National Fuel Cell Vehicle Learning Demonstration: Status and Results

California Air Resources Board
2009 ZEV Symposium

Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden\textsuperscript{1}, John Garbak\textsuperscript{2}

September 21, 2009
Cal/EPA, Sacramento, CA

\textsuperscript{1}NREL, \textsuperscript{2}US Dept. of Energy

This presentation does not contain any proprietary, confidential, or otherwise restricted information

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

• Project Objectives and Partners
• Overall Project Status
• Vehicle Analysis Results
• Infrastructure Analysis Results
• Summary
Fuel Cell Vehicle Learning Demonstration
Project Objectives and Targets

- Objectives
  - Validate H₂ FC Vehicles and Infrastructure in Parallel
  - Identify Current Status and Evolution of the Technology
  - Objectively Assess Progress Toward Technology Readiness
  - Provide Feedback to H₂ Research and Development

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>2009</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Stack Durability</td>
<td>2000 hours</td>
<td>5000 hours</td>
</tr>
<tr>
<td>Vehicle Range</td>
<td>250+ miles</td>
<td>300+ miles</td>
</tr>
<tr>
<td>Hydrogen Cost at Station</td>
<td>$3/gge</td>
<td>$2-3/gge</td>
</tr>
</tbody>
</table>

Photo: NREL

Solar Electrolysis Station, Sacramento, CA

Photo: NREL
Industry Partners: Four Automaker/Energy-Supplier Teams
Vehicle Deployment Complete at 140 FCVs, Some Early Vehicles Retired

Vehicle Deployment by On-Board Hydrogen Storage Type

- 700 bar on-road
- 350 bar on-road
- Liquid H2 on-road
- 700 bar retired
- 350 bar retired
- Liquid H2 retired

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
DOE Learning Demo Fleet Has Surpassed 100,000 Vehicle Hours and 2.3 Million Miles

Gen 2 vehicles make up most of 2nd bulge at low hours/miles

Some Gen 1 vehicles have now been retired (red bars)
Project Exploring 4 Types of Hydrogen Refueling Infrastructure: Delivered and Produced On-Site

Mobile Refueler
Sacramento, CA

Delivered Liquid, 700 bar
Irvine, CA

Steam Methane Reforming
Oakland, CA

Water Electrolysis
Santa Monica, CA

Total of 115,000 kg H₂ produced or dispensed
Refueling Stations Test Performance in Various Climates; Learning Demo Stations Comprise ~1/3 of all U.S. Stations

- SF Bay Area: 5 stations
- Detroit Area: 7 stations
- DC to New York: 6 stations
- Los Angeles Area: 17 stations
- Orlando Area: 2 stations

Legend:
- ▲ Chevron & Hyundai/Kia
- ▲ DaimlerChrysler & BP
- ▲ Ford & BP
- ▲ General Motors & Shell
- ▲ Air Products
- ▲ Other Companies
Average Ambient Temperature of Learning
Demo Vehicles Spans Most Climates

Average Ambient Trip Temperature: DOE Fleet

- Max Op = 140.0 °F
- Min Op = -5.8 °F
- 26.9 % trips above 28 °C
- 1.4 % trips below 0 °C

Data distributed normally around 20°C

More time spent below freezing due to Gen 2 freeze capability

Created: Aug-14-09 4:47 PM
72 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months

A small subset of the 72 latest results follow

Last Briefing to CARB Was 3 Years Ago with 24 Results
While Improving Durability and Freeze Capability, FC System Efficiency Stays High

**Diagram:**

**Fuel Cell System Efficiency**

- **Gen 1:**
  - Eff. at 25% Pwr: 51 - 58%
  - Eff. at 100% Pwr: 30 - 54%

- **Gen 2:**
  - Eff. at 25% Pwr: 53 - 59%
  - Eff. at 100% Pwr: 42 - 53%

**DOE Target at 25% Power:**
- Gen 1: 51 - 58%
- Gen 2: 53 - 59%

**DOE Target at 100% Power:**
- Gen 1: 30 - 54%
- Gen 2: 42 - 53%

---

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

- **Dyno (1)**
  - One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAE J2572.
- **Window-Sticker (2)**
  - Adjusted combined City/Hwy fuel economy (0.78 x Hwy, 0.9 x City).
- **On-Road (3)(4)**
  - Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
  - Calculated from on-road fuel cell stack current or mass flow readings.

Created: Aug-27-09 3:32 PM
Driving Range for Gen 1 and Gen 2 Vehicles: Based on Fuel Economy and Usable H₂

Vehicle Range¹

Dyno Range (2)  Window-Sticker Range (3)  On-Road Range (4)(5)

- 250-mile 2008 milestone met
- Gen 2 Vehicle Range Shows Significant Improvement from 700 bar Storage
- Note: All Learning Demo Vehicles Based on Existing Platforms

(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.

Created: Aug-27-09 3:32 PM
Gen 1 and Gen 2 Stack Operating Hours and Projected Time to 10% Voltage Drop

DOE Learning Demonstration Fuel Cell Stack Durability: Based on Data Through 2009 Q2

- **Actual Operating Hours Accumulated To-Date**
- **Projected Hours to 10% Voltage Degradation**

**Gen 1** projections are encouraging.

- **Max Hrs Accumulated**: Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
- **Avg Hrs Accumulated**: Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM's fleet.
- **Projection to 10% Voltage Degradation**: Degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEMs end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure.

Range bars are created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.

- **Gen 1 FC stacks have demonstrated >2000 hours without repair**

Projections will change as additional data are accumulated. The shaded projection bars represent an engineering judgment of the uncertainty on the "Avg Projection" due to data and methodology limitations. Projections were modified beginning with 2009 Q2 data, includes an upper projection limit based on demonstrated op hours.
Fuel Cell Stack Operation Hours; Early in Gen 2 Life, But Results Encouraging

Many Gen 1 Stacks Retired with <400 Hours; Some with Very High Hours

Very Few Gen 2 Stacks Retired Due to Low Performance; Most Still in Operation

1) Stack currently accumulating hours
2) Stack removed for low performance
3) Stack not currently accumulating hours, but not removed because of low performance

Created: Sep-09-09 10:48 AM
Max Fuel Cell Power Degradation – Gen 1

Note that degradation flattens out after ~200 hours

Need ~1000 hours to see degradation curve flatten out

1) Normalized by fleet median value at 200 hours.
2) Each segment point is median FC power (+/-50 hrs).
   Box not drawn if fewer than 4 points in segment.
Max Fuel Cell Power Degradation – Gen 2

From limited Gen 2 data received so far, trend of flattening after 200 hours appears similar. Too early to tell how much flatter the tail will be.

1) Normalized by fleet median value at 200 hours.
2) Each segment point is median FC power (+/-50 hrs).
Box not drawn if fewer than 4 points in segment.
Projected Hours to OEM Low Power Operation Limit

Projections based on OEM power limits will improve with more hours.

1. Low fuel cell power limit is dependent on the fuel cell vehicle system and is unique to each company in this Learning Demonstration.
2. Acceptable low vehicle performance limit will be determined by retail customer expectations.
3. Power projection method based on the voltage degradation techniques, but uses max fuel cell power instead of voltage at a specific high current.
4. Stacks with less than 200 operation hours are in separate groups because the projection is based on operation data and with operation hours greater than 200 the degradation rate tends to flatten out.
Fuel Cell System (including H2 storage)
Close to 2010 and 2015 W/L and W/kg Targets

Significant Improvements Seen in Specific Power
(…systems getting lighter)

Power Density Held Similar Between Gen 1 and Gen 2
(…same size or larger)
Refueling Times are Short; Amounts are Reflective of Demonstration-Sized Systems

Average Refueling Time is 3.26 minutes.

Average Refueling Amount is 2.14 kg.
Actual Vehicle Refueling Rates from 21,000 Events: Measured by Stations or by Vehicles

Histogram of Fueling Rates
All Light Duty Through 2009Q2

5 minute fill of 5 kg at 350 bar
3 minute fill of 5 kg at 350 bar

Average rate = 0.78 kg/min
24% of refueling events exceeded 1 kg/min

Created: Aug-14-09 10:08 AM
Refueling Rates by Year: ~1/4 Now Exceed 1 kg/min, 2009 to be Highest # of Fills

Histogram of Fueling Rates
All Light Duty by Year Through 2009Q2

<table>
<thead>
<tr>
<th>Year</th>
<th>Avg (kg/min)</th>
<th>%&gt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.66</td>
<td>16%</td>
</tr>
<tr>
<td>2006</td>
<td>0.74</td>
<td>21%</td>
</tr>
<tr>
<td>2007</td>
<td>0.81</td>
<td>26%</td>
</tr>
<tr>
<td>2008</td>
<td>0.77</td>
<td>23%</td>
</tr>
<tr>
<td>2009</td>
<td>0.79</td>
<td>26%</td>
</tr>
</tbody>
</table>

Comparison by Year
Communication H₂ Fills Achieving 39% Higher Average Fill Rate than Non-Communication

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2009Q2

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Avg (kg/min)</th>
<th>%&gt;1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comm</td>
<td>0.92</td>
<td>36%</td>
</tr>
<tr>
<td>Non-Comm</td>
<td>0.66</td>
<td>13%</td>
</tr>
</tbody>
</table>

Comm. Fills Can Achieve Higher Fill Rates

Non-Comm Has a 2nd Peak at ~0.2 kg/min

Comparison by Comm.
H₂ FCVs Offer Significant Reduction of GHGs, even from Natural Gas Ref.

1. Well-to-Wheels greenhouse gas emissions based on DOE’s GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all teams (as used in CDP #6); conversion efficiency values are the production efficiency data used in CDP #13.

2. Baseline conventional passenger car and light duty truck GHG emissions are determined by GREET 1.8b, based on the EPA window-sticker fuel economy of a conventional gasoline mid-size passenger car and mid-size SUV, respectively. The Learning Demonstration fleet includes both passenger cars and SUVs.

3. The Well-to-Wheels GHG probability distribution represents the range and likelihood of GHG emissions resulting from the hydrogen FCV fleet based on window-sticker fuel economy data and monthly conversion efficiency data from the Learning Demonstration.

4. On-site electrolysis GHG emissions are based on the average mix of electricity production used by the Learning Demonstration production sites, which includes both grid-based electricity and renewable on-site solar electricity. GHG emissions associated with on-site production of hydrogen from electrolysis are highly dependent on electricity source. GHG emissions from a 100% renewable electricity mix would be zero, as shown. If electricity were supplied from the U.S. average grid mix, average GHG emissions would be 1245 g/mile.
Summary

- Learning Demo evaluation is ~80% complete
  - 140 vehicles and 20 stations deployed
  - 2.3 million miles traveled, 115,000 kg H₂ produced or dispensed
  - 346,000 individual vehicle trips analyzed
  - Project to continue through 2010

- Emphasis from project has been on providing maximum value from the data collected during project
  - 72 results have been published
  - Updates every 6 months
  - Current results are always available on our web page

- Vehicle/Station Status
  - 2nd generation vehicles have now been on road for >1 year
  - Station deployment nearing completion; some early stations retired

- Similar Evaluations Now Underway at NREL for FC Forklifts & Backup Power
Questions and Discussion

Primary Contact: Keith Wipke, National Renewable Energy Lab
303.275.4451 keith.wipke@nrel.gov

All public Learning Demo and FC Bus Evaluation papers and presentations are available online at http://www.nrel.gov/hydrogen/proj_tech_validation.html

The NREL Learning Demo Analysis Team in Colorado
Additional Results for Reference
Fuel Cell Start Times from Sub-Freezing Soak Conditions

Some FC Systems Today Would Meet Customer Cold Startup Expectations; Improvements Ongoing

(1) Learning Demo soak temperature for freeze tests were between -9 and -20 °C
(2) 2010 & 2015 DOE MYPP Cold Start Up Time Target: 30 seconds to 50% of rated power from -20 °C (soak duration not specified).
Comparison of Fueling Rates for 350 and 700 bar Pressure Fueling Events

Histogram of Fueling Rates
350 vs 700 bar Fills - All Light Duty Through 2009Q2

Comparison by Pressure

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Avg (kg/min)</th>
<th>%&gt;1</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 bar</td>
<td>0.82</td>
<td>29%</td>
<td>17847</td>
</tr>
<tr>
<td>700 bar</td>
<td>0.62</td>
<td>3%</td>
<td>3792</td>
</tr>
</tbody>
</table>

5 minute fill of 5 kg at 350 bar

3 minute fill of 5 kg at 350 bar

700 bar fills are currently 27% slower than 350 bar fills
10% Voltage Drop Is One Metric – Sensitivity of Projections to % Voltage Drop

Fuel Cell Stack Projected Hours as a Function of Voltage Drop

Gen 1 Average Projections
Gen 1 Average Projection to 10% Voltage Degradation
Gen 2 Average Projections
Gen 2 Average Projection to 10% Voltage Degradation

Gen 2 average fleet projections are actually higher than Gen 1 projections, however due to less operation data for Gen 2, these projections are limited by demonstrated hours to minimize extrapolations.

(1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance.
(2) Projections using on-road data – degradation calculated at high stack current.
(3) Curves generated using the Learning Demonstration average of each individual fleet average at various voltage degradation levels.
(4) The projection curves display the sensitivity to percentage of voltage degradation, but the projections do not imply that all stacks will (or do) operate at these voltage degradation levels.
(5) The voltage degradation levels are not an indication of an OEM’s end-of-life criteria and do not address catastrophic stack failures such as membrane failure.
(6) All OEM Gen 2 average fleet projections are higher than Gen1 projections, however due to less operation data for Gen 2, these projections are limited by demonstrated operation hours to minimize extrapolations.