FCV Learning Demonstration: First-Generation Vehicle Results and Factors Affecting Fuel Cell Degradation

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This presentation does not contain any proprietary or confidential information
Outline

• Objectives and Partners
• Methodology and Data Analysis
• How to Access Full Results
• Highlighted Results
  – Fuel Cell Efficiency and Power Points
  – FC Voltage Degradation and Factors Affecting it
  – Driving and Refueling Behaviors
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>

* To verify progress toward 2015 targets
** Subsequent projects to validate 2015 targets

Photo: NREL

Hydrogen refueling station, Chino, CA

Photo: NREL
Vehicle Status: All of First Generation Vehicles Deployed, 2nd Generation Initial Introduction in Fall 2007
~2/3 of the Project’s Infrastructure to Refuel Vehicles Has Been Installed – 4 Types (examples)

Infrastructure Hydrogen Production Methods

Total: 14

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

Production Technology

Online Stations

4 stations added in last six months

Mobile Refueling
San Francisco, CA

Hydrogen and gasoline station
Washington, DC

Autothermal Reformer
Chino, CA

DTE/BP Power Park
Southfield, MI

Created Aug-23-07
Refueling Stations from All Four Teams Test Vehicle/Infrastructure Performance in Various Climates
>2 Years of Data Analyzed To-Date
Current Status of Data Reporting to the Hydrogen Secure Data Center at NREL

Through August 2007:
>149,000 individual vehicle trips
40 GB of on-road data
NREL Web Page Provides Direct Access to All Composite Data Products


 Select New and Updated Learning Demo Results Follow
On-Road FC Operating Power Points: Dyno Tests Validated
High Efficiency at ¼ Power Point – Key to Overall Efficiency

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

~85% time spent at <40% power
Method for Projecting Time to 10% Fuel Cell Stack Voltage Degradation

Note: 10% is an R&D metric for FC stack degradation. It does not necessarily indicate an end-of-life condition. OEMs may use other values or indicators.

Technique makes performance projection based on all available FC data; Includes reporting confidence in results.
As More Gen 1 Data Is Accumulated, Some Teams Are Demonstrating Long FC Durability

DOE Learning Demonstration Fuel Cell Stack Durability:
Based on Data Through 2007 Q2

Accumulation of FC stack operating hours continues to grow, and we’re approaching the first stack reaching 1000 hours of real-world operation.

(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.
Primary Factors Affecting Learning Demo Fleet Fuel Cell Degradation: FC Diversity (Among Teams) Limits Drawing Strong Conclusions

<table>
<thead>
<tr>
<th>~29% Decay rate variance explained by a combination of the data variables below¹</th>
<th>Correlation to Decay Rate Data</th>
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<tbody>
<tr>
<td>Starts per hour (+)</td>
<td>High decay rate²</td>
</tr>
<tr>
<td>Power levels (high &amp; average) (+)</td>
<td></td>
</tr>
<tr>
<td>Trip length (-)</td>
<td></td>
</tr>
<tr>
<td>Time between trips (+)</td>
<td></td>
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<td>Idle time (+)</td>
<td>High decay rate²</td>
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<td>Power levels (low) (+)</td>
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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.

Created: Aug-31-07 9:00 AM
Learning Demo FCVs Tend to Take Many More Trips <2 Miles Than Compared to National Average

Large number of short driving trips could cause life of Learning Demo Fuel Cells to be shorter than if driven by average consumer

Further investigation necessary before strong conclusions can be drawn about trip length affects on FC life
Easier (but Still Difficult!) to Pull Out Dominant Degradation Factors When Looking at One Team’s Stacks at a Time

1. Results are from partial least squares (PLS) regression analysis of each team’s fleet of vehicles individually
2. First two collections of factors cover ~61%-76% of decay rate variance

Created: Aug-31-07 9:00 AM
Most of Infrastructure Safety Reports are Non-Events (and Most of Those, Alarms Only)

No new incidents or near misses in last 9 months
No Single Dominant Factor Triggering H2 Refueling Station Safety Reports

Primary Factors of Infrastructure Safety Reports Through 2007 Q2

- Calibration/Settings/ Software Controls
- Design Flaw
- Environment (Weather, Power Disruption, Other)
- Inadequate/ Non-working Equipment
- Maintenance Required
- Mischief, Vandalism, Sabotage
- Not Yet Determined
- Operator/Personnel Error

Created: Sep-06-07  7:36 AM
Actual Vehicle Refueling Times and Amounts from >6,300 Events: Measured by Stations or by Vehicles

- **Histogram of Fueling Times**
  - All Light Duty Through 2007Q2
  - Average time: 3.66 min
  - 85% of refueling events took <5 min

- **Histogram of Fueling Amounts**
  - All Light Duty Through 2007Q2
  - Average amount: 2.21 kg

Includes Comm. and Non-Comm. Fills
Actual Vehicle Refueling Rates from >6,300 Events: Measured by Stations or by Vehicles

Histogram of Fueling Rates
All Light Duty Through 2007Q2

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

Average rate: 0.76 kg/min
23% of refueling events exceeded 1 kg/min

Includes Comm. and Non-Comm. Fills
Communication H2 Fills Achieving Higher Fill Rate than Non-Communication, But Not Uniformly

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2007Q2

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

5 minute fill of 5 kg at 350 bar
3 minute fill of 5 kg at 350 bar
Large Spread in H2 Tank Level at Refueling
Peak at ~1/4 Full, Median at ~3/8 Full

Median Tank Level = 40% at Fill

Tank Levels: DOE Fleet

Total refuelings\(^1\) = 10303

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.
Refueling by Time of Day; Relatively Uniform
Refueling Infrastructure Demand Between 8-4

% of fills b/t 6 AM & 6 PM: 86.0%

1. Fills between 6 AM & 6 PM
2. The outer arc is set at 12 % total Fill.
3. Some events not recorded/detected due to data noise or incompleteness.

Total Fill^3 Events = 9070

(Night)
Driving Trip Start Time – Day; Roughly Matches National Statistics Except for 5-6 PM

% of driving trips b/t 6 AM & 6 PM: 80.0%

% of NHTS trips b/t 6 AM & 6 PM: 80.1%

1. Driving trips between 6 AM & 6 PM
2. The outer arc is set at 10% total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

Source: http://nhts.ornl.gov/download.shtml#2001, ASCII.csv

2001 NHTS Data: Only Car, Truck, Van, & SUV trips included in data set shown here
Summary

• More than half of project completed
  – 77 vehicles and 14 stations deployed
  – 800,000 miles traveled, 30,000 kg H₂ produced or dispensed
  – 114,000 individual vehicle trips analyzed
  – Project to continue through 2009

• Examination of Factors Affecting FC Degradation Initiated
  – More difficult to identify trends across all 4 teams than for each team individually
  – NREL will collaborate with each team to investigate further

• Total of 41 composite data products published to date
  – This presentation only covered some of the new/updated results
  – Web site allows direct web access to all CDPs

• Roll-out of 2nd generation vehicles is beginning now
  – First public 700 bar station opened in U.S. – Irvine
  – Additional 700 bar refueling being installed in next year
Questions and Discussion

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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