United States National Hydrogen Fuel Cell Vehicle and Infrastructure Learning Demonstration – Status and Results

2009 JHFC Conference

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Outline

• Project Objectives and Partners
• NREL’s Role in the Project and Methodology
• How to Access Complete Results
• 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
  • 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

Bell Electrolysis Station, Sacramento, CA

Photo: NREL
Industry Partners: 4 Automaker/Energy-Supplier Teams

Gen 1
Gen 2
Gen 1
Gen 2
Gen 2
Gen 1 & 2
Significant Number of Gen 2 Vehicles Now Deployed, Some Early Vehicles Retired

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL

Additional vehicles were added in 2008 Q3-Q4
Majority of Project’s Fixed Infrastructure to Refuel Vehicles Has Been Installed – Examples of 4 Types

Production Technology

- Delivered Compressed H2
- Natural Gas On-site Reforming
- Electrolysis
- Delivered Liquid H2

Total of >60,000 kg H2 produced or dispensed

Stations added since June 2008: Burbank, Long Beach, Ardsley, LAX-east

20 stations now deployed through Dec.
Refueling Stations Test Performance in Various Climates; Learning Demo Comprises ~1/4 of all US Stations

Legend:
- ▲ Chevron & Hyundai/Kia
- ▲ DaimlerChrysler & BP
- ▲ Ford & BP
- ▲ General Motors & Shell
- ▲ Air Products
- ▲ Other Companies

SF Bay Area
- 5

Detroit Area
- 7

Los Angeles Area
- 17

DC to New York
- 5

Orlando Area
- 2

Feb-18-2009
Large Data Sets Processed with NREL Tools; Two Types of Results Serve a Diverse Audience

Through December 2008: 311,000 individual vehicle trips 64 GB of on-road data


Individual Team Discussions

NREL HSDC

Data Flow

Composite Data Products

Detailed Data Products
53 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months

Only a subset of these results is presented today
Ranges of Fuel Economy from Dynamometer and On-Road Data Similar for Gen 1 & 2

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

Created: Sep-22-08 11:51 AM
Vehicle Range Based on Dyno Results and Usable H2 Fuel Stored On-Board

Vehicle Range\(^1\)

- **2015 Target**
- **2009 Target**

<table>
<thead>
<tr>
<th>Gen 1</th>
<th>Gen 2</th>
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<tbody>
<tr>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>250</td>
<td></td>
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</tbody>
</table>

250-mile 2008 milestone met

Gen 2 Vehicle Range Shows Significant Improvement with 700 bar Storage

(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.
Comparison of FC System Specific Power and Power Density Between Gen 1 to Gen 2

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

Power Density Did Not Improve Between Gen 1 and Gen 2 (…same size or larger)
Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet

1. **FC Stack** voltage & current polarization fit
Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet

1. **FC Stack** voltage & current polarization fit

2. **FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)
Improved Method for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet

1. **FC Stack** voltage & current polarization fit

2. **FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)

3. **Fleet** weighted average using FC Stack operating hour projections and weights (based on data and confidence in fit)

Note, 10% voltage drop is a DOE target/metric, not an indicator of end-of-life
Some Gen 1 FC Stacks Have Now Accumulated a Significant Number of Hours Without Repair

DOE Learning Demonstration Fuel Cell Stack Durability: Based on Data Through 2008 Q2

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

- 2006 Target (DOE Milestone)
- 2009 Target

(1) Range bars created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.
(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 on the "Avg Projection" due to data and methodology limitations. Projections will change as additional data are accumulated.
(6) Projection method was modified beginning with 2008 Q2 data.

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While Most of FC Time is Spent at Idle, Bulk of Energy is at 20-50% Power

~50% time at <5% FC power

18.4%-43.7% of operating time at idle (Vehicle Speed = 0 & F.C. Power > 0)
Gen 1 Baseline Dyno Tests Validated High Efficiency at ¼ Power Point – Gen 2 Efficiency Results Public in 2009

Fuel Cell System\(^1\) Efficiency\(^2\) at ~25% Net Power.

Steady-State Efficiency at ¼ power on dyno: 52.5% to 58.1%

High-efficiency point is well matched to where most of FCV energy is expended

1 Gross stack power minus fuel cell system auxiliaries, per DRAFT SAEJ2615.

2 Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Excludes power electronics and electric drive.

Created: Aug-29-06 4:09 PM
Fuel cell vehicles are operating in some extreme temperature conditions. 2nd gen vehicle tests will determine ability to start in cold temperatures.
Hydrogen Production Conversion Efficiency

Production conversion efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.
On-Site Hydrogen Production Efficiency vs. Capacity Utilization

1) 100% production utilization assumes operation 24 hrs a day, 7 days a week
2) Production conversion efficiency is defined as the energy of the hydrogen out of the process (on a LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.
3) High correlation with electrolysis data ($R^2 = 0.81$) & low correlation with natural gas data ($R^2 = 0.058$)

Many Learning Demonstration Stations Currently Have Excess Capacity; Higher Utilization Helps Efficiency

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 1296 g/mile.
Hydrogen Impurities by Year and Production Method – Total Sulfur

Data is from Learning Demonstration and California Fuel Cell Partnership testing. Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, and Year 3 is 2007Q3-2008Q2.

*Total S calculated from SO2, COS, H2S, CS2, and Methyl Mercaptan (CH3SH).

Most sulfur measurements continue to be detection-limited, but detection-limits continue to improve with time.

This is 1 of over a dozen impurities now reported by time and production technology.
Actual Vehicle Refueling *Times* and *Amounts* from 11,500 Events: Measured by Stations or by Vehicles

*Histogram of Fueling Times*
All Light Duty Through 2008Q2

Average time: 3.23 min
88% of refueling events took <5 min

*Histogram of Fueling Amounts*
All Light Duty Through 2008Q2

Average fill amount: 2.24 kg

Includes Communication and Non-Communication Fills

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Actual Vehicle Refueling Rates from 11,500 Events: Measured by Stations or by Vehicles

Histogram of Fueling Rates
All Light Duty Through 2008Q2

Average rate = 0.80 kg/min
25% of refueling events exceeded 1 kg/min

Includes Communication and Non-Communication Fills
Communication H2 Fills Achieving Higher Fill Rate than Non-Communication

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2008Q2

Fill Type | Avg (kg/min) | %>1
---|---|---
Comm | 0.94 | 36%
Non-Comm | 0.68 | 17%

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

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Communication H2 Fills Achieving Higher Fill Rate than Non-Communication

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2008Q2

- Comm
- Non-Comm
- 2006 Tech Val Milestone
- 2010 MYPP Adv Storage Materials Target

Fill Type | Avg (kg/min) | %>1 |
---------|-------------|-----|
Comm     | 0.94        | 36% |
Non-Comm | 0.68        | 17% |

5 minute fill of 5 kg at 350 bar
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Comm Fills Can Achieve Higher Fill Rates
Communication H2 Fills Achieving Higher Fill Rate than Non-Communication

Histogram of Fueling Rates
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Non-Comm Has a Peak at ~0.2 kg/min
Comm Fills Can Achieve Higher Fill Rates

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

- **Learning Demo project is ~75% complete**
  - >122 vehicles and 20 stations deployed
  - 1.5 million miles traveled, 60,000 kg H\(_2\) produced or dispensed
  - 311,000 individual vehicle trips analyzed
  - Project to continue through 2010
- **Many new results in the Fall 2008 composite data products**
  - 50 new/updated results, 3 unchanged, for a total of 53
  - Several Gen 1 vs. Gen 2 vehicle comparisons
  - Hydrogen production efficiency related results
  - Vehicle greenhouse gas estimates using actual production efficiencies
  - Fuel cell system W/kg and W/L
  - Hydrogen impurity breakdown by year and production technology
  - All results available on web site
- **Roll-out of 2\(^{nd}\) generation vehicles continues**
  - All remaining vehicles to be deployed this year
  - Additional 700 bar stations coming online soon
Questions and Discussion

Project Contact: Keith Wipke, National Renewable Energy Lab
303.275.4451 keith_wipke@nrel.gov

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