national daily average miles traveled. We also found a large number of Learning Demonstration vehicle "hot-starts," with about 60% of trips occurring within one hour of the previous trip. While this could be beneficial for fuel efficiency, it could also indicate that not all of the short trips could necessarily be electrified because there may not be sufficient time to recharge the battery from the grid in between trips, even if day-time opportunity charging is used. The bottom-line is that a thorough analysis of actual vehicle target-market duty cycles must occur for the benefits of PHEVs to be understood, preferably through using actual PHEV fleets and recharging behavior. Such an evaluation is envisioned through DOE's current solicitation for a PHEV Learning Demonstration (see DOE's Web site for details: http://www.netl.doe.gov/business/solicitations/#00360).

5.3 Fuel Cell Voltage Degradation and Influencing Factors

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



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

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Figure 5: Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation

In the past year and a half, many more hours have been accumulated on the fuel cell stacks, and the range of fleet averages is ~200 to 700 hours, with the range of fleet maximums spanning ~300 to 1,200 hours (Figure 5). This is the first time, to our knowledge, that light-duty passenger fuel cell cars have publicly accumulated more than 1,000 hours in real-world operation without repair, which is a significant project accomplishment. Therefore, the amount of extrapolation we have to make using the slope of the linear voltage degradation method (10% voltage drop target divided by the mV/hour slope), continues to decrease. However, with the additional data we have received, we are also finding that the accuracy of our projection of the 10% voltage degradation time might be improved by using a non-linear fit to account for the more rapid degradation that occurs within the first few hundred hours. It appears as though the current linear fit may be overestimating the time to a 10% voltage drop for the stacks that have a significant number of accumulated hours because the effect of the first data points on the linear fit becomes smaller (less weight) as more data is added. This causes the beginning of life voltage from the fit (from which the 10% drop is calculated) to be lower than it was when we had just a few hundred hours of data. Therefore, NREL will experiment with alternate degradation fits to make the projected time to 10% degradation as accurate as possible.

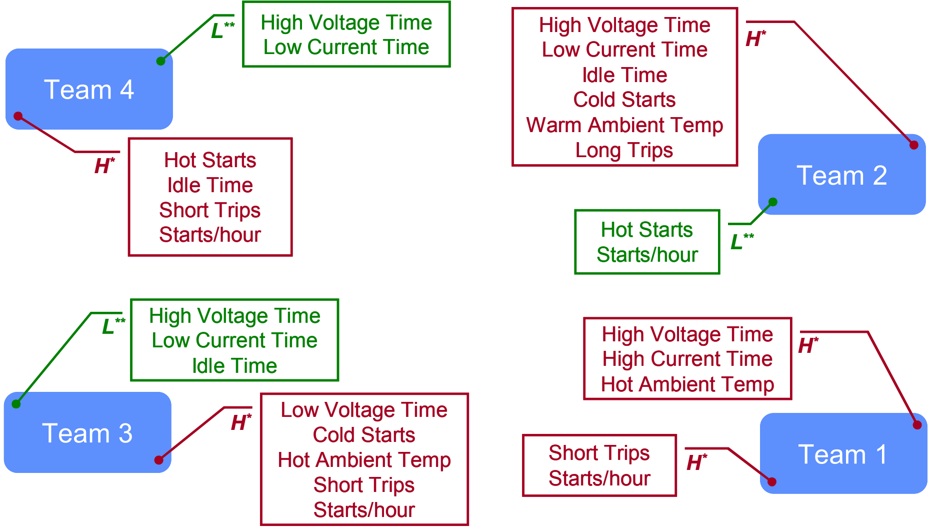
The projected time to 10% fuel cell stack voltage degradation from the four teams using the linear technique had an average of more than 1,200 hours with a high projection of more than 1,900 hours from one team, surpassing the 1,000-hour DOE target. Note that the 10% criterion, which is used for assessing progress toward DOE targets, may differ from the OEM's end-of-life criterion and does not address "catastrophic" failures such as membrane failure. The second-generation stacks introduced in this project in 2008 will be compared to the 2,000-hour target for 2009.

We have continued the multivariate analysis that was initiated 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 now includes the following key factors for each stack:

- Average 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 regression (PLS) 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 on the stack data from all four teams to see if there were any overall trends that covered all of the technology involved. 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 6). 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 at this point the models are not very robust and results are scattered. We found that while there were some common factors among several team's results, there were also normally contradictory trends from one or more of the teams (an example of this conflicting trend is for high voltage time and low current time for team four vs. team two). This analysis effort is continuing in close collaboration with each of our industry partners. NREL will work closely with each team to carefully examine the inputs and outputs from this analysis and identify trends that can be fed back into the companies' research as well as into DOE's R&D program.



1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team.
2) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks

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Figure 6: Primary Factors Affecting Learning Demonstration Team Fuel Cell Degradation

5.4 Status of On-Board Hydrogen Storage Technology

Additional hydrogen storage data have recently been reported to NREL using a more detailed hydrogen storage system breakdown spreadsheet. This spreadsheet included the breakdown of the mass and volume due to the hydrogen itself, the pressure vessel, and the balance-of-plant. The hydrogen storage balance-of-plant category includes:

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

While early published results for this project only included first-generation vehicle data (and included a mix of 350 bar, 700 bar, and liquid hydrogen storage systems, the spring 2008 detailed data were supplied for both first- and second-generation hydrogen storage systems. We compared the difference in the ranges of mass stored in the teams' 350 bar and 700 bar systems as shown in Figure 7, and found the best 700 bar Learning Demonstration weight percentage improves from just under 4% to just under 4.5% (the DOE 2007 target for advanced materials-based storage technologies is 4.5%). It is important to recognize that the second-generation (700 bar) systems also typically have the benefit of economies of scale because they will have a larger total mass of hydrogen stored to meet the 250-mile range target.

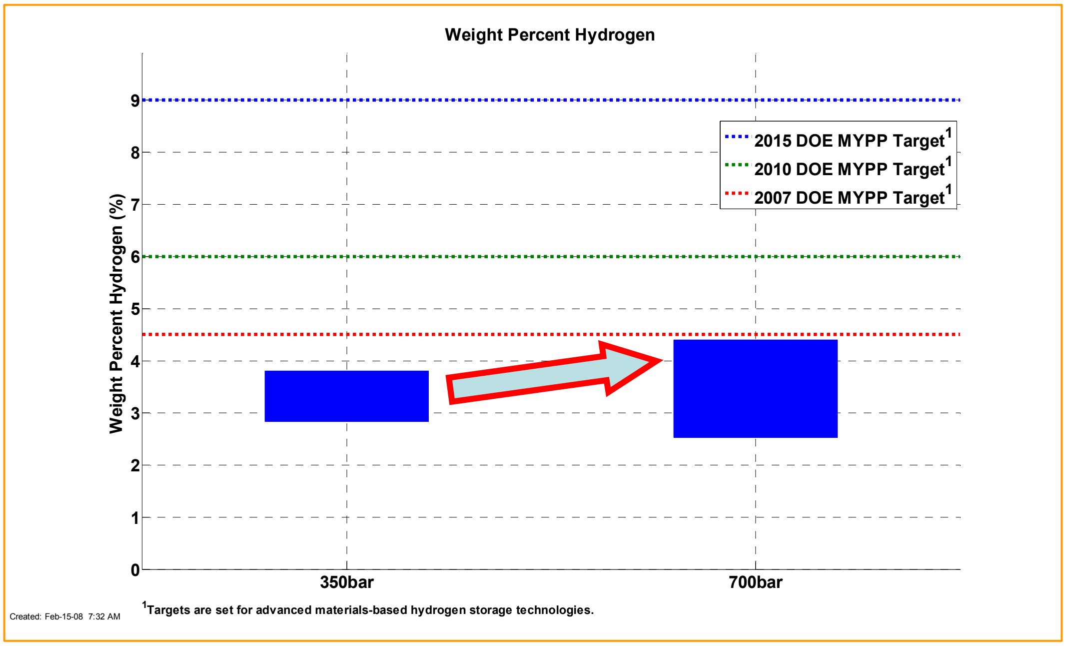


Figure 7: Weight Percent of Hydrogen Stored in 350 bar and 700 bar Systems

We also compared the storage technologies for volumetric capacity (how much hydrogen can be stored per volume), shown in Figure 8. This is where the advantage of going to a higher pressure really emerges, showing the potential for a significant increase in the mass of hydrogen stored per liter (the best of the range increasing from almost 20 g/L up to about 25 g/L), making the packaging of the system on a vehicle more attractive.

Finally, the percentage breakdown by each of these categories was averaged across the four teams so that the differences between 350 bar and 700 bar could be examined for mass and volumetric characteristics (Figure 9). The pie-chart comparison shows that while the average hydrogen weight percentages are similar for 350 and 700 bar, and the pressure vessel and balance-of-plant at 700 bar take up a larger percentage of the system volume, the 700 bar systems are attractive because they enable a more compact package and extended range.

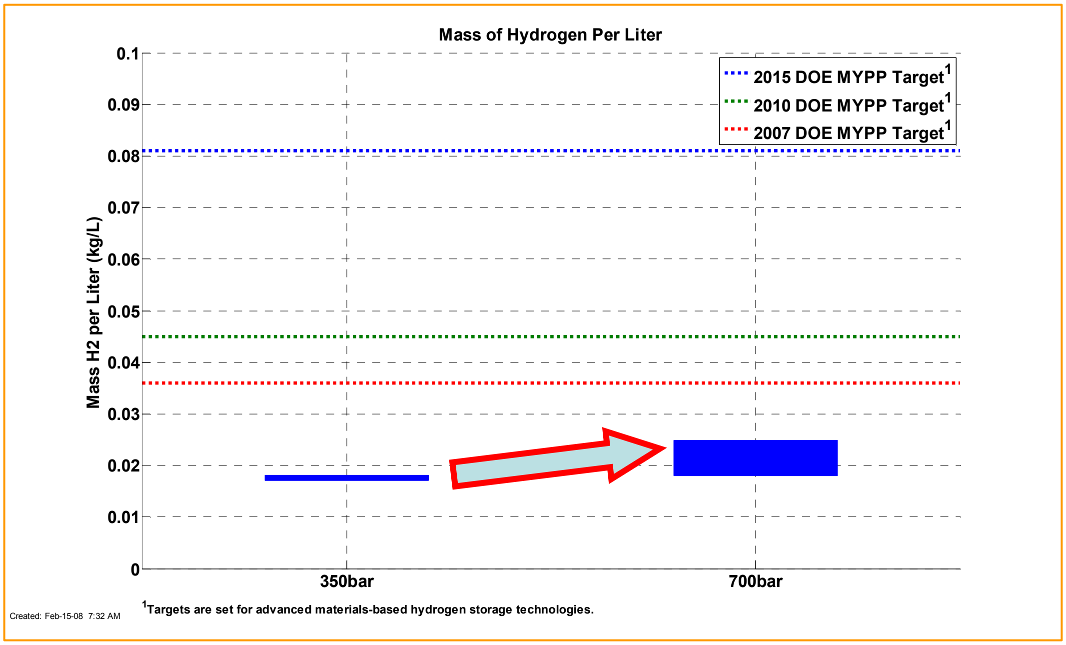


Figure 8: Comparison of Mass of Hydrogen Stored per Liter of System

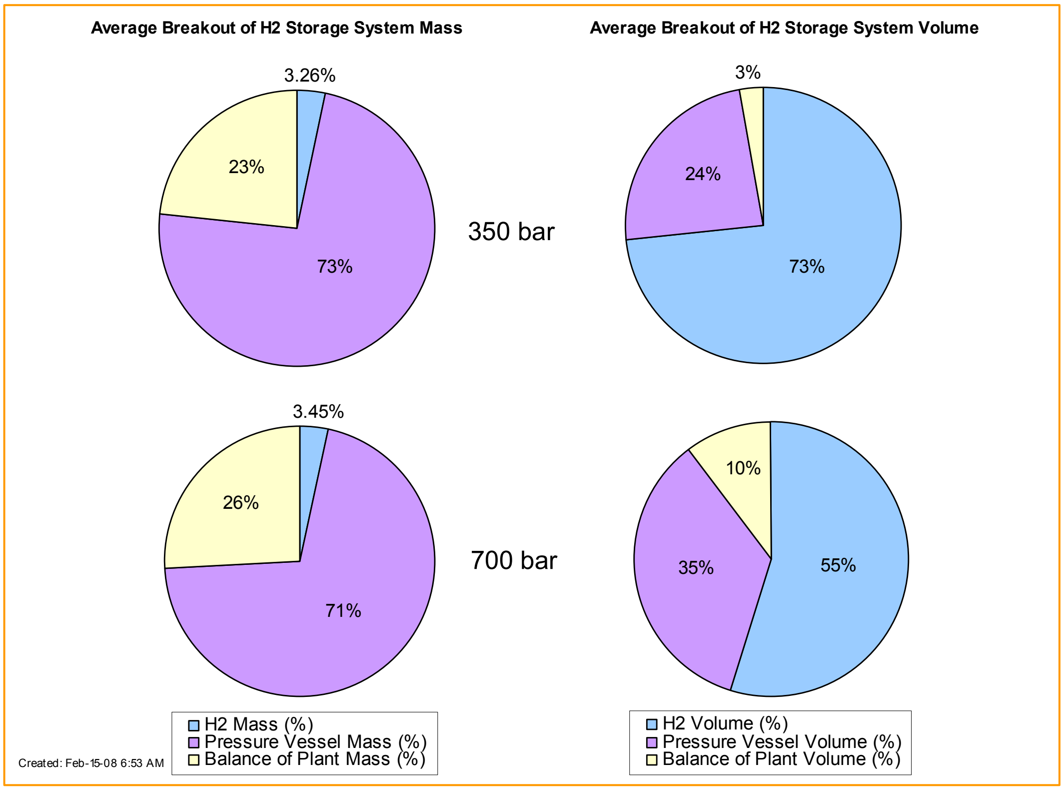


Figure 9: Average Breakout of Mass and Volume for Hydrogen, Pressure Vessel, and Balance-of-Plant

5.5 Vehicle Refueling Performance

Hydrogen vehicle refueling needs to be as similar as possible to conventional vehicle refueling to allow an easier commercial market introduction. Over 8,700 refueling events have been analyzed to date, and the refueling amount, time, and rate have been quantified. The average time to refuel was 3.43 minutes with 87% of the refueling events taking less than five minutes. The average amount per fill was 2.25 kg, reflecting both the limited storage capacity of these vehicles (~4 kg max) and peoples' comfort with letting the fuel gauge get close to empty (to be discussed later). DOE's target refueling rate is 1 kg/minute, and these Learning Demonstration results indicate an average of 0.79 kg/min, with 24% of the refueling events exceeding 1 kg/minute (Figure 10). Therefore, we can conclude that high-pressure gases are approaching adequate refueling times and rates for consumers; however, the challenge is still in packaging enough high-pressure hydrogen onboard to provide adequate range, or finding alternate advanced hydrogen storage materials that can replace the need for high-pressure tanks.

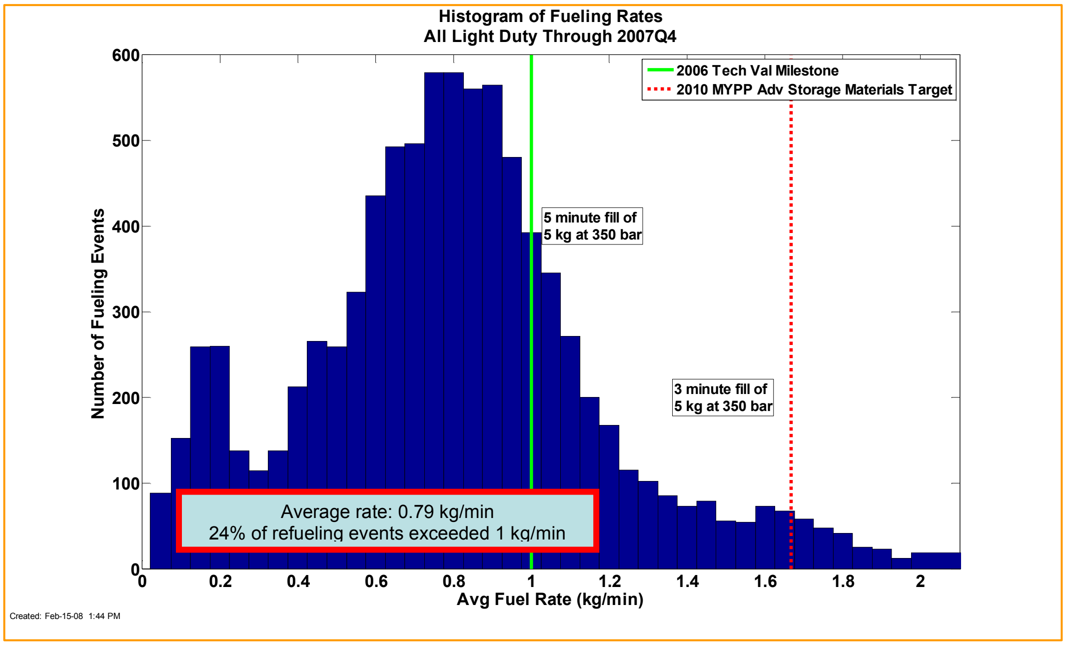
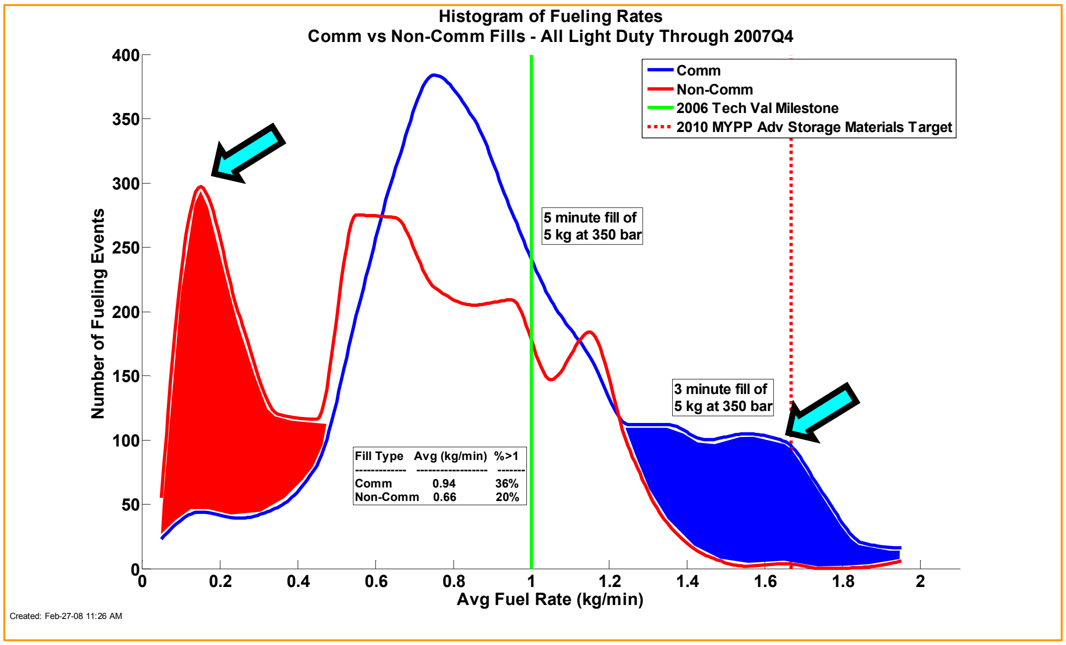


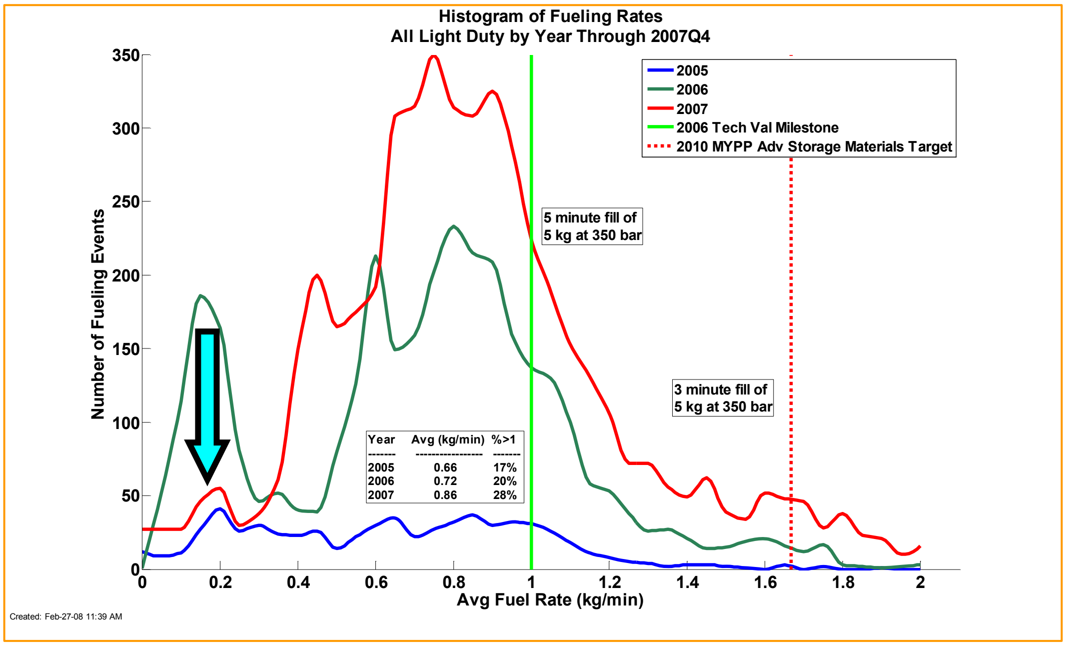
Figure 10: Refueling Rates

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



Fill Type	Avg (kg/min)	%>1
Comm	0.94	36%
Non-Comm	0.66	20%

Figure 11: Fueling Rates – Communication and Non-Communication Fills



Year	Avg (kg/min)	%>1
2005	0.66	17%
2006	0.72	20%
2007	0.86	28%

Figure 12: Comparison of Fueling Rates by Year

When the data is analyzed by year (Figure 12), we find that this slower refueling rate was heavily used in 2006 but was almost completely phased out in 2007. With these differences in distribution in mind, the average fill rate for all communication fills is 0.94 kg/min vs. 0.66 kg/min for non-communication fills, with 36% and 20%, respectively, exceeding DOE's 1 kg/min target.

5.6 Vehicle Driving Behavior

Some questions have arisen about whether the Learning Demonstration vehicles are being used 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 13 shows a clock-face radial histogram, with the green data representing the time of day when people initiated their trips. Overlaid on top of that we have placed pink diamonds to show the national statistics based on the 2001 National Household Travel Survey (NHTS) Data [5]. What we find is that the Learning Demonstration vehicles are driven at similar times of day 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 kids from school, driving home from work, or running errands. Since the first-generation Learning Demonstration vehicles are primarily used for professional or fleet activities, it is not surprising that there would be a difference. The percentage of trips taken between 6 a.m. and 6 p.m. is similar to the national statistics (88.7% vs. 81.5%). The nighttime driving behavior trend is also similar to the national statistics, although there are overall more evening trips driven nationally than within the Learning Demonstration.

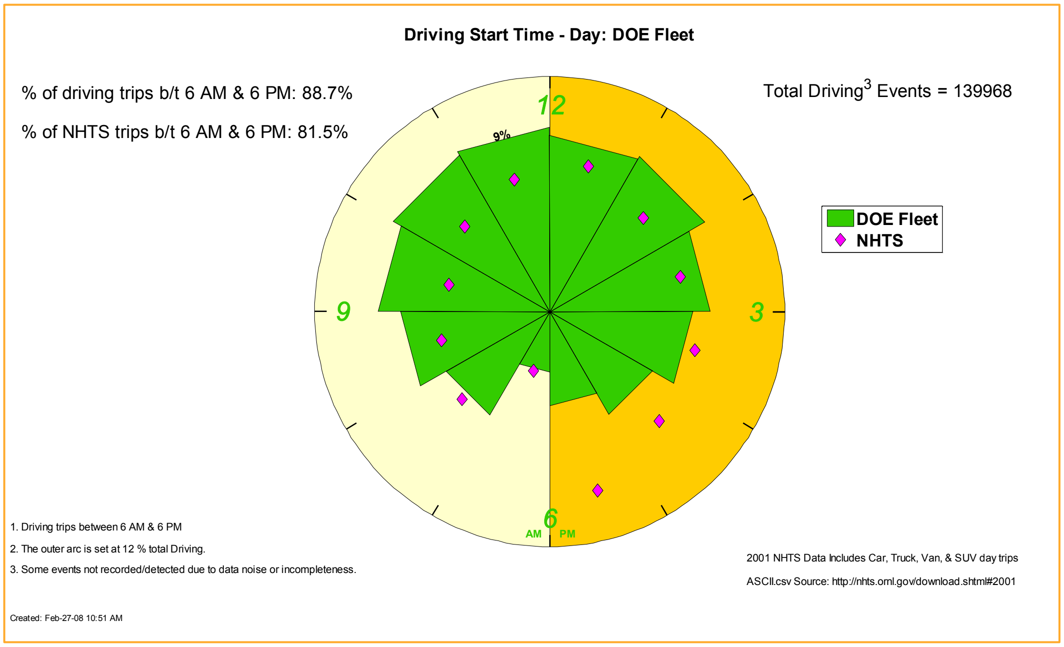
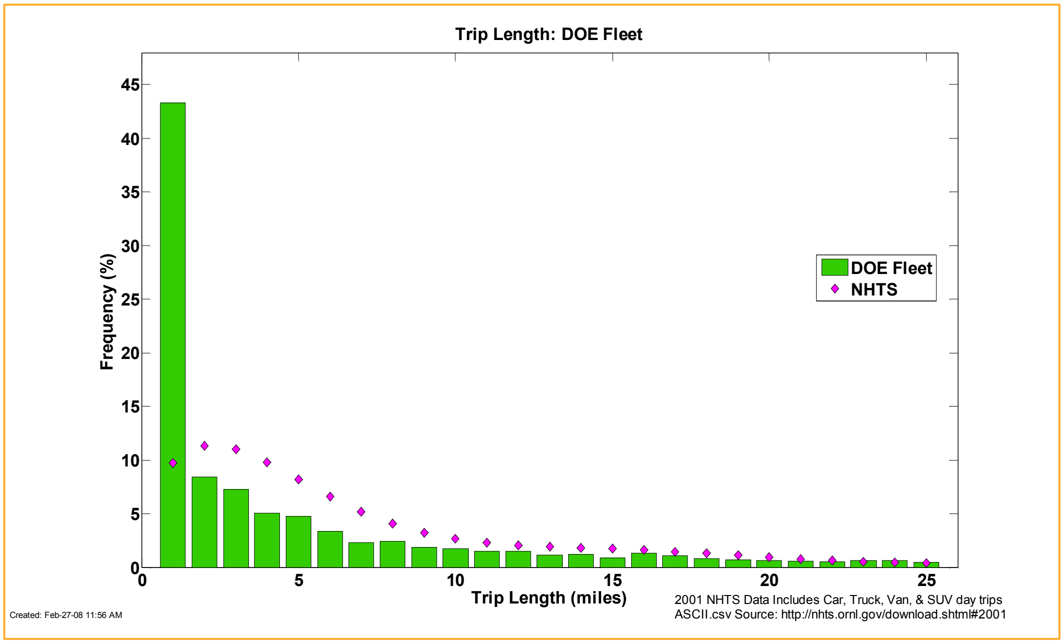


Figure 13: Driving Start Times between 6AM and 6PM Compared with National Statistics

We also examined the days of the week that people drove the Learning Demonstration FCVs and compared this with the national statistics. Nationally the trips are relatively uniform on weekdays, with a slight dip on the weekends, but 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 doesn't matter to the car's performance, it might indicate 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 the first generation vehicle duty cycles.

We analyzed the length of trips and compared these results to national statistics, as shown in Figure 14. With more than 40% of the Learning Demonstration trips being less than one mile long, it is clear that the amount of time spent at low fuel cell power (discussed earlier) is due in part to a large number of short trips for which the vehicle is not likely accelerated to higher speeds and powertrain demands. This differs from the national driving statistics, which show that only about 10% of the trips are less than one mile long. If a large number of starts/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 is necessary before that linkage can be made based on our analysis of the real-world data.



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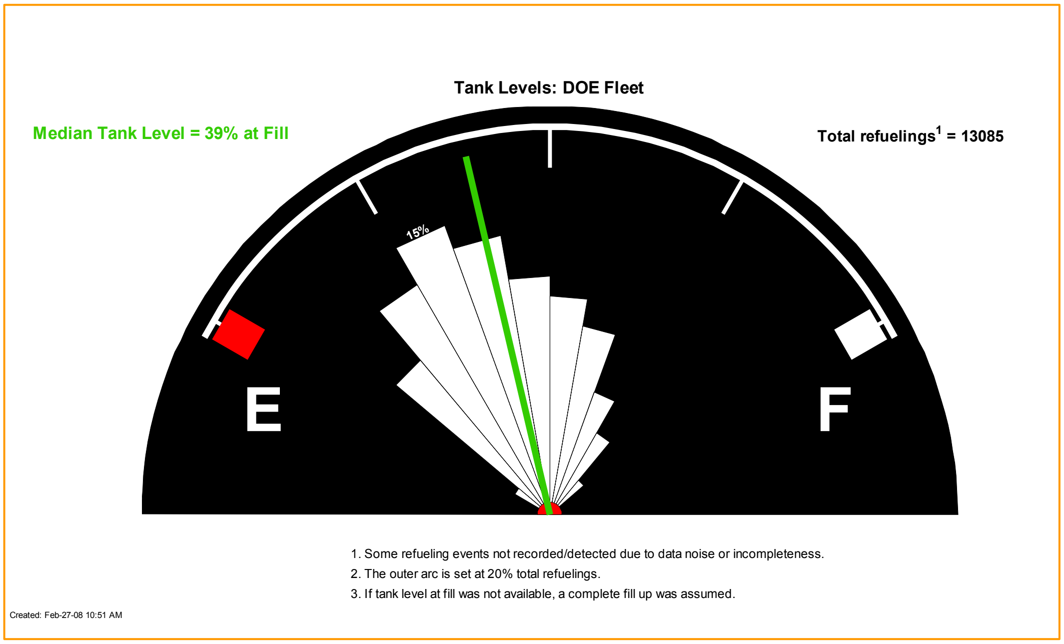
2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

Figure 14: Trip Length Histogram Comparison with National Statistics

5.7 Vehicle Refueling Behavior

As previously mentioned, with limited hydrogen refueling 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 analyzed the data submitted in a new and unique way, which was to look at what the fuel level in the tank was just prior to each refueling 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 be to the “full” level, allowing a subtraction of the amount fueled to determine the initial tank level.

Figure 15 shows the results from this analysis, where a histogram has been placed radially on an image of a fuel gauge to make interpreting the graph as intuitive as possible. The level at which people most commonly refuel the Learning Demonstration vehicles is at just over ¼ full; this covers 15% of the refuelings. While some drivers are letting the tank get even lower than that, few let it get close to being empty. Additionally, we placed a green needle on the chart which indicates the median tank level at fill (½ above, ½ below), which is a little above ⅜ of a tank (40% of full). In the future, we would like to compare these data results to data from conventional liquid-fueled vehicles, if they exist publicly, to see if people are refueling their fuel cell vehicles differently than their conventional vehicles.



1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. The outer arc is set at 20% total refuelings.
3. If tank level at fill was not available, a complete fill up was assumed.

Figure 15: Hydrogen Tank Level at Refueling

We also looked at the time of day people refueled in order to understand the usage patterns at the hydrogen refueling stations and better allow new or potential station operators to understand the potential demand by time of day. For traditional liquid fuels, with big tanker truck deliveries periodically, the time of day people refuel does not normally matter. Instead, the station operator must simply ensure that the next tanker comes before he runs out of fuel. For today's hydrogen fuel stations, with very limited storage capacity and some sites producing hydrogen throughout the day, it is important to know the time of day that people refuel in order to match the supply (on-site production) with the demand.

We found that 86% of the fills occurred between 6 a.m. and 6 p.m., with 14% occurring at night. The distribution is relatively uniform with steady usage between 8 a.m. and 4 p.m., and a mild peak at lunchtime (9%). The conclusion from this analysis is that with a uniform distribution of when people refuel 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. Finally, we looked at what day of the week people were refueling and found that the Learning Demonstration vehicles are primarily refueled Monday through Friday, with very few vehicles refueled on the weekend. 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.

6. Conclusions

NREL has now analyzed data from almost three years of the five-year project with 92 vehicles having been deployed, 14 project refueling stations in use, and no fundamental safety issues identified. We've analyzed data from over 200,000 individual vehicle trips covering 1,100,000 miles traveled and over 40,000 kg hydrogen produced or dispensed. With additional hours of operation accumulated on the fuel cell stacks the four-team average projection to 10% voltage degradation is 1,200 hours. During 2008, we will determine if we can improve the accuracy of our projections by adding a non-linear fit (or a two-step linear fit) to avoid overestimating the projected time as the accumulated hours continues to grow.

To answer the question of what is causing the stacks to gradually degrade, NREL continues to characterize how each stack is used and perform multivariate analysis on this dataset to examine dominant variables affecting stack voltage degradation rates. Results to date indicate we are probably not going to be able to extract strong trends across all four teams due to differences among the teams, but that individual results may be useful to the teams individually and for feeding trends back into the R&D program. We've analyzed fuel cell system efficiency at ¼-power and compared it to the DOE target of 60%; system efficiency results from the four teams ranged between 52.5% and 58.1%.

Using data on communication vs. non-communication fills, we found that communication fills demonstrated a higher rate of fill than non-communication fills while the slowest of the non-communication fill rates are being phased out. We also examined refueling and driving behavior, and found the Learning

Demonstration fleet to be representative of national statistics with the exception of fewer late afternoon and weekend trips, an abundance of short trips, and a shorter average distance traveled per day. Finally, we've published a total of 47 CDPs to date and made them directly accessible to the public through our Hydrogen Technology Validation Web site (http://www.nrel.gov/hydrogen/proj_learning_demo.html).

In the future, we will further explore the correlations of real-world factors influencing fuel cell degradation and strive to separate their interwoven dependencies. We will semi-annually (spring/fall) compare technical progress to program objectives and targets and provide results to the public by participating in technical conferences and writing reports. For the second-generation vehicles introduced in 2008, we will begin evaluating improvements in fuel cell durability, range, fuel economy, and safety, and publish results when there are sufficient second-generation vehicles to mask the companies' identities. As an important part of the project, we will identify opportunities to feed project findings back into HFCIT Program R&D activities to maintain the project as a "learning demonstration."

7. References

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1. REPORT DATE *(DD-MM-YYYY)* April 2008	**2. REPORT TYPE** Conference Paper	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Fuel Cell Vehicle Learning Demonstration: Spring 2008 Results	**5a. CONTRACT NUMBER** DE-AC36-99-GO10337
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) K. Wipke, S. Sprik, J. Kurtz, and J. Garbak	**5d. PROJECT NUMBER** NREL/CP-560-43055
	5e. TASK NUMBER H2708100
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	**8. PERFORMING ORGANIZATION REPORT NUMBER** NREL/CP-560-43055
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

Conference paper presented at the 2008 National Hydrogen Association Meeting that describes the spring, 2008 results of the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project.

15. SUBJECT TERMS

NHA; learning; demonstration; hydrogen vehicles; fuel cell vehicles

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18