FCV Learning Demonstration: Project Midpoint Status and First-Generation Vehicle Results[1]

Keith Wipke*, Sam Sprik°, Jennifer Kurtz°, Holly Thomas°, and John Garbak**

The "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," also known as the Fuel Cell Vehicle and Infrastructure Learning Demonstration, is a 5-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. Four industry teams are currently operating more than 77 vehicles and 14 refueling stations, with plans to add over 50 additional vehicles and several additional refueling stations during the remainder of the project duration. This paper covers the progress accomplished by the demonstration and validation project since inception, including results from analysis of six months of new data.

With three sets of public results having been presented previously, this paper comes at roughly the mid-point of the project, just as second-generation fuel cell stacks and vehicles are being introduced and some early vehicles are being retired. With many fuel cell stacks having accumulated well over 500 hours of real-world operation, there is now a higher level of confidence in the trends and projections relating to the durability and voltage degradation of these first-generation fuel cell stacks.

Public 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. In addition to generating composite data products, NREL is performing additional analyses to provide detailed recommendations back to the R&D program. This includes analysis to identify sensitivities of fuel cell durability to factors such as vehicle duty cycle, number of on/off cycles, time at idle, and ambient temperature. An overview of this multivariate analysis and preliminary findings will be shared, with future project activities discussed.

Keywords: Fuel Cell Vehicle, Demonstration, Hydrogen Infrastructure, Analysis, Refueling

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

The 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), safety, and codes and standards. Many key technical barriers, such as hydrogen storage and fuel cell durability, have previously 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 was focused primarily in California with limited quantity and geographic

*Senior Engineer II, National Renewable Energy Laboratory
1617 Cole Blvd, Golden CO, 80401
Phone: 303-275-4451
Fax: 303-275-2905

°National Renewable Energy Laboratory

**U.S. Department of Energy

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.

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. Seventy-seven first-generation vehicles have already entered into service with customers, and many new hydrogen refueling stations have opened, with more vehicles and stations planned. Estimated government investment in this five-year project will be about $170 million; with cost-share from industry, total projected expenditures are over $350 million.

2. PROJECT OBJECTIVES AND TARGETS

This project's objective is to conduct parallel learning demonstrations of hydrogen infrastructure and fuel cell vehicles to allow the government and industry to assess progress towards technology readiness. We are accomplishing this objective through validating the vehicle and infrastructure as a complete integrated system. The quantity and breadth of data collected and analyzed enables evaluation of technology status versus DOE program targets, as well as feedback to DOE-funded research and development as appropriate. The ability to feedback results to the research and development as an integrated part of DOE's program makes this project unique from typical demonstration projects.

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, 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 as 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. INDUSTRY PARTNERS

Automotive OEMs are leading three of the four teams, and an energy provider is the leader of the fourth. Figure 1 shows the teaming arrangement of the four teams along with their first-generation fuel cell vehicles. The major companies making up the four teams are as follows:

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

4. APPROACH

NREL's approach to accomplishing the project's objectives is structured around a highly collaborative

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 targets		

Table 1: Project performance targets

Figure 1: OEM & fuel supplier teams, along with their first-generation vehicles

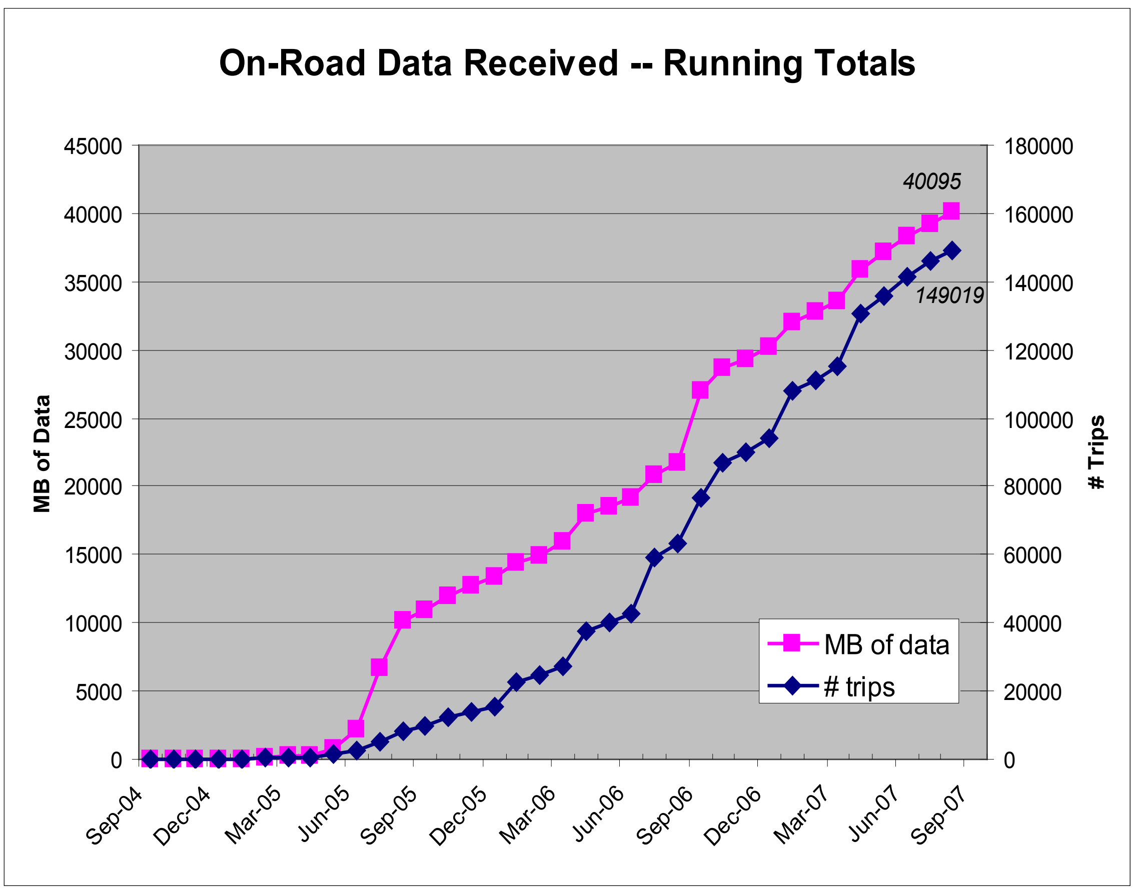

Figure 2: Process flow for hydrogen secure data center analyses and results

relationship with each of the four industry teams previously discussed. We are receiving raw technical data from 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 DOE Hydrogen 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. Figure 2 shows the flow of data and results, along with the quantity of data received by month since September 2004. To date, NREL has received data from more than 149,000 individual vehicle trips, amounting to more than 40 GB of raw, on-road data.

To ensure value is fed back to the hydrogen community, we publish composite data products twice a year at technical conferences. These data products report on the progress of the technology and the project, focusing on the most significant results. Additional composite data products are conceived as additional trends and results of interest are identified. NREL has created a new web site to house all of the current composite data products at: http://www.nrel.gov/hydrogen/cdp_topic.html, along with all previous versions as archives. We also provide our detailed analytical results privately back to each individual company on the data it provided in order to maximize the industry benefit from NREL's analysis work and obtain feedback on our methodologies.

5. COMPOSITE DATA PRODUCT RESULTS

5.1 Fuel Cell Operating Power Points

Previous publications [1,2] reported on the very high efficiency of the Learning Demonstration fuel cell systems at ¼ power, spanning between 52.5% and 58.1%, very close to the DOE target of 60%. Recent work included an analysis of the amount of time each fleet spent operating their fuel cells within various ranges of power levels. Because we found such a large percentage of time within the 0% to 5% maximum power range, we chose to use unequal bins in order to present the results so that the values at the higher powers would not get washed out by an otherwise large scale. Figure 3 shows these results, with the blue arrow pointing to the bin in which the ¼ power point resides. What this graph shows is that the ¼ power point is important relative to power points higher than 40%, but also that the region at <20% power is also extremely important in establishing an overall high efficiency for an automotive system on-road. It also suggests that implementing idle-off for the fuel cell system could substantially reduce energy consumption, as has been done with today's gasoline-electric hybrids.

5.2 Vehicle Fuel Economy and Range

While fuel economy and range are critical metrics to validating fuel cell vehicles' merit for the environment and consumers, these results have been previously covered in detail in a June 2007 progress report [3]. The on-road fuel economy has improved slightly since previously reported, now spanning the range of 30 miles/kg H_2 to almost 50 miles/kg H_2. Since the driving range is based on the same fixed hydrogen

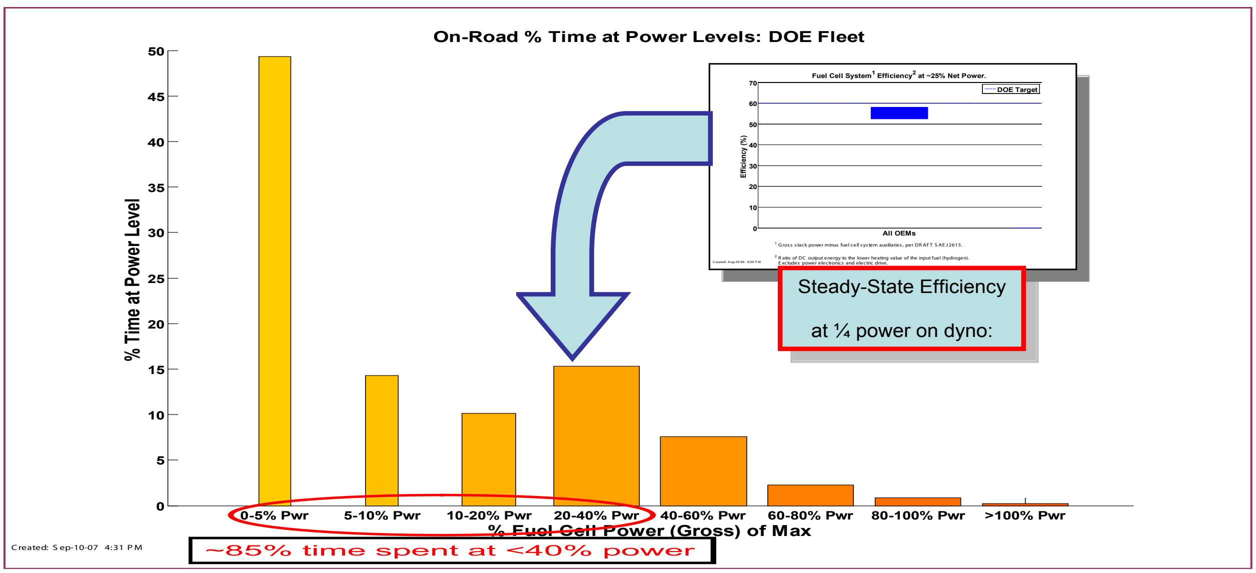

Figure 3: On-road data show most FC system operation is at low power

tanks and the fuel economy, there have not been any major changes to driving range significant enough to discuss here. There is the potential for higher range from the second-generation vehicles due to higher H_2 storage pressure (700 bar) and more vehicles that may be designed with storage system limitations in mind. Progress on H_2 storage will be reported after second-generation vehicles are introduced.

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 at 1,000 hours in 2006 and 2,000 hours in 2009. Results were first published one year ago 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. 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. We then compared these results to the first-generation target of 1,000 hours for 2006. In the past year, many more hours have been accumulated on the fuel cell stacks, and the range of fleet averages is ~200-600 hours, with the range of fleet maximums spanning ~300-900 hours. Therefore, the amount of extrapolation we have to make, using the slope of the voltage degradation method (mV/hour times the 10% voltage drop target), continues to decrease. The projected times to 10% fuel cell stack voltage degradation from the four teams had an average of more than 800 hours with a high projection of more than 1,600 hours from one team, straddling the 1,000-hour DOE target (Figure 4). We anticipate that in the next few months one of the teams will be first in the world to reach 1,000 hours of fuel cell system operation (without stack repair) in real-world operation on a light-duty passenger vehicle. 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"

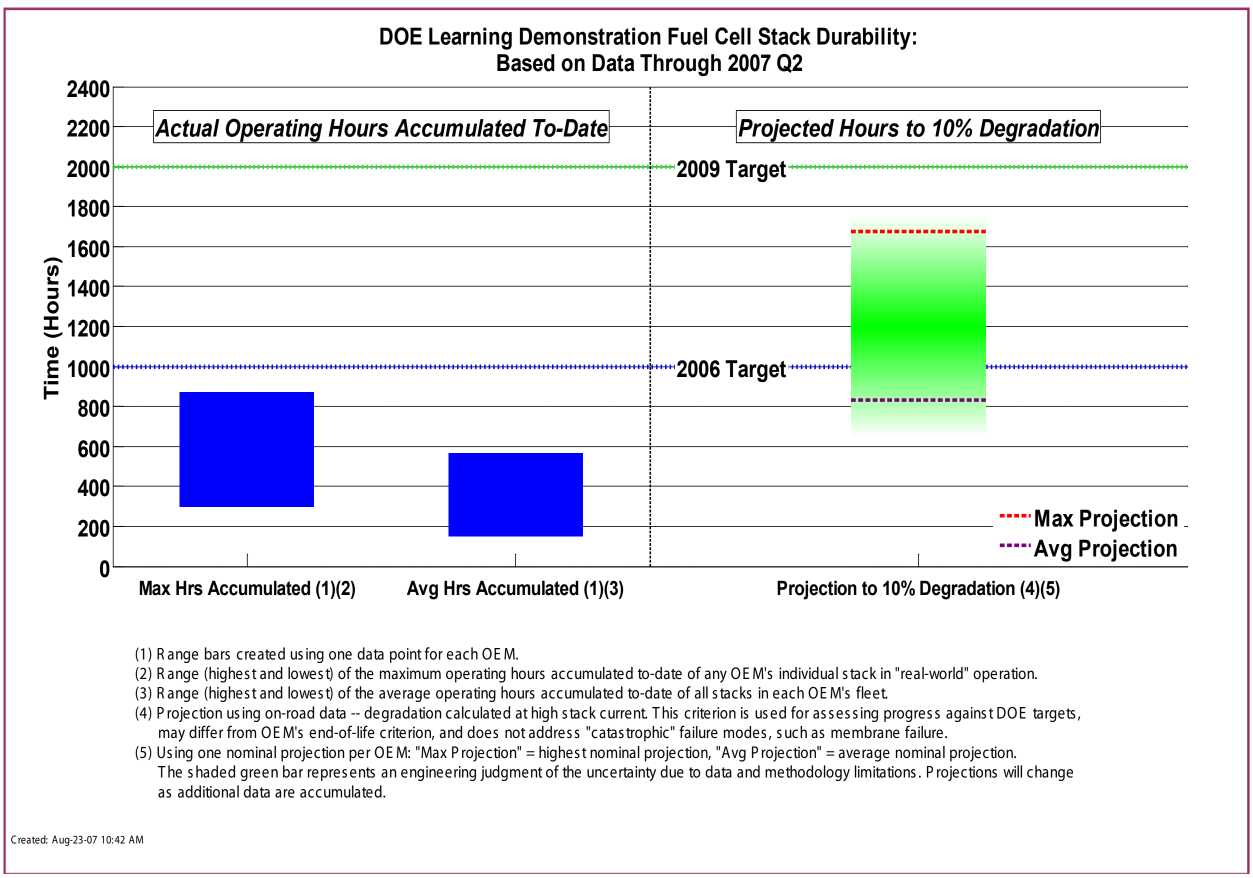

Figure 4: Stack durability based on 10% voltage degradation projections

~29% Decay rate variance explained by a combination of the data variables below[1]	Correlation to Decay Rate Data
Starts per hour (+)	High decay rate[2]
Power levels (high & average) (+)	
Trip length (-)	
Time between trips (+)	
~10% Decay rate variance explained by a combination of the data variables below[1]	**Correlation to Decay Rate Data**
Idle time (+)	High decay rate[2]
Power levels (low) (+)	

1. Findings based on a Learning Demonstration Fleet, Partial Least Squares (PLS) regression model. Approximately 39% decay rate variance explained by the model.
2. As part of the variable combination, a (+) indicates a directional relation to high decay rate and a (-) indicates an inverse relation.

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Figure 5: Dominant factors affecting Learning Demo fleet fuel cell degradation

failure modes such as membrane failure. The second-generation stacks introduced in this project beginning in late 2007 will be compared to the 2,000-hour target for 2009.

In addition to tracking the voltage degradation using this NREL-developed method, we have also initiated multivariate analysis to see if we can determine the dominant factors that are affecting the rates of degradation. We started out by creating a database of all of the Learning Demo stacks and various performance attributes. Each individual stack was examined to look at the hours of data accumulated to date, its amount of time in non-DOE vehicles before data was received, 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:

- o Average degradation rate (key dependent variable)
- o Region of operation (% of time in each)
- o Temperature (% of team in 3 bins of cold, moderate, and hot)
- o Specific refueling stations used
- o Average number of stack starts/hour
- o Time between trips (to get at cold start impact)
- o Trip length
- o Power levels (% of time in several power bins)
- o Idle time

Once we compiled this database, we performed graphical analyses using one variable at a time to see if there were any obvious single factors that appeared to influence the voltage degradation in a dominant way, but nothing stood out. Therefore, we knew that we needed to take the next step and perform a multivariate analysis in which groups of factors are lumped together to allow their interactions to be included. We performed many different types of analyses, including factor analysis (FA), principal component analysis (PCA), and finally partial least squares (PLS) regression analysis. We ended up focusing our efforts on using the PLS because it was the most direct way of getting what we wanted, which was 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 were not strong, with only about 39% of the variance able to be explained by the first two groupings of variables. The trends identified are shown in Figure 5, with the (+) or (-) indicating a directional relation for each variable relative to decay rate, with a (+) indicating a directional relation to high decay rate and a (-) indicating an inverse relation.

Next we looked at each team's data individually and performed the same PLS analysis. The connection between voltage degradation rate and the variables improved significantly, and was able to explain between 61% and 76% of the variance in voltage degradation. What is interesting to note is that some teams' degradation was influenced by 2 to 3 key variables, while others had a more complex influence from 4 to 5 variables. Figure 6 shows which variables had the dominant influence on degradation for each team. This overall degradation factors analysis effort is not complete, and NREL will work closely with each team to carefully examine the inputs and outputs from this analysis, and see if there are valuable lessons that can be fed back into the companies' research as well as into DOE's R&D program.

5.4 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 6,300 refueling events have been analyzed to date, and the amount, time, and rate have been quantified. The average time to refuel was 3.66 minutes with 85% of the refueling events taking less than 5 minutes. The average amount per fill was 2.21 kg, reflecting both the limited storage capacity of these vehicles (~4 kg max) and peoples' comfort level with letting the fuel gauge get close to empty (see Figure 7 for the shape of the distributions), which will be shown in a separate analysis. DOE's target refueling rate is 1 kg/minute, and these Learning Demo results indicate an average of 0.76 kg/min, with 23% of the refueling events exceeding 1 kg/minute (Figure 8). 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.

The previous three histograms included all types of refueling events. There has been much interest from industry and from the codes and standards community in the potential for communication fills to occur at a higher rate and with a more complete fill. Last fall the project refueling data templates were updated to include a classification of each fill as either communication or non-communication to begin gathering this data. We now have acquired enough data to publish results. Figure 9 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.

A few points can be gleaned from these results. There is a large group of vehicle/station combinations still

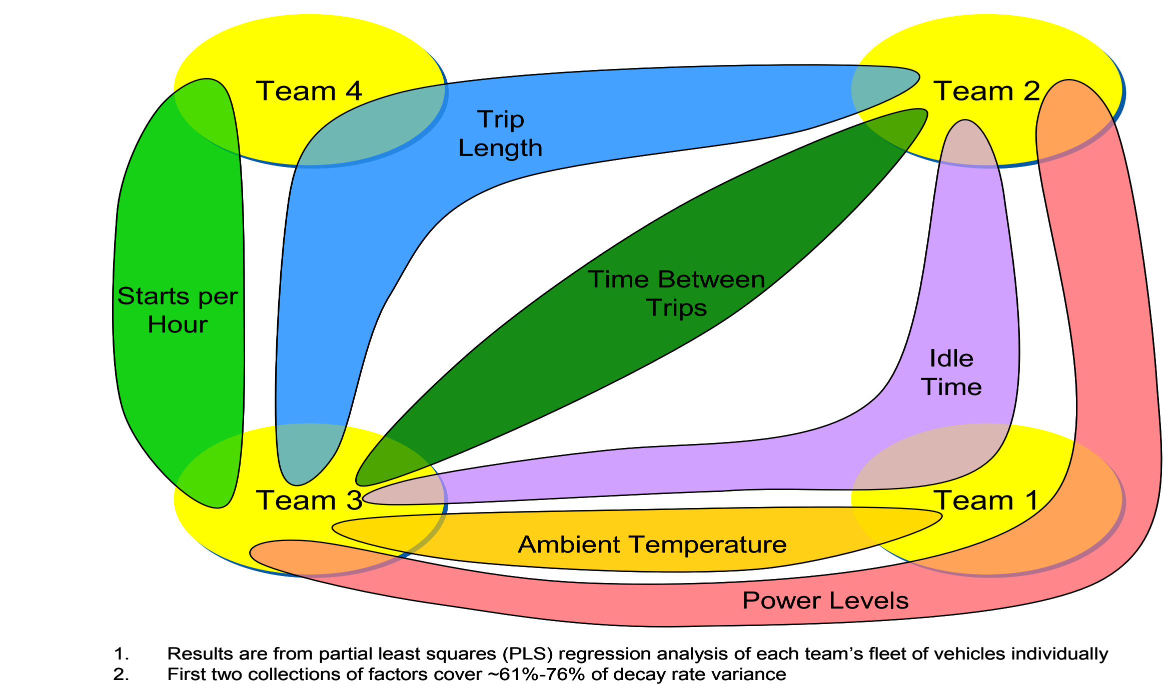


Figure 6: Dominant factors affecting stack degradation for each team individually

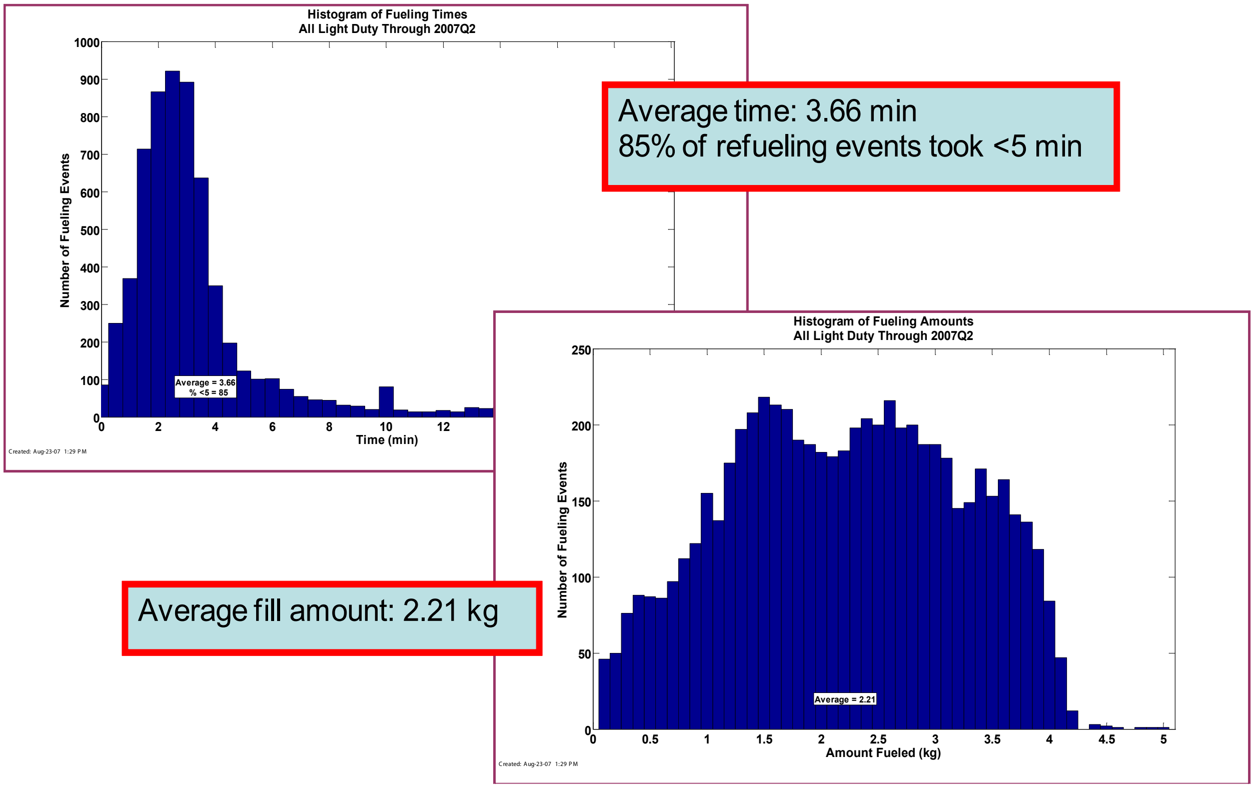


Figure 7: Refueling times (left) and refueling amounts (right)

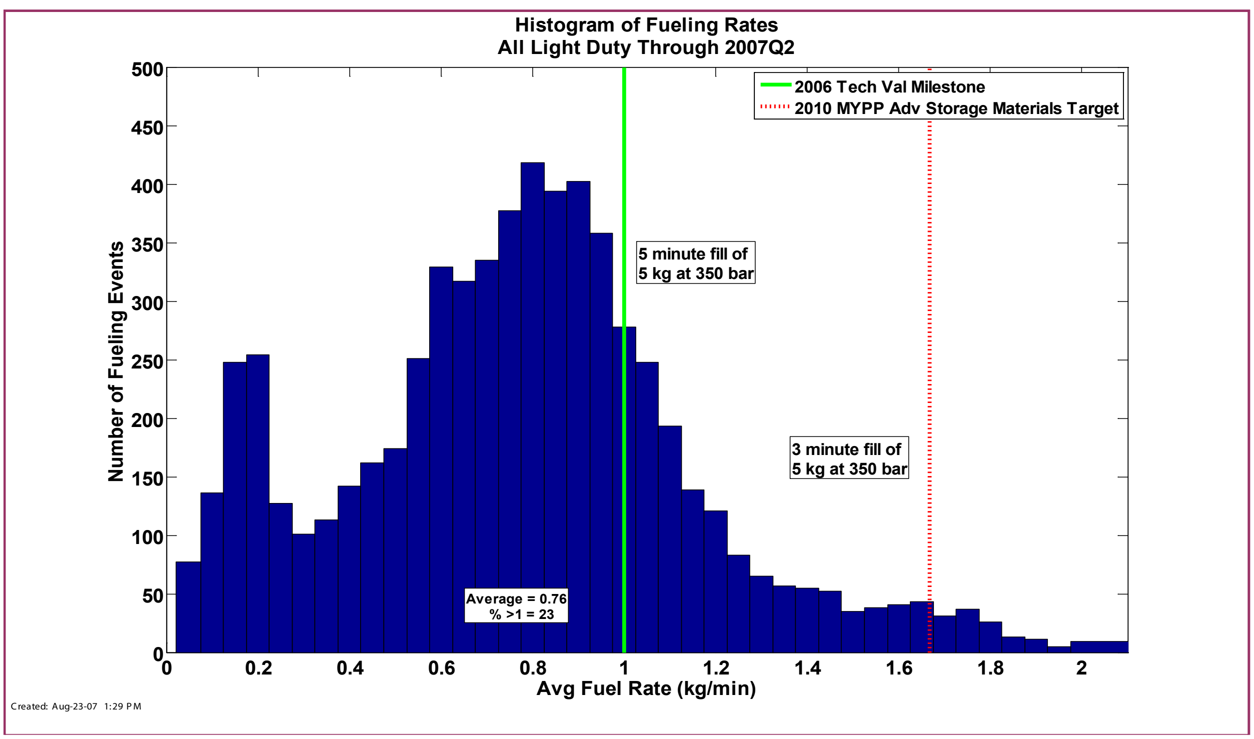


Figure 8: Refueling rates for all Learning Demo fills

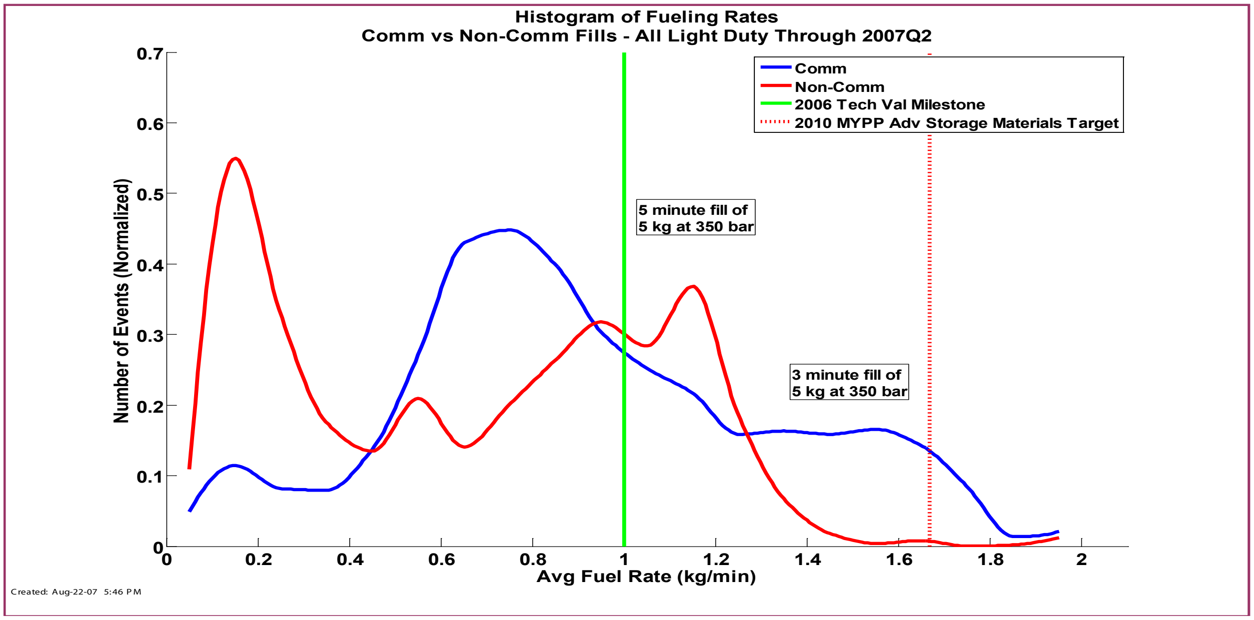


Figure 9: Comparison of fill rates between communication and non-communication fills

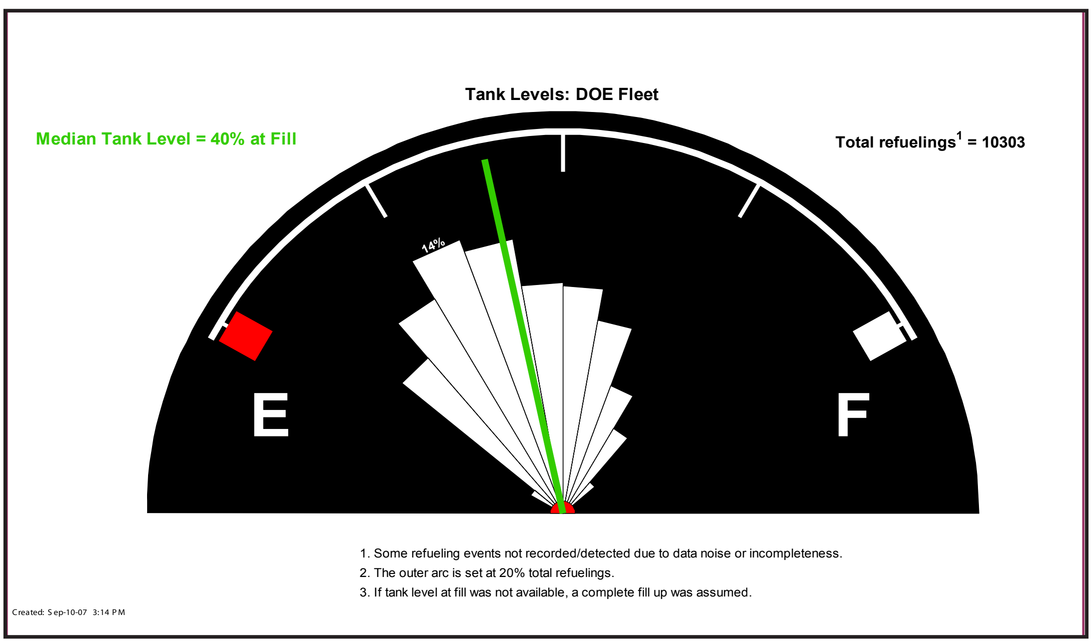


Figure 10: Level in the tank at which people refuel Learning Demo FCVs

doing non-communication fills at the slower rate of ~0.2 kg/min. 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. There is also a second peak of vehicles performing non-communication fills at higher than 1 kg/min, at around 1.2 kg/min, higher than DOE's 2006 target. NREL will seek to understand what protocols some of the non-communication fills are following that allow them to reach such a high fill rate.

Looking at communication fills (blue curve) we see that while the peak is at around 0.7 kg/min, a large percentage of the communication fills are higher than 1 kg/min (more than for non-communication fills). In particular, there is a fairly flat and significant number of communication fills at between 1.2 and 1.7 kg/min.

So in summary, while communication fills definitely appear to be able to refuel at a higher rate than non-communication, the bulk of data gathered to date actually show the peak for communication fills being lower than the peak for non-communication fills. This will be followed closely as more data is gathered.

5.5 Vehicle Refueling and Driving 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 for fear of running out of fuel. To investigate this further, NREL used the data submitted in a new and unique way, which was to look at what the 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 10 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.

This figure shows that the level at which people most commonly refuel the Learning Demonstration vehicles is at just over ¼ full, and covers 14% of the refuelings. While some are letting the tank get even lower than that, few let it get close to being empty. Additionally, we've 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%). We would like to compare these data results to data from conventional liquid fueled vehicles if it exists, to see if people are behaving any differently in how they refuel their fuel cell vehicles.

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 stations to understand the potential demand by time of day. For traditional liquid fuels, with big tanker deliveries periodically, the time of day people refuel does not really matter. Instead, the station operator must simply ensure that the next tanker comes before he runs out. For today's hydrogen fuels, with very limited storage capacity and some sites producing hydrogen

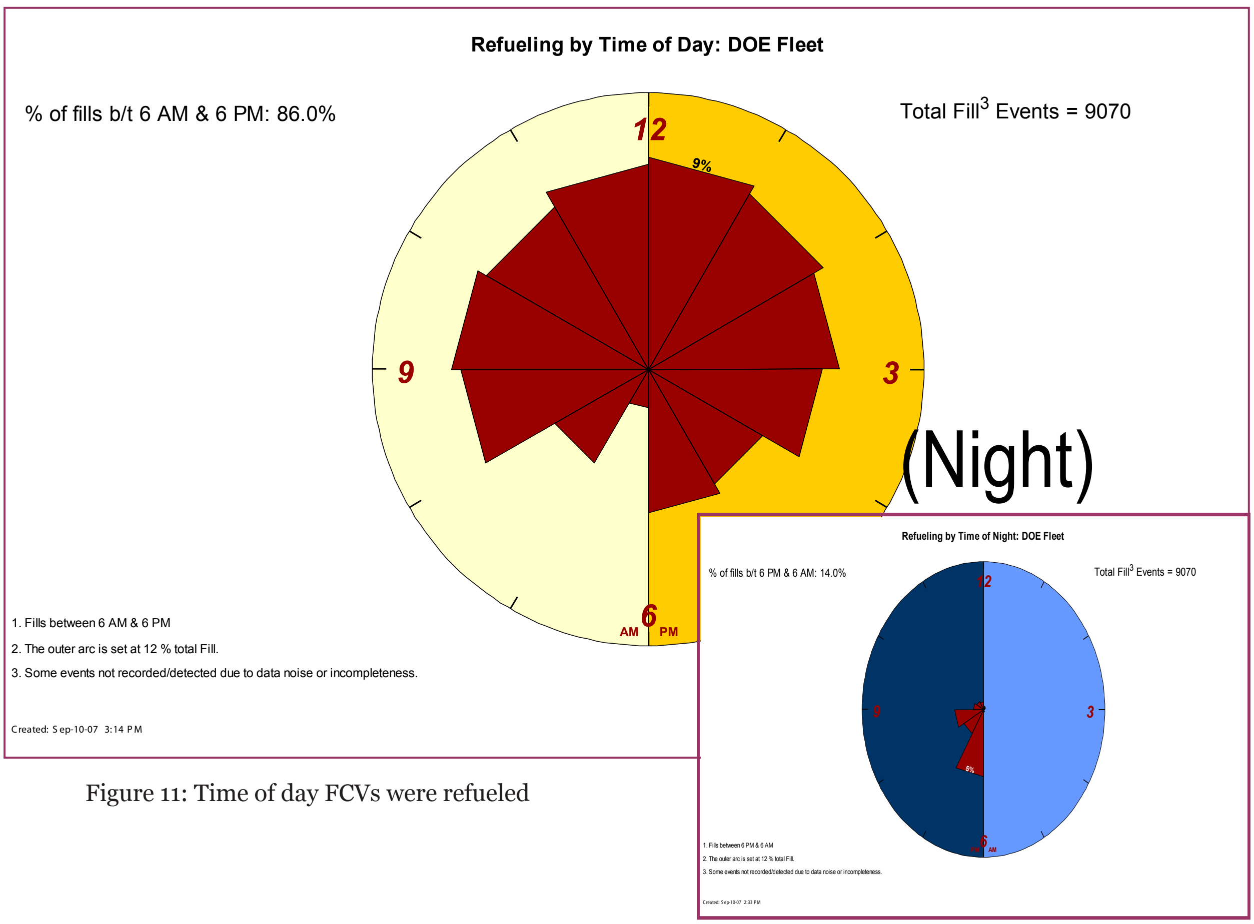
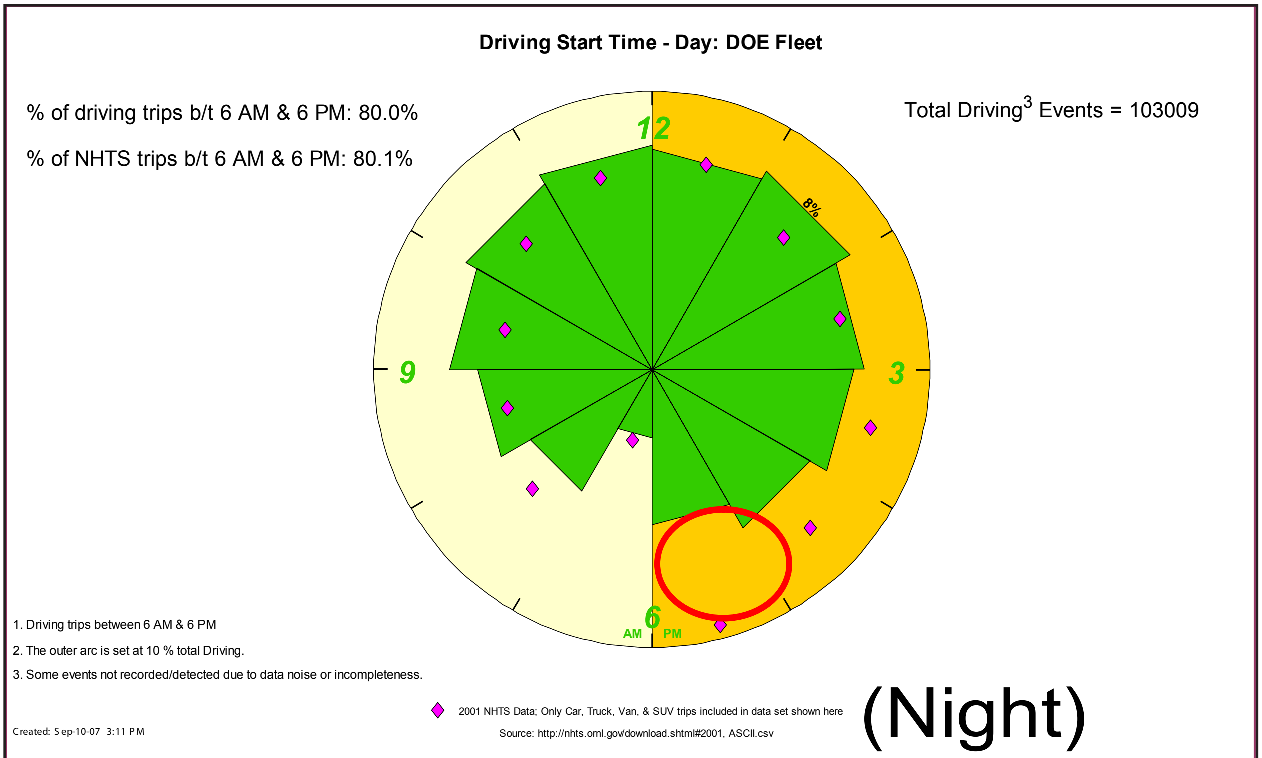


Figure 11: Time of day FCVs were refueled



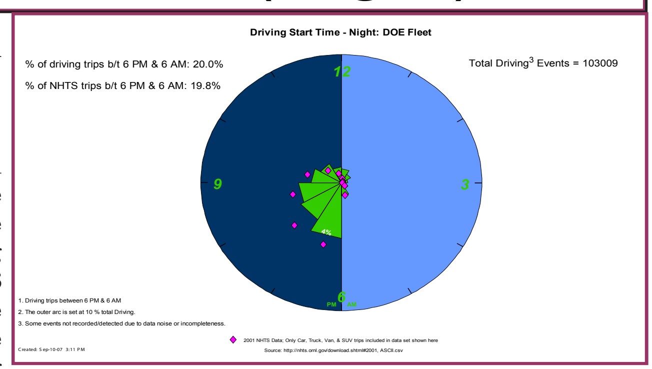


Figure 12: Time of day Learning Demonstration vehicles were driven relative to national statistics

throughout the day, the time of day that people refuel is much more critical to know in order to match the supply (on-site production) with the demand. Figure 11 shows a radial histogram of the time of day Learning Demo vehicles were refueled between 6 a.m. and 6 p.m., with a small inset for the remainder of the time between 6 p.m. and 6 a.m. We found that 86% of the fills occurred between 6 a.m. and 6 p.m., with 14% being done at night. The distribution is relatively uniform with steady usage between 8 a.m. and 4 p.m., with a mild peak at lunchtime with 9% occurring then. The conclusion from this analysis is that with a uniform distribution of when people refuel, a station that has on-site production can either be sized to meet that demand and then essentially shut off at night, or it can be sized (smaller) for the average over a 24-hour period and have a larger on-site hydrogen storage buffer.

Many questions have arisen about whether the Learning Demonstration vehicles are really being exercised like conventional vehicles, or whether their usage being too "controlled" to match typical driving behavior. To investigate this we looked the time of day people initiated their trips and which day of the week the trips were occurring on. Figure 12 shows the familiar clock-face radial histogram, but now the data represent the time of day at which people initiated their trips rather than when they refueled their vehicles. Overlaid on top of that we have placed red diamonds to show the national statistics, based on the 2001 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 to 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. However, overall the percentage of trips taken between 6 a.m. and 6 p.m. matches extremely

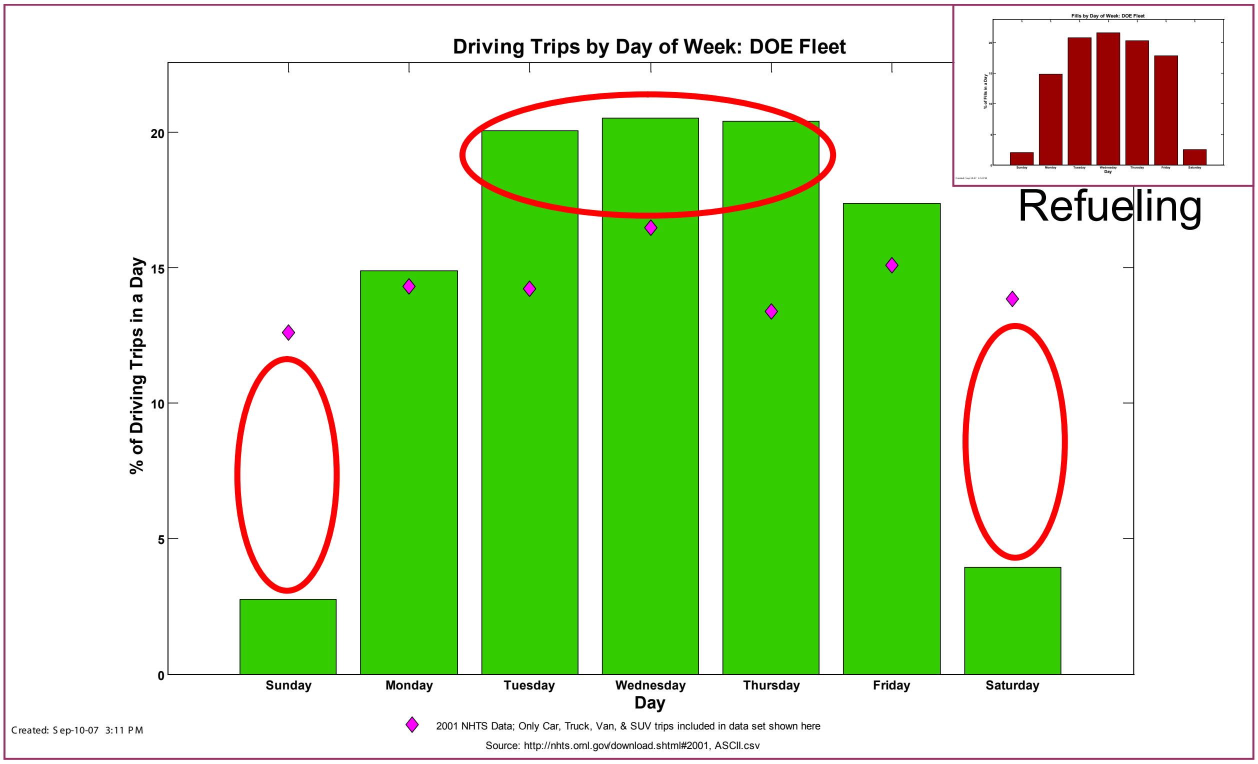


Figure 13: Day of week Learning Demonstration vehicles were driven (and refueled) relative to national statistics

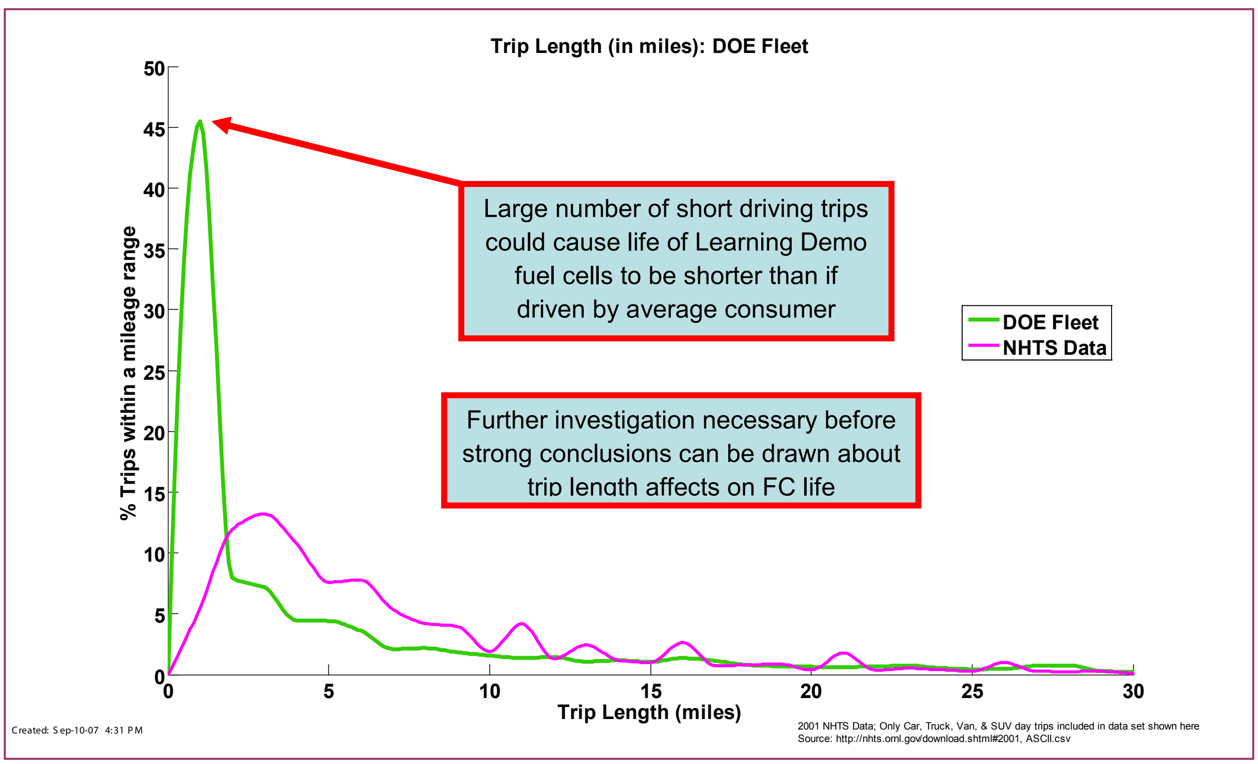


Figure 14: Length of Learning Demonstration trips compared to national statistics

close to the national statistics (80.0% vs. 80.1%). Nighttime driving behavior also matches closely with the national statistics.

We also examined the days of the week that people drove the FCVs and compared this with the national statistics. This was where we found the biggest difference, and really the only place where operation of the first-generation vehicles might be considered too "controlled." Figure 13 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 throughout the week (including 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 is not reflective of typical national behavior.

Finally, we examined the length of Learning Demonstration driving trips and compared that to the national statistics. Figure 14 shows that the Learning Demonstration fleet (green curve) has a sharp peak with almost ½ the trips being shorter than two miles. 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 tied together based on our analysis rather of the real-world data. We will also focus additional time to make sure that there are not a large number of bad data files (with essentially no data in them) that could be unduly influencing these trip distance results.

7. CONCLUSIONS

The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project has now completed over two years of operation with the data being delivered to NREL's Hydrogen Secure Data Center for analysis. This represents more than 149,000 individual vehicle trips and 40 GB of raw on-road data, coming from 77 vehicles and 14 project stations. Aggregate results, called composite data products, have been developed to report on project progress, with this most recent set being the fourth and including 41 results. While this paper highlights just some of the results, they are all available to the public from NREL's new Web site. As more first-generation vehicle data are accumulated, some teams are demonstrating long fuel cell durability with the highest team projection at more than 1,200 hours and the average rising to more than 800 hours. To answer the question of what is causing the stacks to degrade, NREL initiated work to characterize how each stack is used and then performed multivariate analysis on this database to examine dominant variables affecting stack voltage degradation rate. Early results indicate that trends across all four teams may be hard to make, but that individual results for each team should be useful to the teams and for feeding back trends into the R&D program. Using new data on communication vs. non-communication fills, we found that while communication fills demonstrated a higher rate of fill than non-communication, the bulk of the communication fills were actually slower than the non-communications fills. 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, and an abundance of short trips.

ENDNOTE

[1]This work has been authored by an employee of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy. The publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

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LEAD AUTHOR

Mr. Keith Wipke has worked at NREL in the area of advanced vehicles for 14 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 Master's degree in mechanical engineering from Stanford University. Mr. Wipke can be reached at keith_wipke@nrel.gov.