Outline

- Project Goals
- Vehicle and H2 Station Deployment Status
- Performance Compared to Targets
- Highlights of Latest Vehicle and Infrastructure Analysis Results and Progress
- Conclusions and Future work
Fuel Cell Electric Vehicle Learning Demo Project Objectives, Relevance, and Targets

• Objectives
  – Validate H₂ FC Vehicles and Infrastructure in Parallel
  – Identify Current Status and Evolution of the Technology

• Relevance
  – Objectively Assess Progress Toward Technology Readiness
  – Provide Feedback to H₂ Research and Development

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

Note: Project extended 2 years to 2011
Two Teams Concluded Their Projects in 2009, Three are Continuing through 2011

Ford/BP and Chevron/Hyundai-Kia Concluded in 2009

Daimler, GM, and Air Products Continue to Demonstrate Vehicles/Stations within Project through 2011
Vehicle Status: All 350 bar Vehicles Retired, Only 700 bar Vehicles Continuing

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

 Cumulative Vehicles Deployed/Retired

- 2005Q2
- 2005Q3
- 2006Q1
- 2006Q2
- 2006Q3
- 2006Q4
- 2007Q1
- 2007Q2
- 2007Q3
- 2007Q4
- 2008Q1
- 2008Q2
- 2008Q3
- 2008Q4
- 2009Q1
- 2009Q2
- 2009Q3
- 2009Q4
- 2010Q1
- 2010Q2

(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009

Total of ~40 project vehicles expected on road in 2011, for total of ~170 deployed
Fueling Station Status: Stations that Continue to Operate are Mostly Delivered Compressed Hydrogen

Learning Demonstration Hydrogen Stations By Type

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

- Operating Outside of Project
- Operating Within Project
- Historical 2005-2009*

*Some project teams concluded Fall/Winter 2009. Markers show the cumulative stations operated during the 2005-2009 period.
Out of 24 Project Stations, 15 Are Still Operational (2/3 outside of DOE project)

SF Bay Area

Los Angeles Area

DC to New York

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

Cumulative Stations

Reporting Period

Number of Stations

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### Evaluation Against 3 Primary Metrics

<table>
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<tr>
<th>Vehicle Performance Metrics</th>
<th>Gen 1 Vehicle</th>
<th>Gen 2 Vehicle</th>
<th>2009 Target</th>
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<tbody>
<tr>
<td><strong>Fuel Cell Stack Durability</strong></td>
<td></td>
<td></td>
<td>2000 hours</td>
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<tr>
<td>Max Team Projected Hours to 10% Voltage Degradation</td>
<td>1807 hours</td>
<td>2521 hours</td>
<td></td>
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<tr>
<td>Average Fuel Cell Durability Projection</td>
<td>821 hours</td>
<td>1062 hours</td>
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<tr>
<td>Max Hours of Operation by a Single FC Stack to Date</td>
<td>2375 hours</td>
<td>1261 hours</td>
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<tr>
<td><strong>Driving Range</strong></td>
<td>103-190 miles</td>
<td>196-254 miles</td>
<td>250 miles</td>
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<tr>
<td><strong>Fuel Economy (Window Sticker)</strong></td>
<td>42 – 57 mi/kg</td>
<td>43 – 58 mi/kg</td>
<td>no target</td>
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<tr>
<td><strong>Fuel Cell Efficiency at ¼ Power</strong></td>
<td>51 - 58%</td>
<td>53 - 59%</td>
<td>60%</td>
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<tr>
<td><strong>Fuel Cell Efficiency at Full Power</strong></td>
<td>30 - 54%</td>
<td>42 - 53%</td>
<td>50%</td>
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<tr>
<th>Infrastructure Performance Metrics</th>
<th>2009 Target</th>
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<tr>
<td><strong>H₂ Cost at Station (early market)</strong></td>
<td>$3/gge</td>
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<tr>
<td>On-site natural gas reformation</td>
<td>$7.70 - $10.30</td>
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<tr>
<td>On-site Electrolysis</td>
<td>$10.00 - $12.90</td>
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<tr>
<td>Average H₂ Fueling Rate</td>
<td>0.77 kg/min</td>
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<td>1.0 kg/min</td>
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Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
- Distributed natural gas reformation at 1500 kg/day: $2.75-$3.50/kg (2006)
- Distributed electrolysis at 1500kg/day: $4.90-$5.70 (2009)
What are the Differences Between the Spring 2010 and Fall 2010 Results?

**80 Spring 2010 Results**
- Most comprehensive set we ever published
- Includes durability, range, fuel economy, etc.
- Covers data from all 4 Learning Demo teams + CHIP project over 5 year period
- Majority of these will now stay static, serving as a historical record of Gen 1 & Gen 2 comparisons.

**16 Fall 2010 Results**
- No “new” CDPs, but we updated 16 previously published CDPs with data from last 6 months
- Results on most recent durability, range, fuel economy, not yet possible to publish until more data accumulated (in 2011)
- Covers data from 2 Learning Demo OEMs + CHIP project
- Emphasized changes observed in last 6 months through use of gray (old) and colors (new)
Quantified Gen 2 Fuel Cell System Durability* Improvement from Gen 1

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

One Gen 1 stack accumulated almost 2400 hours without maintenance

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

2009 Target

2006 Target

Max Projection
Avg Projection

(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 projection bars 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 2009 Q2 data, includes an upper projection limit based on demonstrated op hours.

* Durability is defined by DOE as projected hours to 10% voltage degradation

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Spring 2010
Fuel Cell Stack Operation Hours Histograms Show Differences Between Gen 1 and Gen 2

- Gen1: 24% of stacks in operation
- Gen2: 34% of stacks 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.

Some project teams concluded in Fall/Winter 2009

Only 2 Gen 2 stacks removed for low performance
Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation

**Gen1**

- Max Fuel Cell Power Loss vs Op Hours: Gen1
- Data Range
- 25th & 75th Percentiles
- Group Median
- Outlier

**Note that degradation flattens out after ~200 hours**

**Need ~1000 hours to have higher confidence in slope of degradation**

All vehicles continuing in the project will be Gen 2 vehicles

**Gen2**

- Max Fuel Cell Power Loss vs Op Hours: Gen2
- Data Range
- 25th & 75th Percentiles
- Group Median
- Outlier

From limited Gen 2 data received so far, trend of flattening after 200 hours appears similar

Gen 2 results have larger degree of uncertainty projected against 2000 hour target

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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 3 points in segment.
Developed Methodology for Tracking FC System Voltage Transients

1) Define a voltage transient cycle

Cycle Definition:
\[ dV \geq 10\% \text{ Nom Stack V} \]
\[ dT_{ss} \geq 10 \text{ sec} \]
\[ dV_{ss} \leq 5\% \text{ Nom Stack V} \]

2) Find voltage transient cycles

3) Categorize and collect voltage transient cycle details

Cycle Categories:
(a) (b) (c) (d) (e)
Quantified Transient Cycle Reduction Between Gen 1 and Gen 2 FC Systems

1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

Significant reduction in transients observed
Characterized Fuel Cell Transient Rates by Cycle Category

Type: The slow down, fast up are the most common transients

This characterization of transients will be used in future multivariate analysis

1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change >= 5 seconds. SS = Steady State, where the time change is >= 10 seconds and the voltage change is <= 2.5% max stack voltage.
Average Hydrogen Per Fill Has Increased 24%, But Based on Much Smaller Sample

Histogram of Fueling Amounts
Vehicle and Infrastructure

- Through 2009Q4
- After 2009Q4

Need more data after 2009Q4 to be able to identify whether there is a solid trend on fueling data

25,464 fills
Average = 2.13 kg

1,730 fills
Average = 2.65 kg
Fueling Times Also Increased: +28%
Putting Those Together: Average Refueling Rate Decreased 14%

Histogram of Fueling Rates
Vehicle and Infrastructure

- 2006 MYPP Tech Val Milestone
- 2012 MYPP Tech Val Milestone
- Through 2009Q4
- After 2009Q4

- 25464 Events
  - Average = 0.77 kg/min
  - 23% >1 kg/min
- 1730 Events
  - Average = 0.66 kg/min
  - 3% >1 kg/min

- 5 kg in 5 minutes
- 5 kg in 3 minutes
Real-World Driving Range Between Refuelings Continues to Improve as Demonstration Progresses

Distance Driven Between Refuelings: All OEMs

Gen1
Refuelings \(^1\) = 18941
Median distance between refuelings = 56 Miles

Gen2
Refuelings \(^1\) = 6870
Median distance between refuelings = 81 Miles

After 2009Q4
Refuelings \(^1\) = 3185
Median distance between refuelings = 91 Miles

+45% improvement

+63% improvement

1. Some refueling events are not detected/reported due to data noise or incompleteness.
2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.

“window-sticker” range from adjusted dyno tests is 196-254 miles
Rate of Mileage Accumulation Has Decreased in the Last Year, But Vehicles Still Added 550,000 Miles

Cumulative Vehicle Miles: All OEMs, Gen 1 and Gen 2

Through 2010 Q2

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Vehicle Miles Traveled: 2,872,533
Based on Limited Number of Fuelings in Last 6 Months, Higher Level of Tank at Refueling Observed

Median Tank Level (At Fill) = 42%
Median Tank Level (At Fill) = 48%

Total refuelings$^1$ = 27113
Total refuelings$^1$ = 3196

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.
Driving Behavior in Last 6 Months
Much More Similar to National Average

% of driving trips b/t 6 AM & 6 PM: 85.3%
% of driving trips b/t 6 AM & 6 PM: 77.1%
% of NHTS trips b/t 6 AM & 6 PM: 81.5%

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

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

Driving by Day of Week

- Through 2009Q4
- After 2009Q4
- NHTS

Sun Mon Tues Wed Thurs Fri Sat

% of Trips in a Day

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

- Project has completed >5 full years of operation
- Vehicle operation: 114,000 hours, 2.87 million miles, 436,000 trips
- H2 station operation: 134,000 kg produced or dispensed, 27,000 refuelings
- DOE Key Technical Targets Met: FC Durability and Range
- Two of the OEMs will be continuing operation of Gen 2 vehicles through end of 2011; progress will be tracked
- Future work: Additional collaboration with remaining auto OEM teams to make analyses useful for technology evolution and preparation for 2014-2015 market entry
- New CA fueling stations planned for inclusion in future results as they come online
Questions and Discussion

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