

# National Hydrogen Learning Demonstration Status



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**February 6, 2012**

**DOE's Informational  
Webinar Series**

**NREL/PR-5600-54244**

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# Outline

- U.S. DOE Learning Demonstration Project Goals
- Fuel Cell Vehicle and H<sub>2</sub> Station Deployment Status
- Technical Highlights of Vehicle and Infrastructure Analysis Results and Progress
- Next Steps and Project Wrap-up



# Fuel Cell Electric Vehicle Learning Demo

## Project Objectives, Relevance, and Targets

- Objectives

- Validate H<sub>2</sub> FC Vehicles and Infrastructure in Real-World Setting
- Identify Current Status and Evolution of the Technology

- Relevance

- Objectively Assess Progress Toward Targets and Market Needs
- Provide Feedback to H<sub>2</sub> Research and Development
- Publish Results for Key Stakeholder Use and Investment Decisions

### Key Targets

Performance Measure	Interim (2009)*	Ultimate (2020)
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	\$3/gge	\$2-4/gge**

Outside review panel

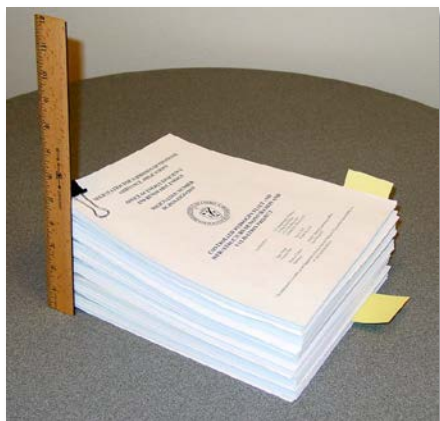
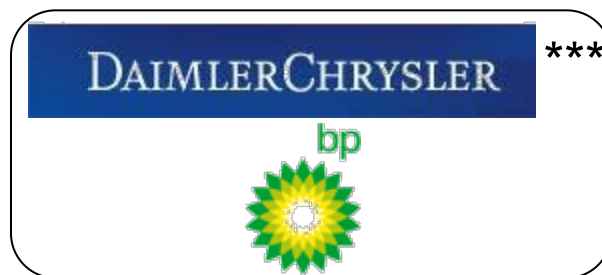
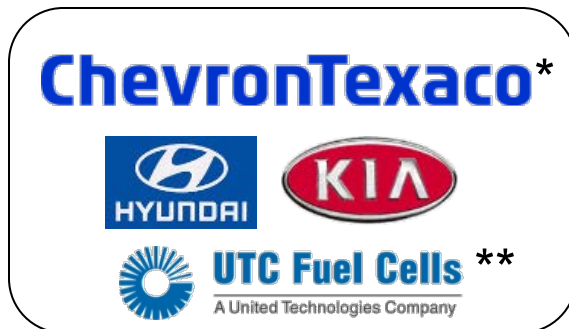
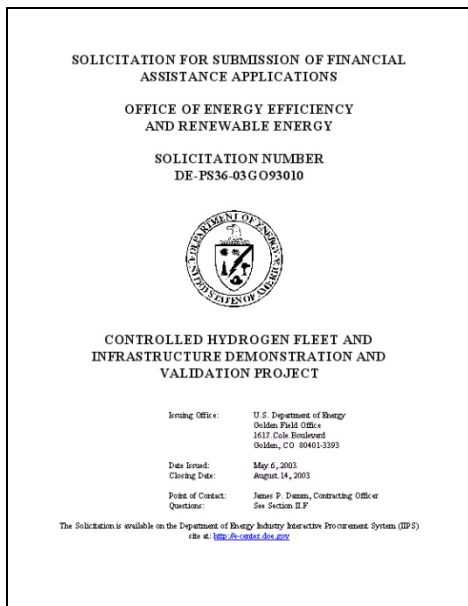
\*Project extended 2 years through 2011; \*\*Previously \$2-3/gge for 2015

Details of each of these 3 results shown later



Burbank, CA station. Photo: NREL

# History: 4 OEM/Energy Teams Selected Competitively through FOA in 2004



DOE funding: \$170M  
 Industry cost share: \$189M  


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 Total: \$359M

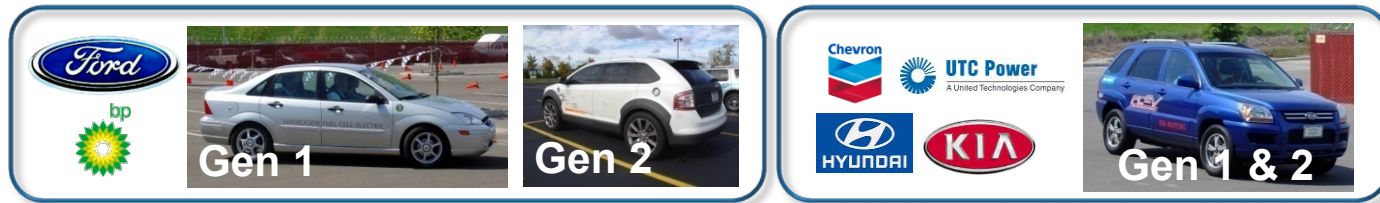
NREL received \$6.6M from DOE for analysis and support of this project since FY03

\* now \*\* now \*\*\* now DAIMLER

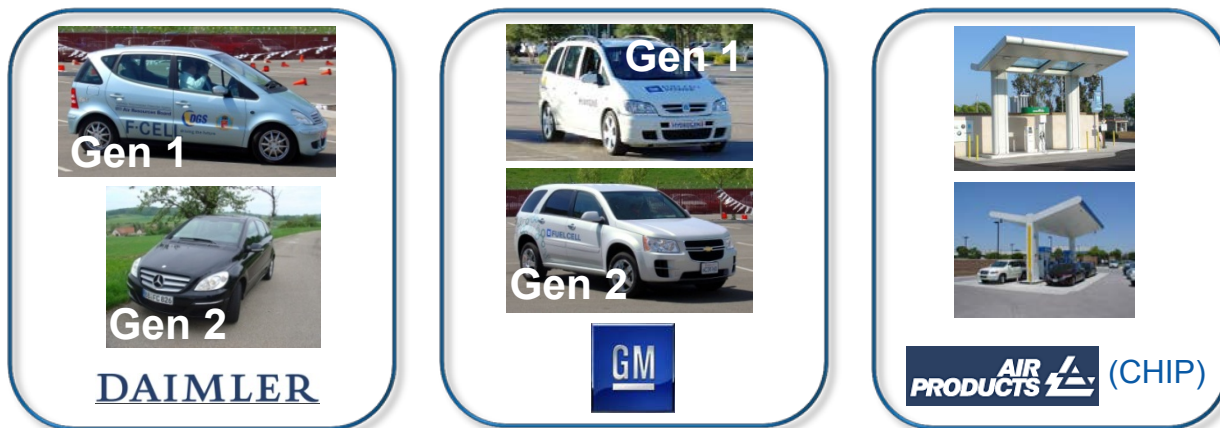
# Involvement of Industry Teams Over 7 Years



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



Daimler, GM, and Air Products (CHIP) Demonstrated Vehicles/Stations within Project through CY2011



# What is NREL's Role? Project Approach

## Supporting Both DOE/Public as Well as Fuel Cell Developers

Bundled data (operation & maintenance/safety) delivered to NREL quarterly



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Bundled data (operation & maintenance/safety) delivered to NREL quarterly



Internal analysis completed quarterly

# HSDC



NREL's Hydrogen Secure Data Center



# What is NREL's Role? Project Approach

## Supporting Both DOE/Public as Well as Fuel Cell Developers

Bundled data (operation & maintenance/safety) delivered to NREL quarterly



DDPs

Internal analysis completed quarterly

# HSDC

NREL's Hydrogen Secure Data Center



Results



CDPs

### Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data<sup>1</sup>

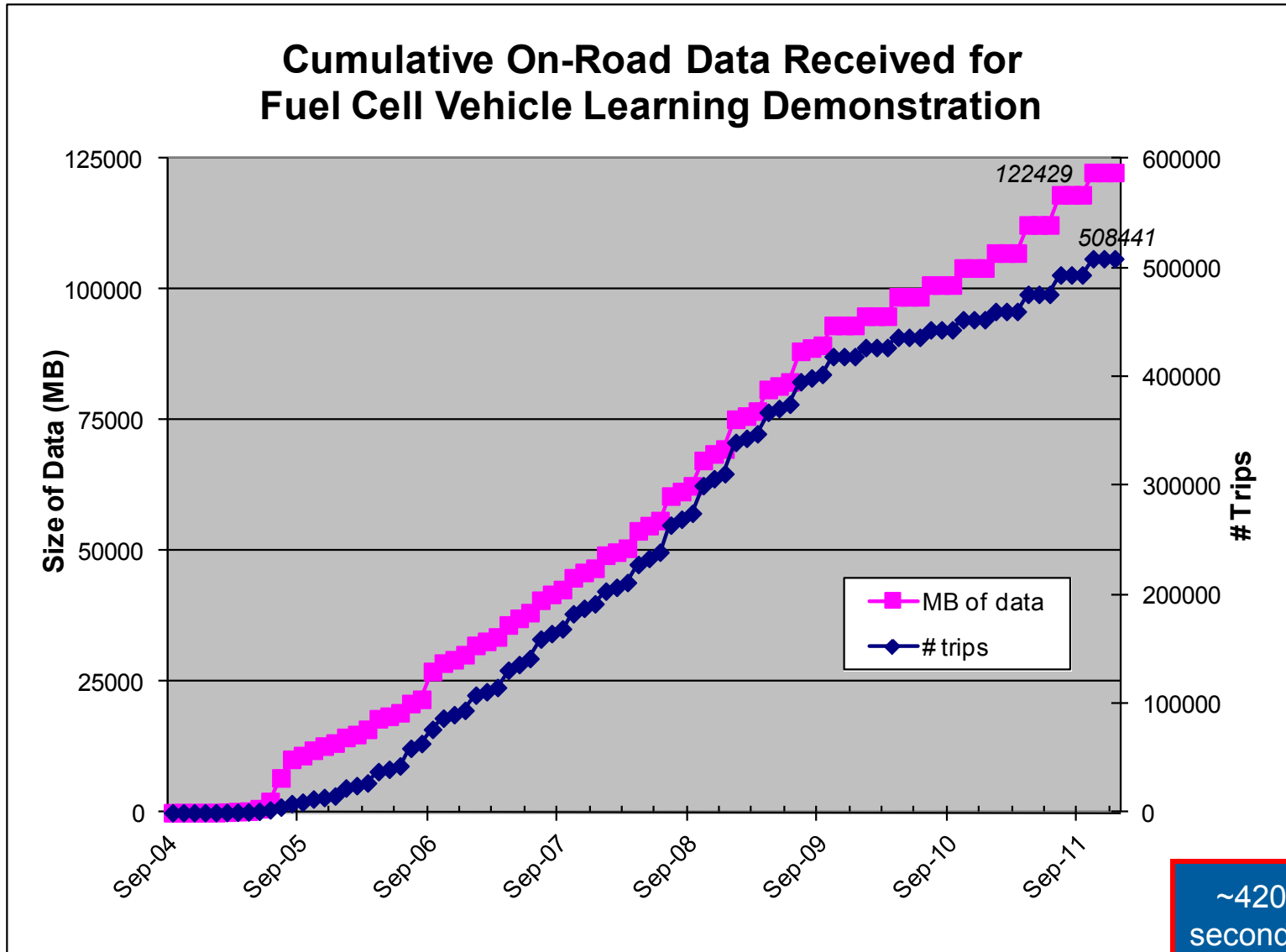
### Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data<sup>2</sup>

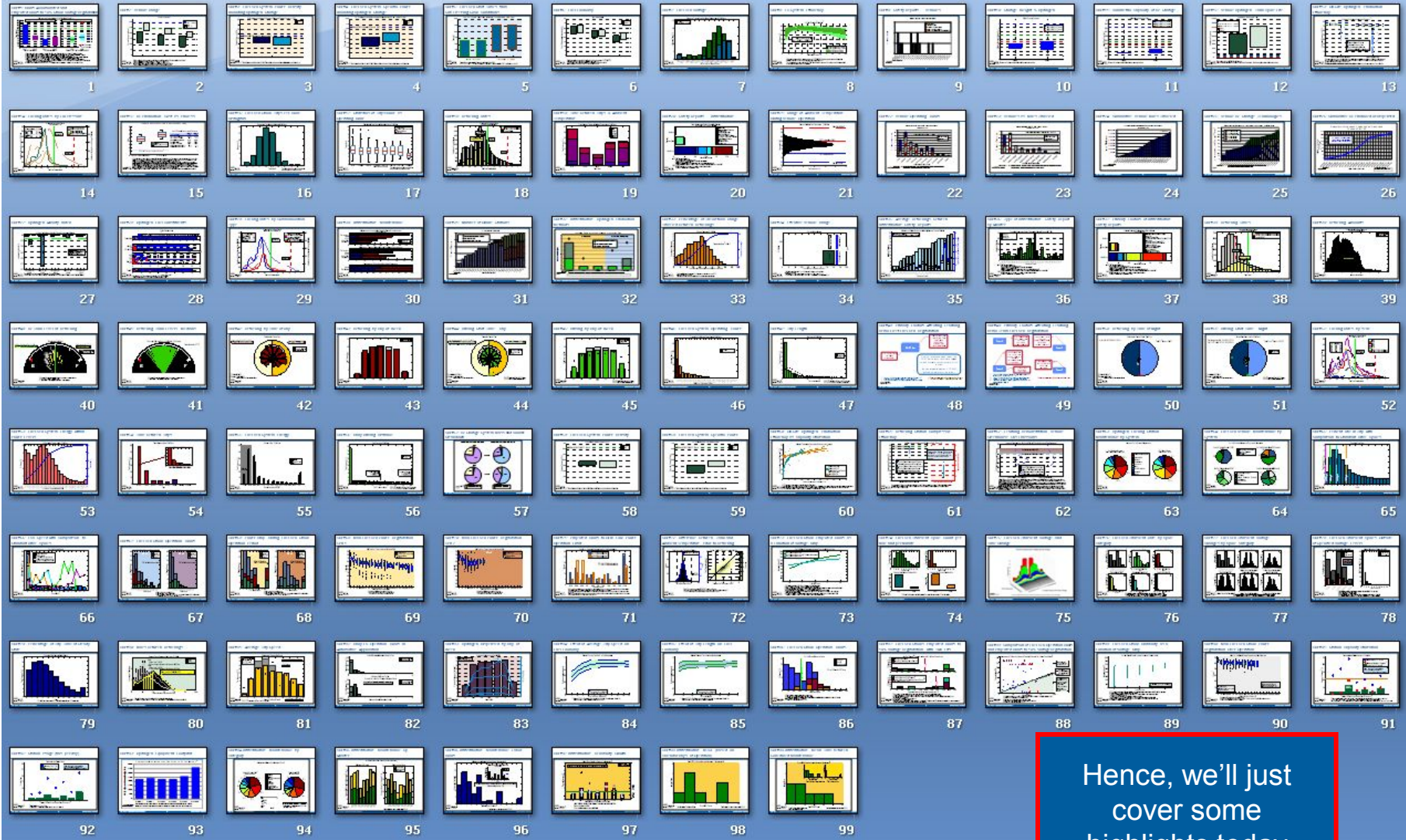
- 1) Data exchange may happen more frequently based on data, analysis, & collaboration
- 2) Results published via NREL Tech Val website, conferences, and reports ([http://www.nrel.gov/hydrogen/proj\\_learning\\_demo.html](http://www.nrel.gov/hydrogen/proj_learning_demo.html))



# This Project Analyzed Massive Amounts of Data: 3.5 M miles and >500,000 vehicle trips (second-by-second)



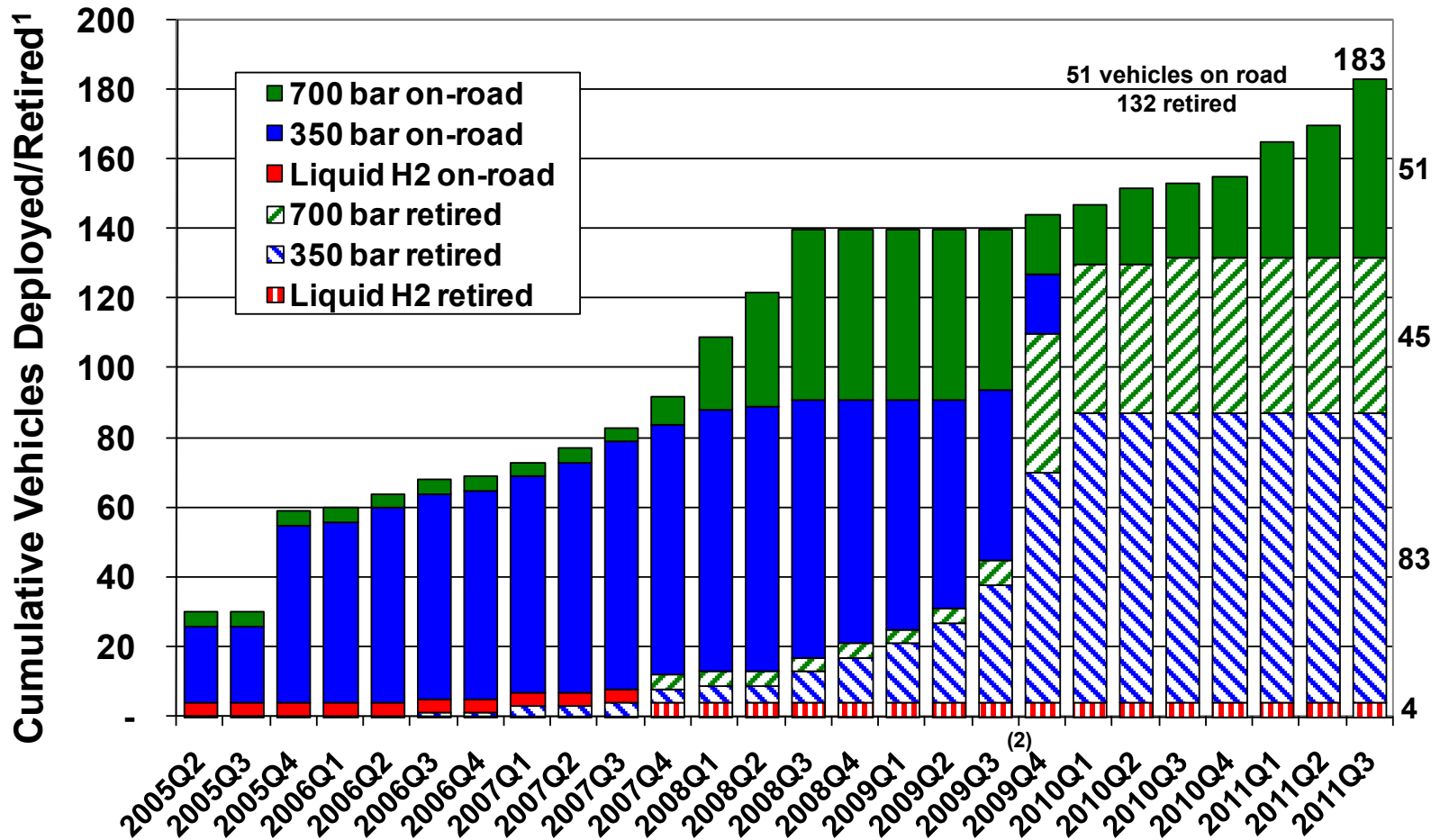
# 99 CDPs in Total (40 Winter 2011 CDPs)



Hence, we'll just cover some highlights today

# Current Vehicle Deployment Status at End of Evaluation Period (9/30/11)

## Vehicle Deployment by On-Board Hydrogen Storage Type



Large # vehicles required for statistical significance

# 2<sup>nd</sup> Generation Vehicles Demonstrated Technology Improvements Over Gen 1

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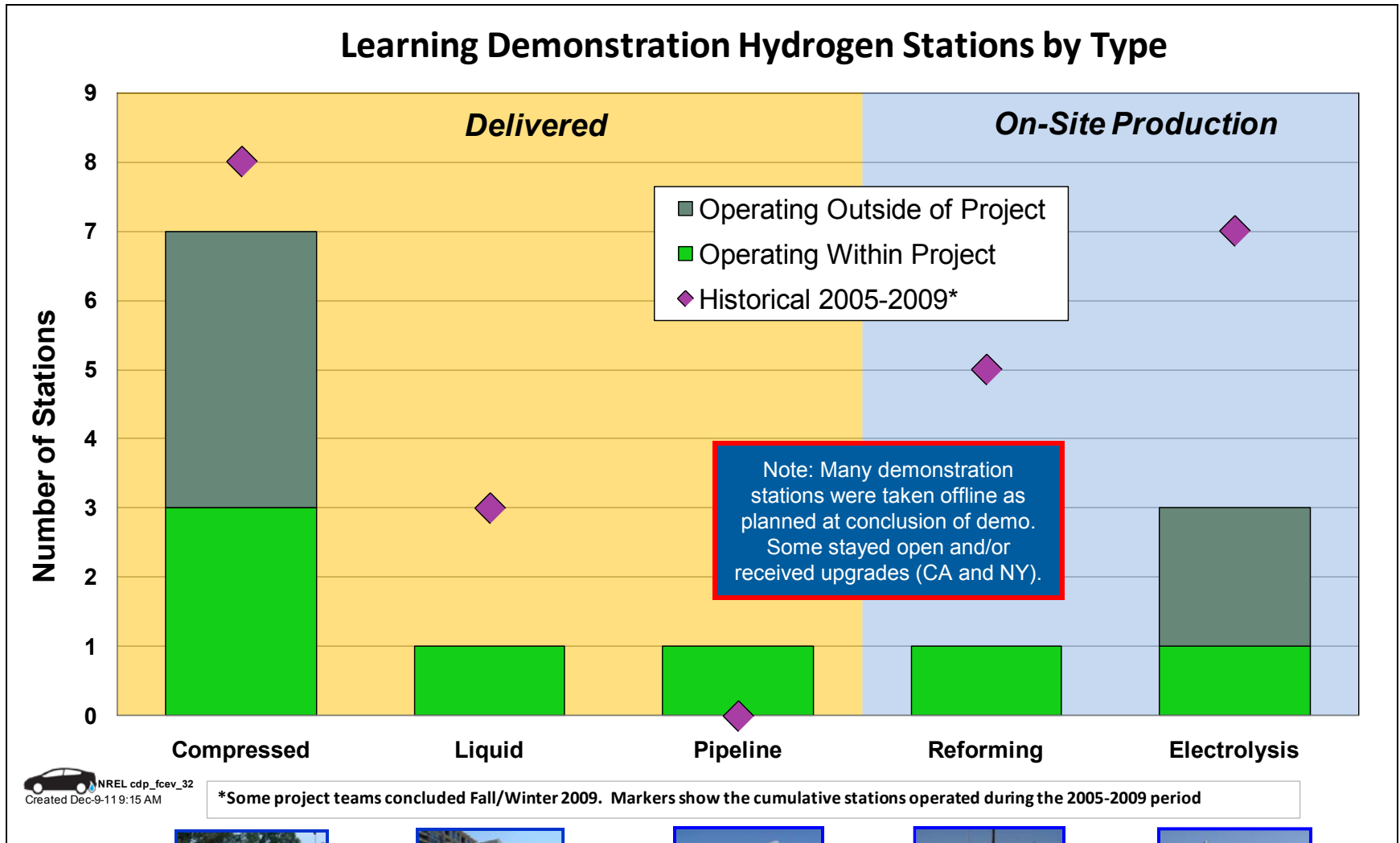
## Generation 1 Vehicles

- FC not freeze-capable
- ~2003 stack technology
- Storage: liquid H<sub>2</sub> & 350 and 700 bar
- Range: 100-200 miles
- Efficiency: 51-58% at 1/4 power

## Generation 2 Vehicles

- FC freeze-capable
- ~2007-2009 stack tech.
- Storage: All 700 bar
- Range: 200-250 miles
- Efficiency: 53-59% at 1/4 power
- Longer FC durability

# Current Infrastructure Status: Demonstration Station Testing Successfully Completed as Planned

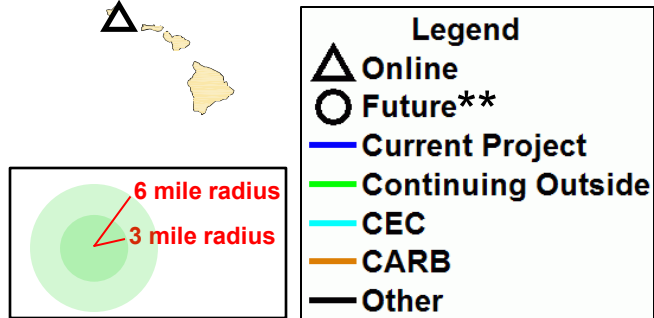
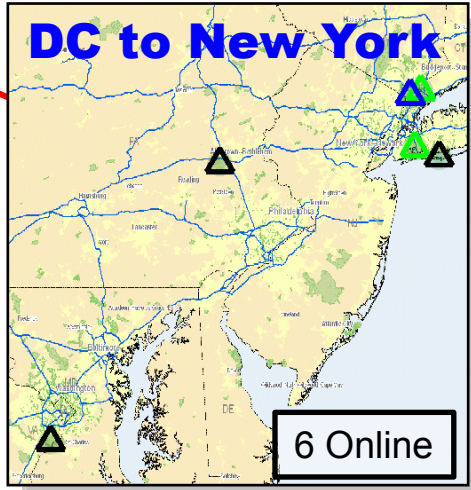
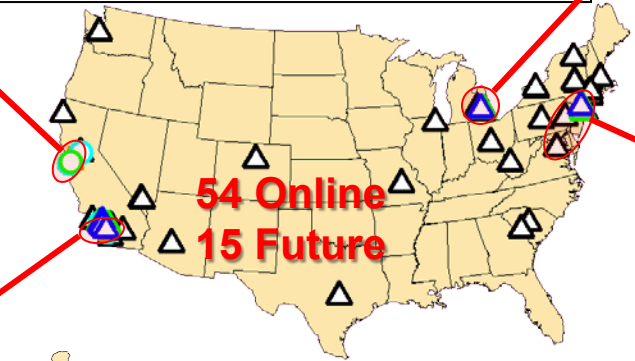
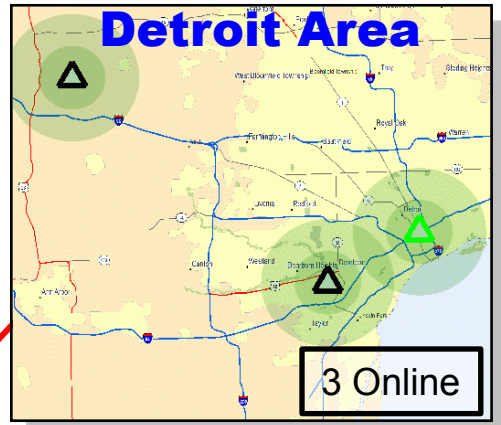
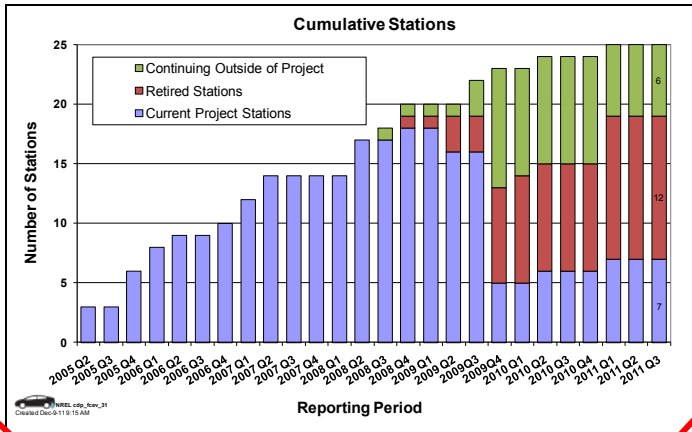
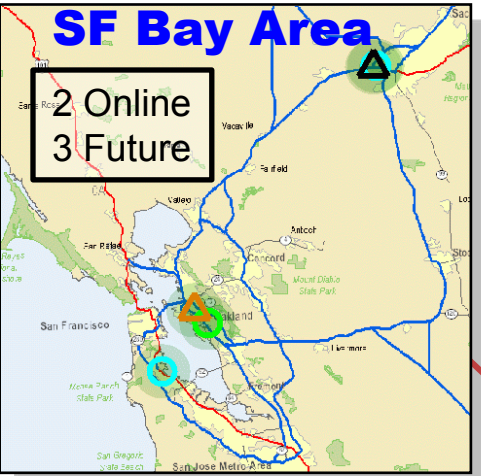


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# Infrastructure Status: Out of 25 Project Stations, 13 Are Still Operational\* (~1/2 outside of DOE project)

\* CDP station status is as of 9/30/11



\*\* Funded by state of CA or others, outside of this project

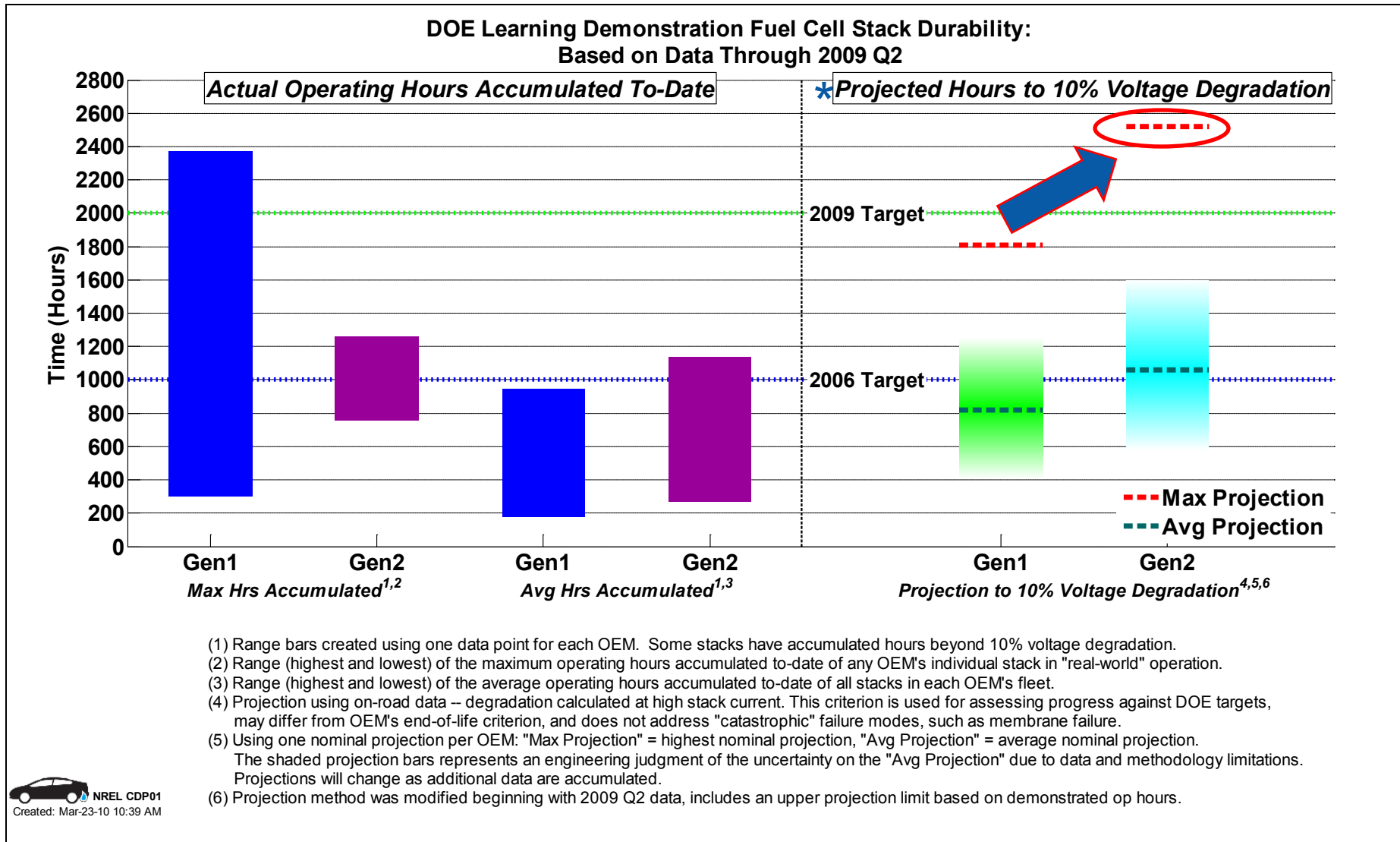
# Project Achieved Both Technical Goals; Outside Analysis Used for Cost Evaluation

Vehicle Performance Metrics			2009 Target
1) <b>Fuel Cell Stack Durability</b>			<b>2000 hours</b>
	Max Team Projected Hours to 10% Voltage Degradation	<b>1807 hours</b>	<b><u>2521</u> hours</b> 
	Average Fuel Cell Durability Projection	821 hours	1062 hours
	Max Hours of Operation by a Single FC Stack to Date	2375 hours	1261 hours 
2) <b>Driving Range</b>		<b>103-190 miles</b>	<b>196-<u>254</u> miles</b> 
	<i>Fuel Economy (Window Sticker)</i>	42 – 57 mi/kg	43 – 58 mi/kg
	<i>Fuel Cell Efficiency at ¼ Power</i>	51 - 58%	53 - <u>59</u> %
	<i>Fuel Cell Efficiency at Full Power</i>	30 - 54%	42 - <u>53</u> %
Infrastructure Performance Metrics			2009 Target
3) <b>H<sub>2</sub> Cost at Station (early market)</b>	On-site natural gas reformation	On-site Electrolysis	<b>\$3/gge</b>
	<b>\$7.70 - \$10.30</b>	<b>\$10.00 - \$12.90</b>	
<i>Average H<sub>2</sub> Fueling Rate</i>	0.77 kg/min		1.0 kg/min

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)



# 1) FC Durability Target of 2000 Hours Met By Gen 2 Projections

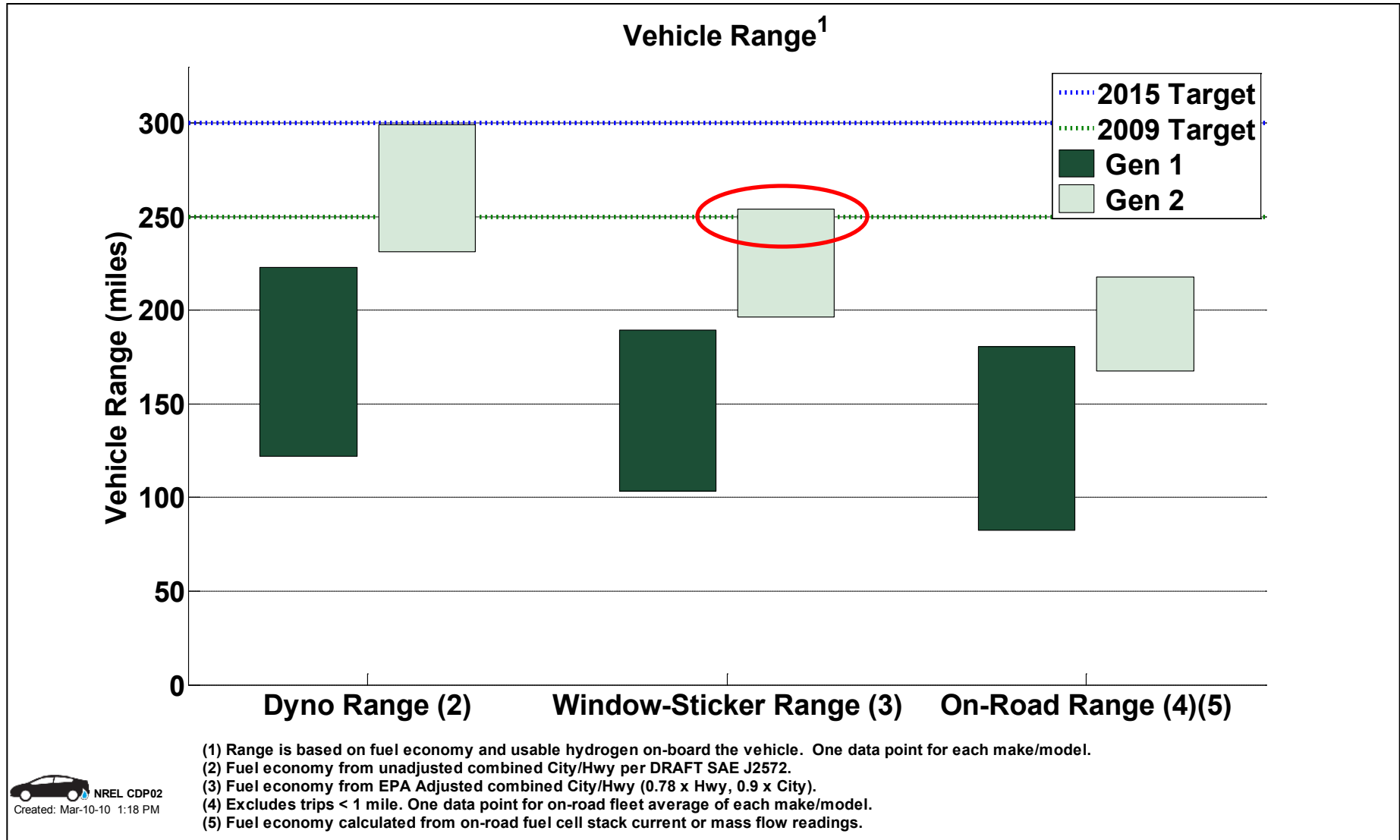


\* Durability is defined by DOE as projected hours to 10% voltage degradation

Spring 2010

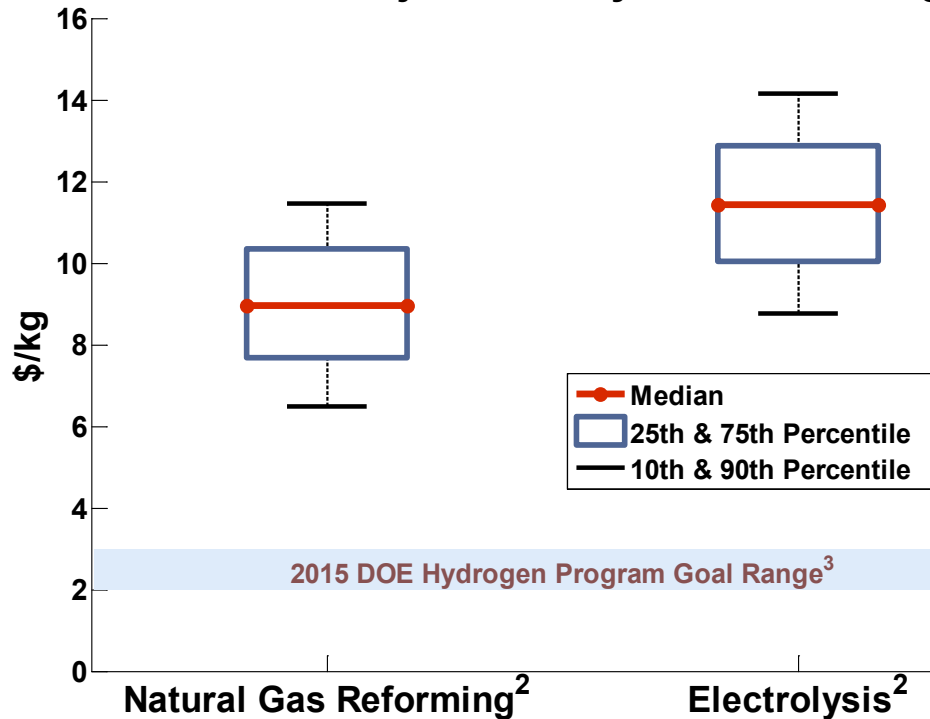


# 2) Vehicle Range Achieved 2009 Target of 250 Miles with Gen 2 Adjusted Fuel Economy



# 3) Projected Early Market H<sub>2</sub> Production Cost from Learning Demo Energy Partners' Inputs

Projected Early Market 1500 kg/day Hydrogen Cost<sup>1 \*</sup>



Key H2 Cost Elements and Ranges		
Input Parameter	Minimum (P10)	Maximum (P90)
Facility Direct Capital Cost	\$10M	\$25M
Facility Capacity Utilization	85%	95%
Annual Maintenance & Repairs	\$150K	\$600K
Annual Other O&M	\$100K	\$200K
Annual Facility Land Rent	\$50K	\$200K
Natural Gas Prod. Efficiency (LHV)	65%	75%
Electrolysis Prod. Efficiency (LHV)	35%	62%

This project provides an excellent learning opportunity, but stations are not meant to emulate high volume replicate stations of the future. Permitting was in transition.

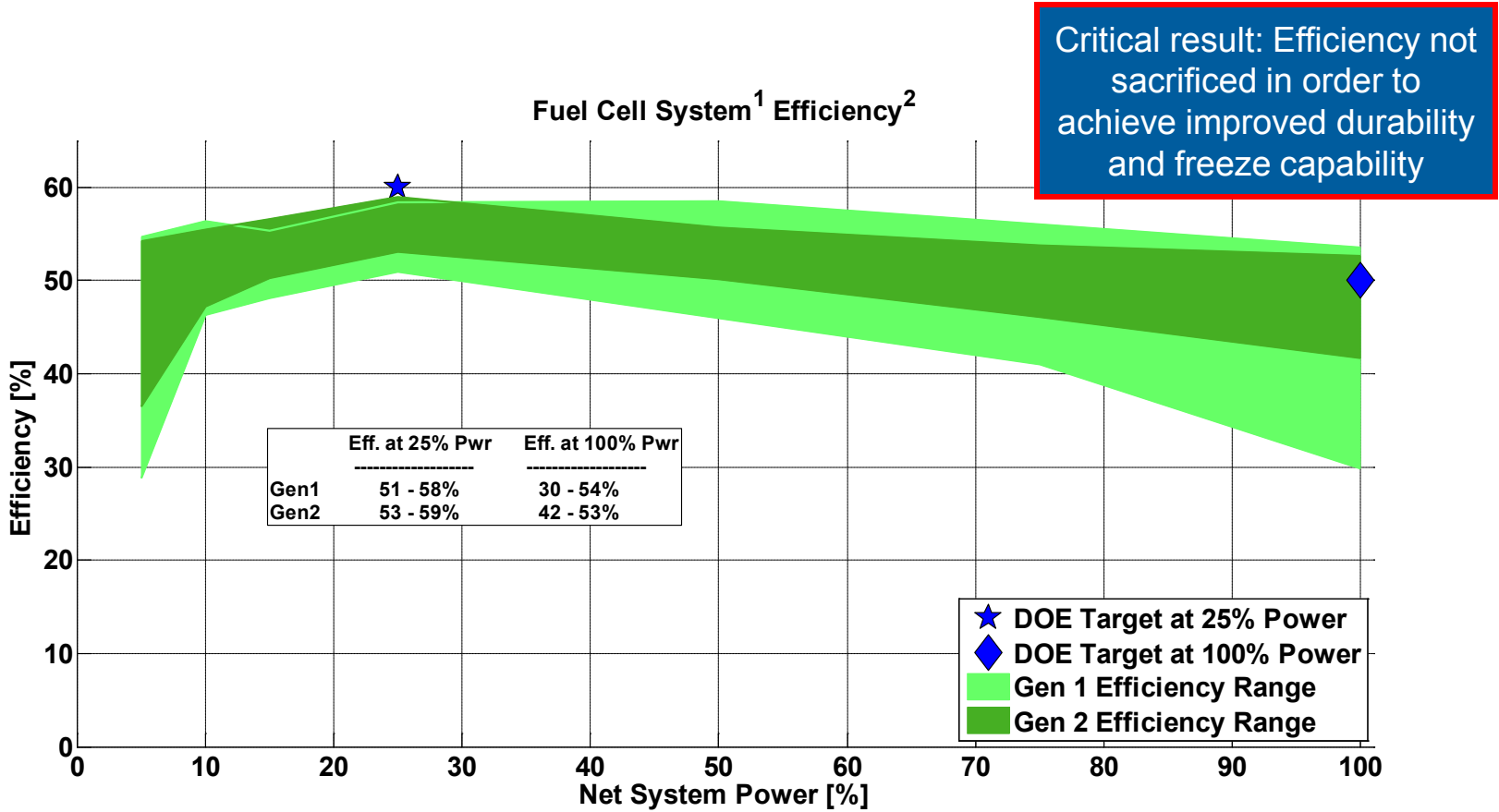
(1) Reported hydrogen costs are based on estimates of key cost elements from Learning Demonstration energy company partners and represent the cost of producing hydrogen on-site at the fueling station, using either natural gas reformation or water electrolysis, dispensed to the vehicle. Costs reflect an assessment of hydrogen production technologies, not an assessment of hydrogen market demand.

(2) Hydrogen production costs for 1500 kg/day stations developed using DOE's H2A Production model, version 2.1. Cost modeling represents the lifetime cost of producing hydrogen at fueling stations installed during an early market rollout of hydrogen infrastructure and are not reflective of the costs that might be seen in a fully mature market for hydrogen installations. Modeling uses default H2A Production model inputs supplemented with feedback from Learning Demonstration energy company partners, based on their experience operating on-site hydrogen production stations. H2A-based Monte Carlo simulations (2,000 trials) were completed for both natural gas reforming and electrolysis stations using default H2A values and 10th percentile to 90th percentile estimated ranges for key cost parameters as shown in the table. Capacity utilization range is based on the capabilities of the production technologies and could be significantly lower if there is inadequate demand for hydrogen.

(3) DOE has a hydrogen cost goal of \$2-\$3/kg for future (2015) 1500 kg/day hydrogen production stations installed at a rate of 500 stations per year.

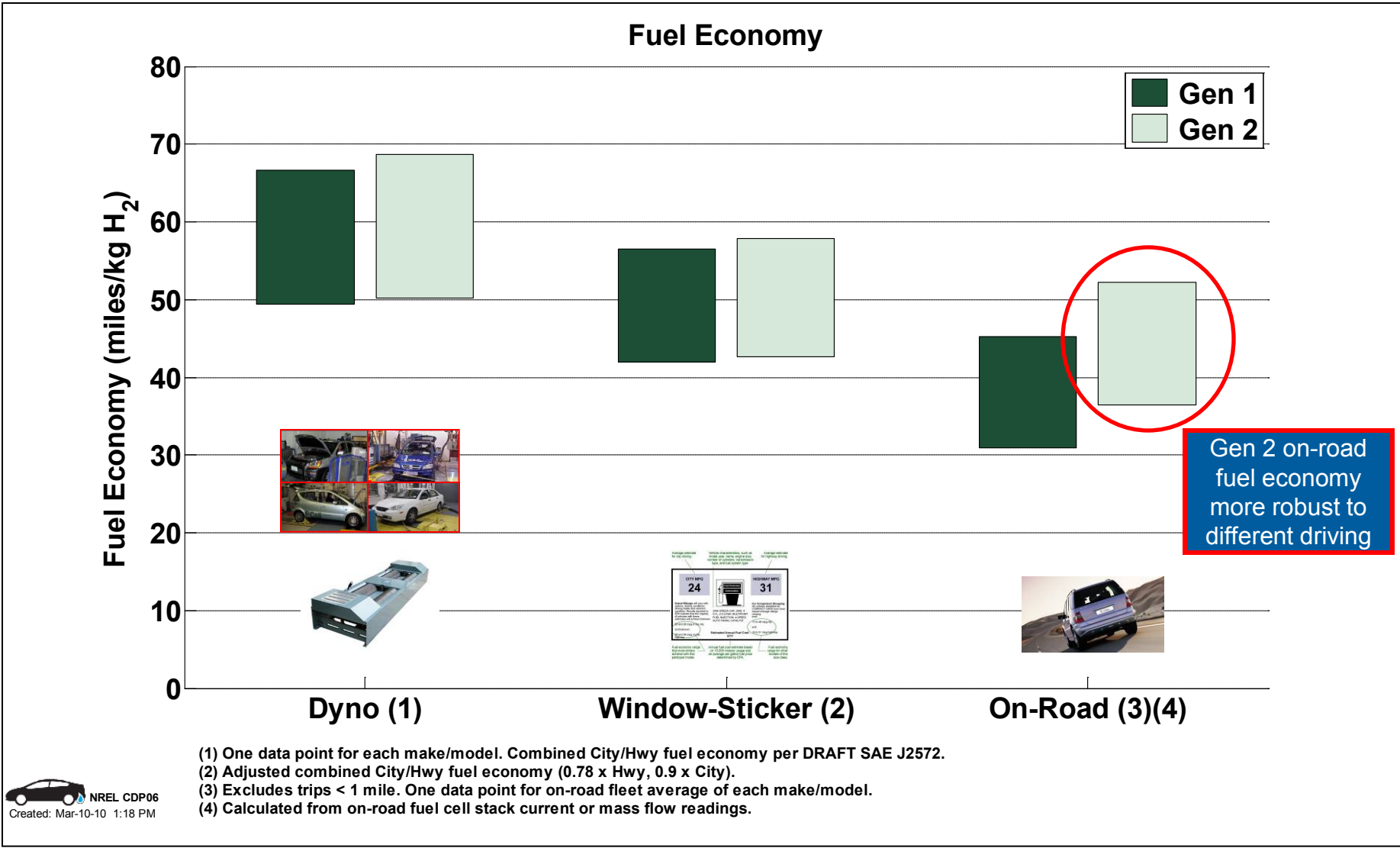
Outside of this project, DOE independent panels concluded at 500 replicate stations/year:  
 Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg** (2006)  
 Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70** (2009)

# EFFICIENCY: Verified High Gen 2 Fuel Cell System Efficiency Maintained (Compared to Gen 1)

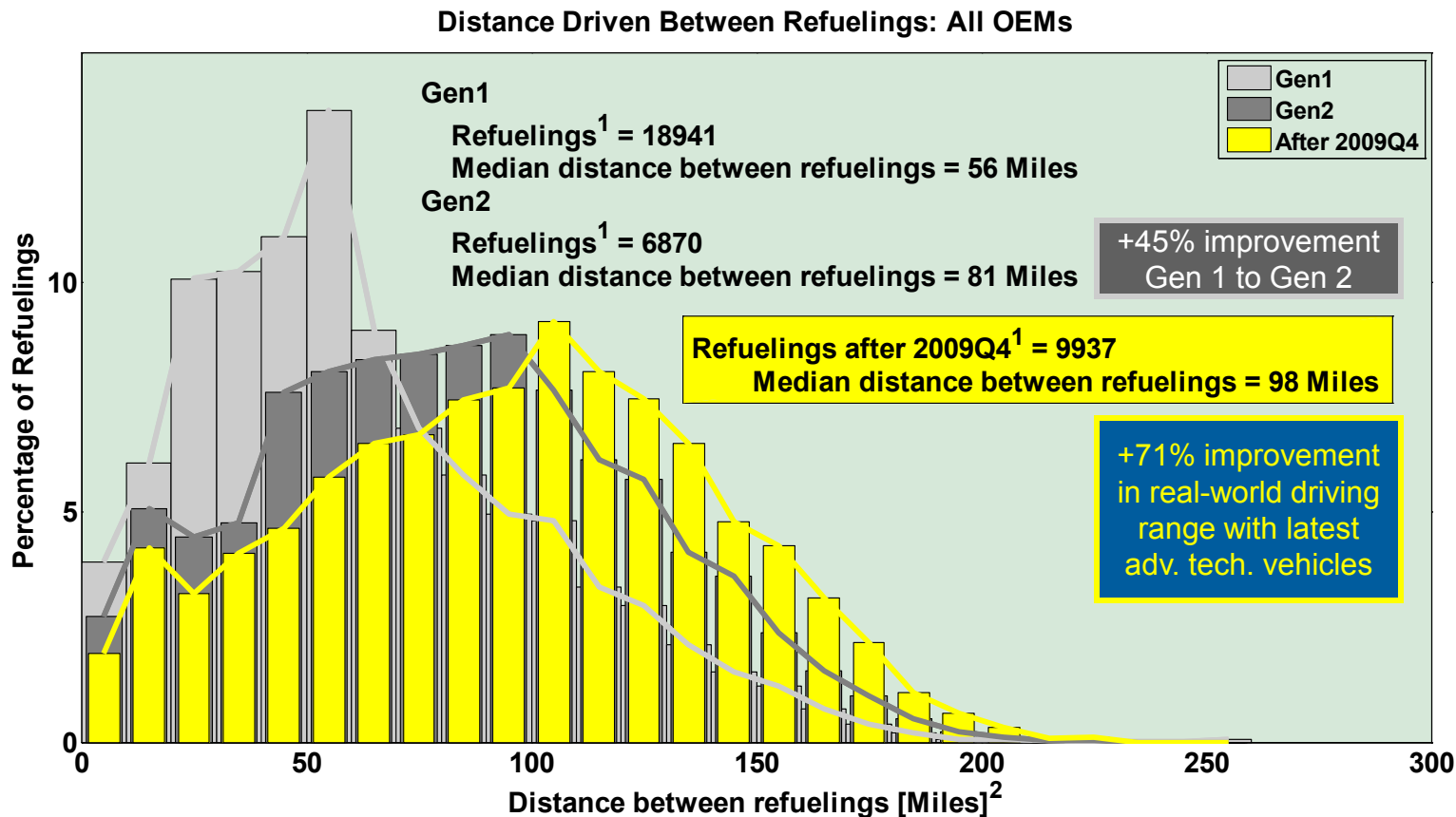


<sup>1</sup> Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.  
<sup>2</sup> Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).  
<sup>3</sup> Individual test data linearly interpolated at 5,10,15,25,50,75,and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

# FUEL ECONOMY: Ranges of Fuel Economy from Dynamometer and On-Road Data Similar for Gen 1 & 2



# RANGE: Results Show Significant Improvement in Real-World Driving Range Between 3 Sets of Vehicles

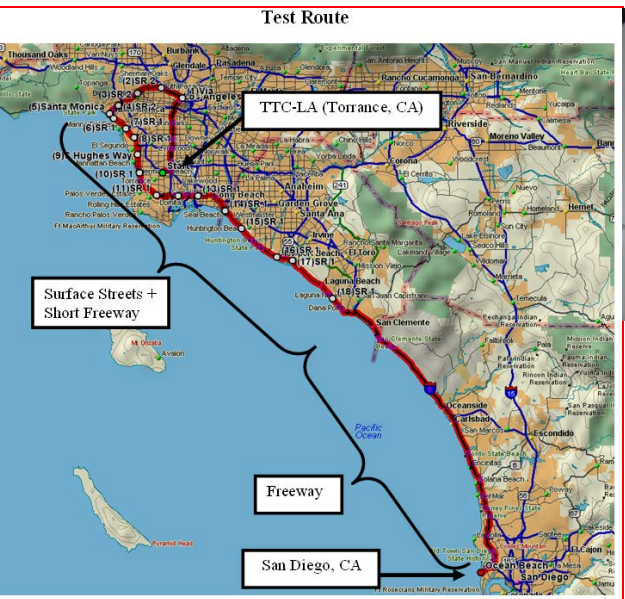


1. Some refueling events are not detected/reported due to data noise or incompleteness.

2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.

Note: Actual range possible >200 miles

# RANGE: NREL/SRNL Experiment Verified Toyota FCHV-adv Capable of up to 430-Mile Driving Range Without Refueling on June 30, 2009



SRNS-STI-2009-00446

## Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions

Keith Wipke<sup>1</sup>, Donald Anton<sup>2</sup>, Sam Sprik<sup>1</sup>

August 10, 2009  
PTS-05 of SRNS CRADA No. CR-04-003

Innovation for Our Energy Future

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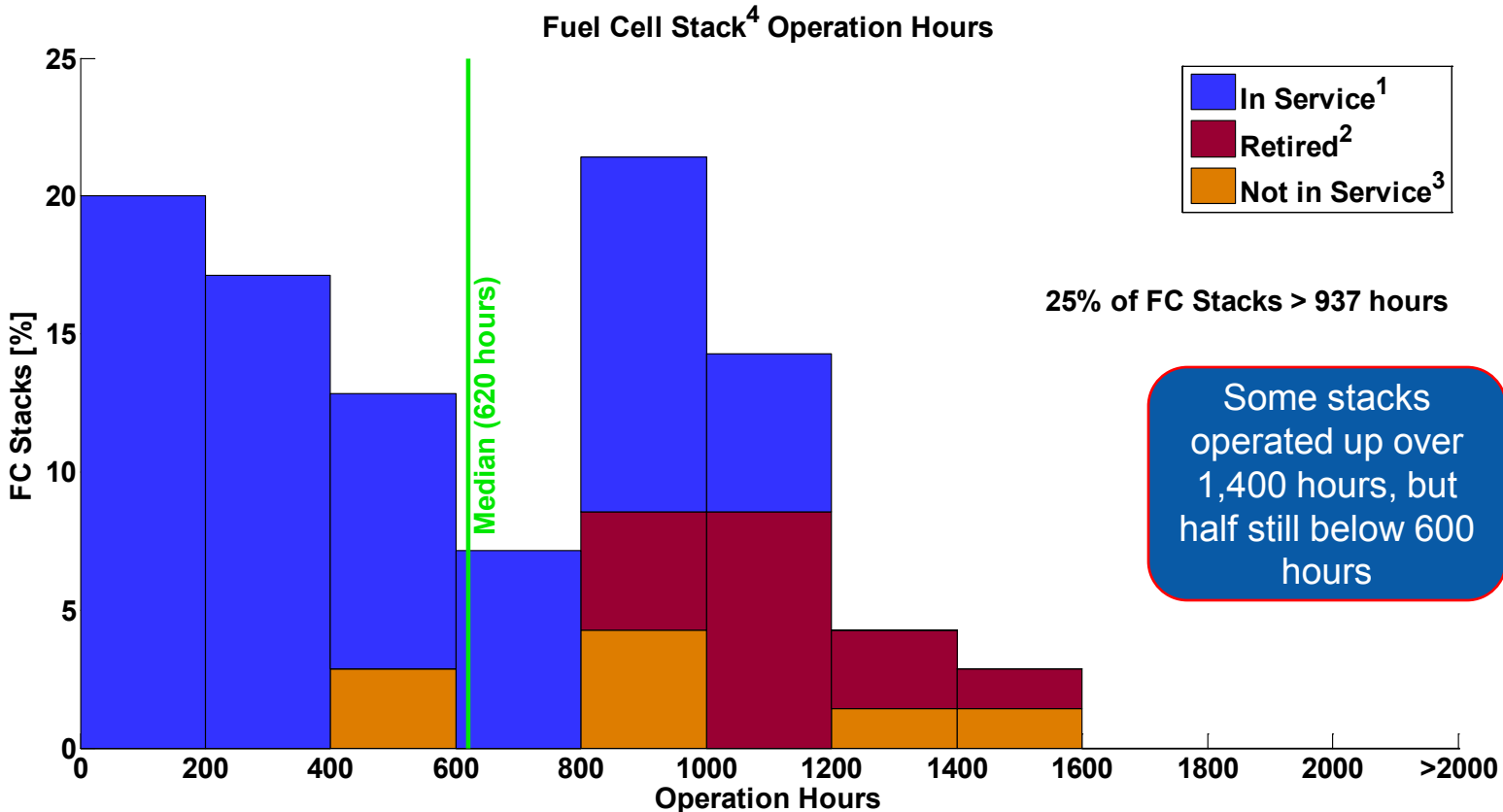
	Average trip distance (miles)	H <sub>2</sub> consumed (kg)	Remaining usable H <sub>2</sub> (kg)	Calculated remaining range (miles)	(miles)	(miles)
Vehicle #1	331.50	4.8255	1.4854	102.04	433.55	<b>431</b>
Vehicle #2	331.45	4.8751	1.4328	97.41	428.87	

Toyota video: <http://www.youtube.com/watch?v=iz0vD5E7glA>

Report: [http://www.nrel.gov/hydrogen/pdfs/toyota\\_fchv-adv\\_range\\_verification.pdf](http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf)

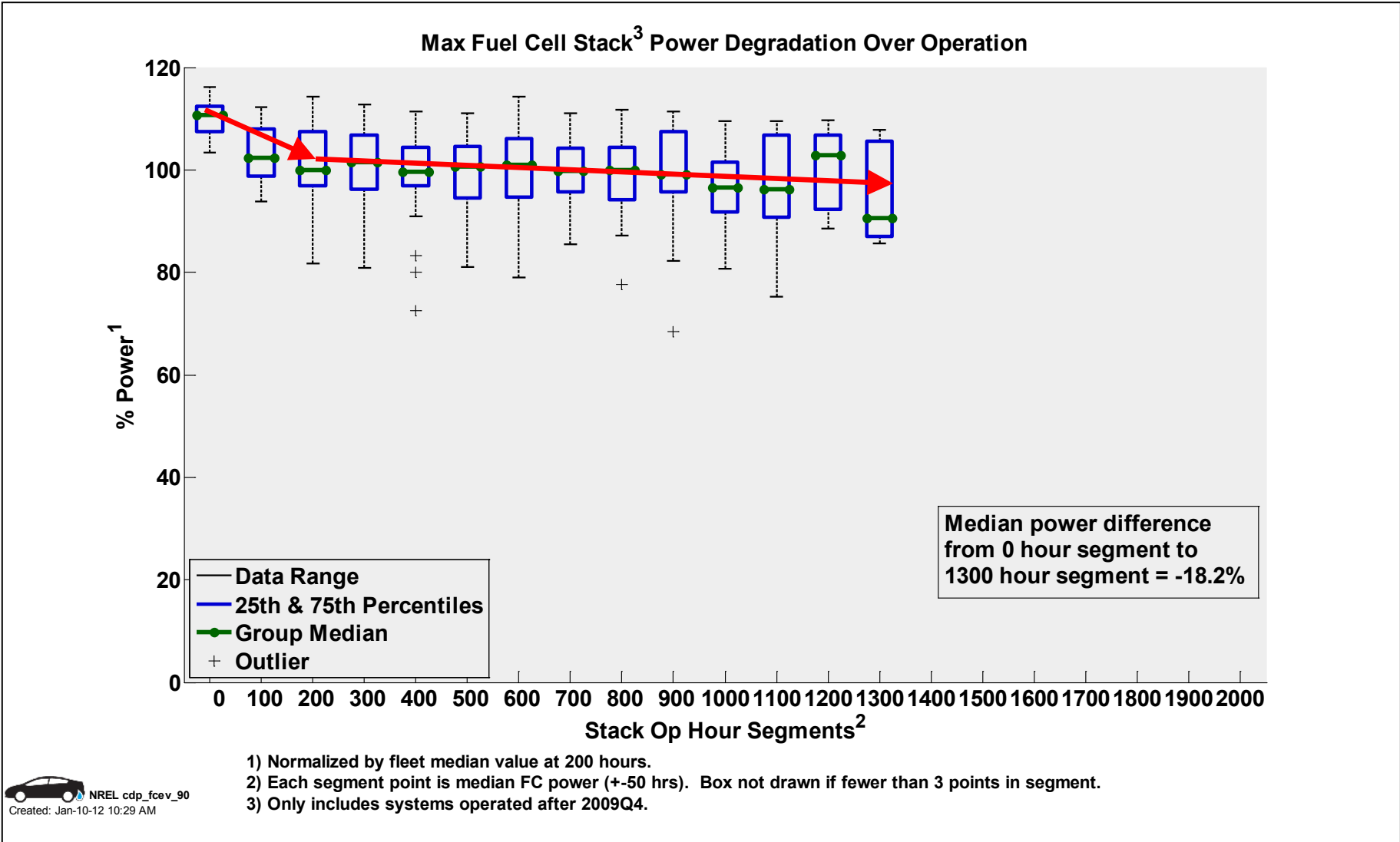
# DURABILITY: Data from FCEVs After 2009 Q4

## Fuel Cell Stack Operation Hours



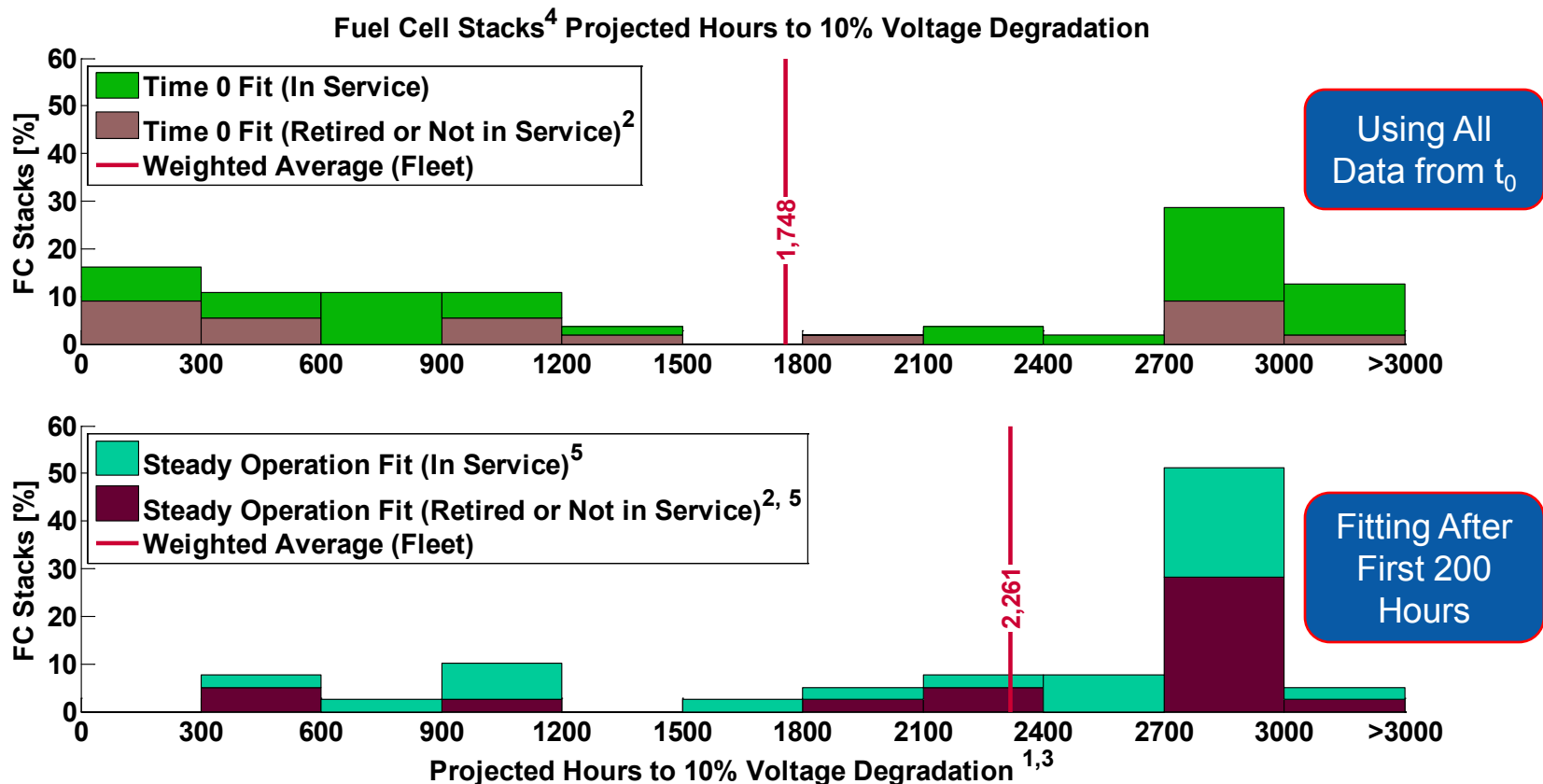
1) Stacks that are in service and accumulating operation hours.  
 2) Stacks retired due to low-performance or catastrophic failure.  
 3) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non-stack performance related issues or c) removed from DOE program.  
 4) Only includes systems operating after 2009Q4.

# DURABILITY: What Does the Stack Aging Look Like? Max FC Power Degradation Rate Drops with Aging



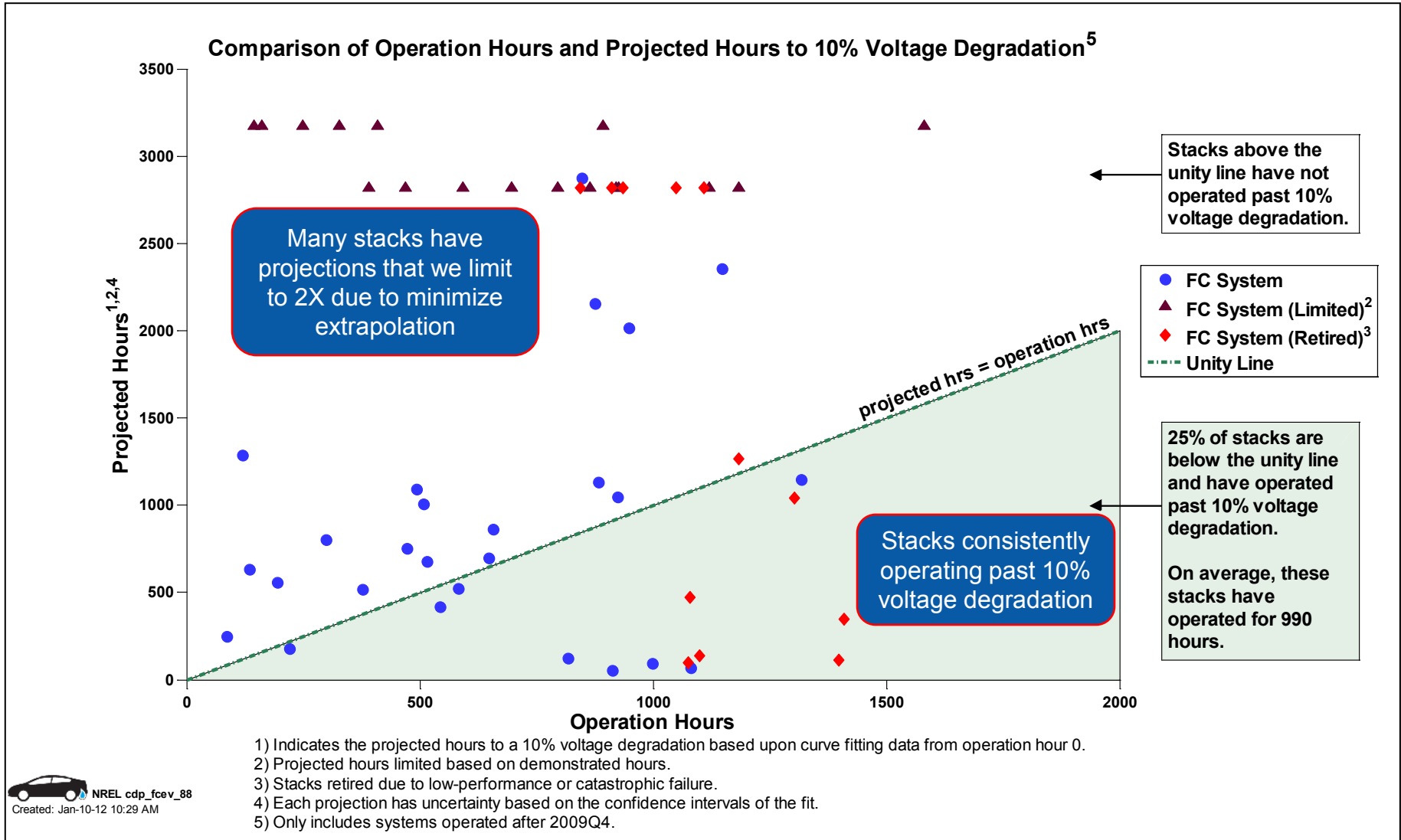


# DURABILITY: Fuel Cell Stacks Projected Hours to 10% Voltage Degradation; Two Fits

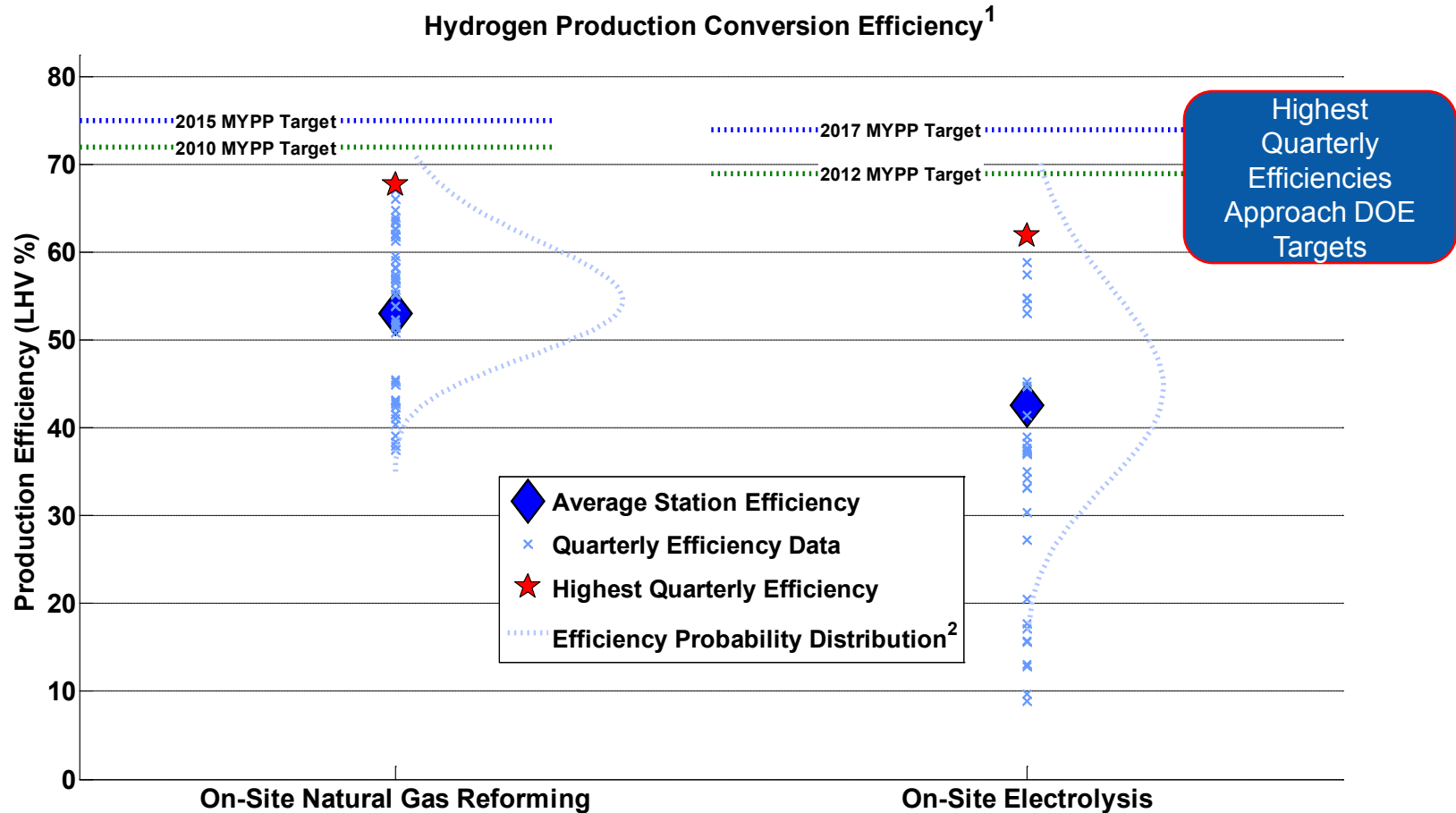


- 1) Projection using field data, calculated at high stack current, from operation hour 0 or a steady operation period. Projected hours may differ from an OEM's end-of-life criterion and does not address "catastrophic" failure modes.
- 2) Indicates stacks that are no longer accumulating hours either a) temporarily or b) have been retired for non- stack performance related issues or c) removed from DOE program.
- 3) Projected hours limited based on demonstrated hours.
- 4) Only includes systems operating after 2009Q4.
- 5) Not all stacks have a steady operation fit which is calculated from data after 200 hr break-in period. The steady operation starting hour is an approximation of the period after initial break-in where degradation levels to a more steady rate.

# DURABILITY: Comparison of Fuel Cell Operation Hours and Projected Hours to 10% Voltage Degradation



# INFRASTRUCTURE: Evaluated On-Site Hydrogen Production Efficiency

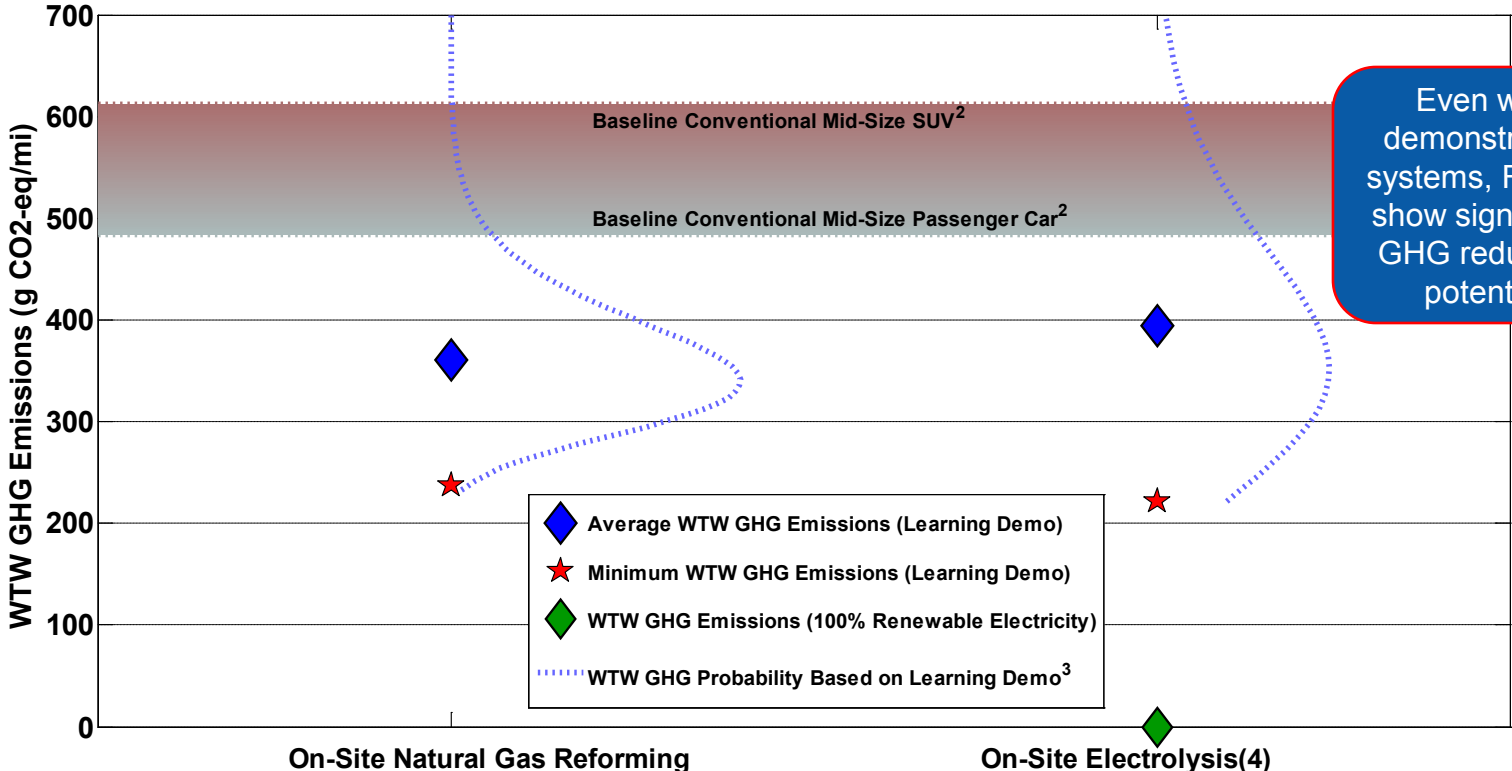


<sup>1</sup>Production conversion efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.

<sup>2</sup>The efficiency probability distribution represents the range and likelihood of hydrogen production conversion efficiency based on monthly conversion efficiency data from the Learning Demonstration.

# GHG: Learning Demonstration Vehicle Greenhouse Gas Emissions (WTW)

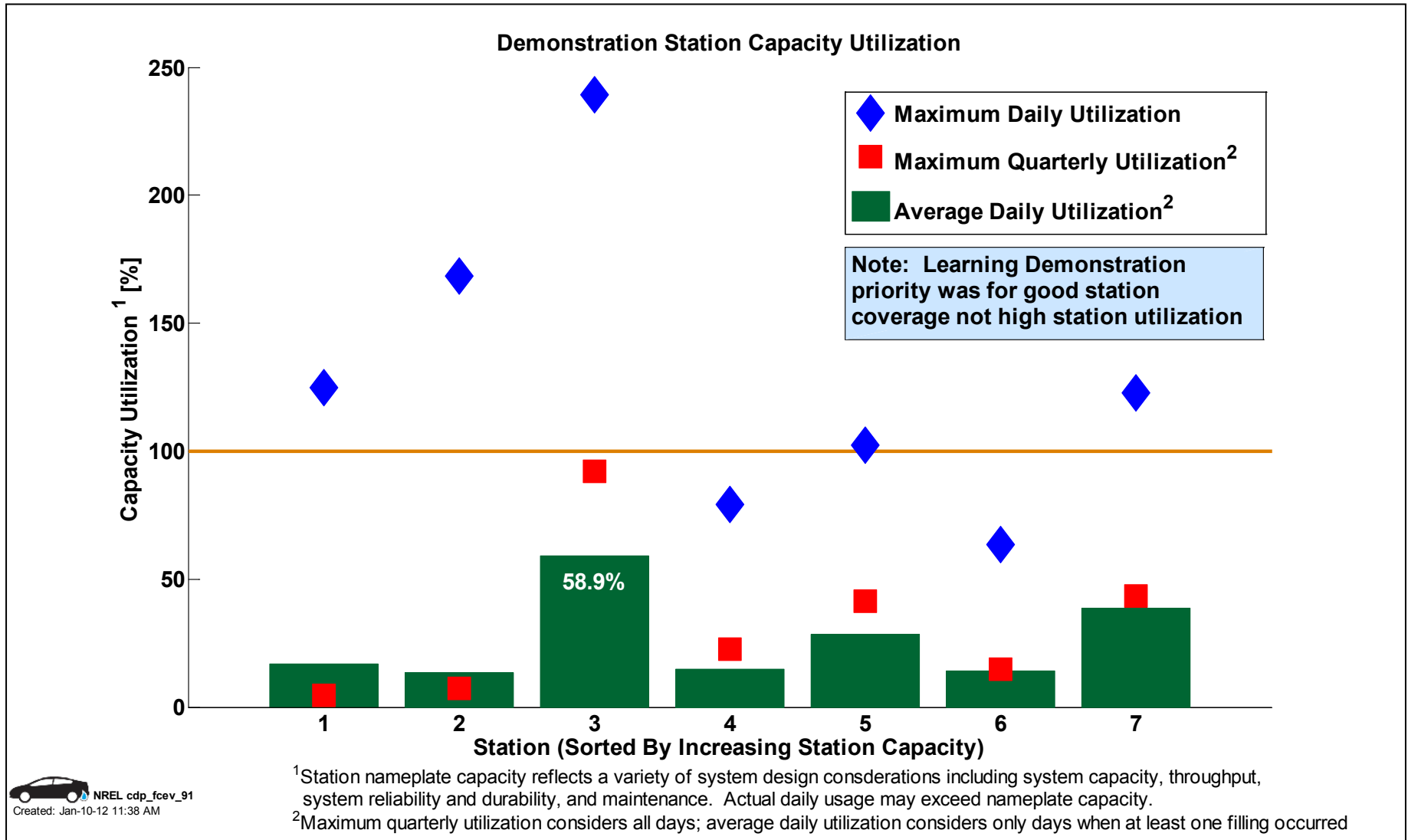
Learning Demonstration Fuel Cycle Well-to-Wheels Greenhouse Gas Emissions<sup>1</sup>



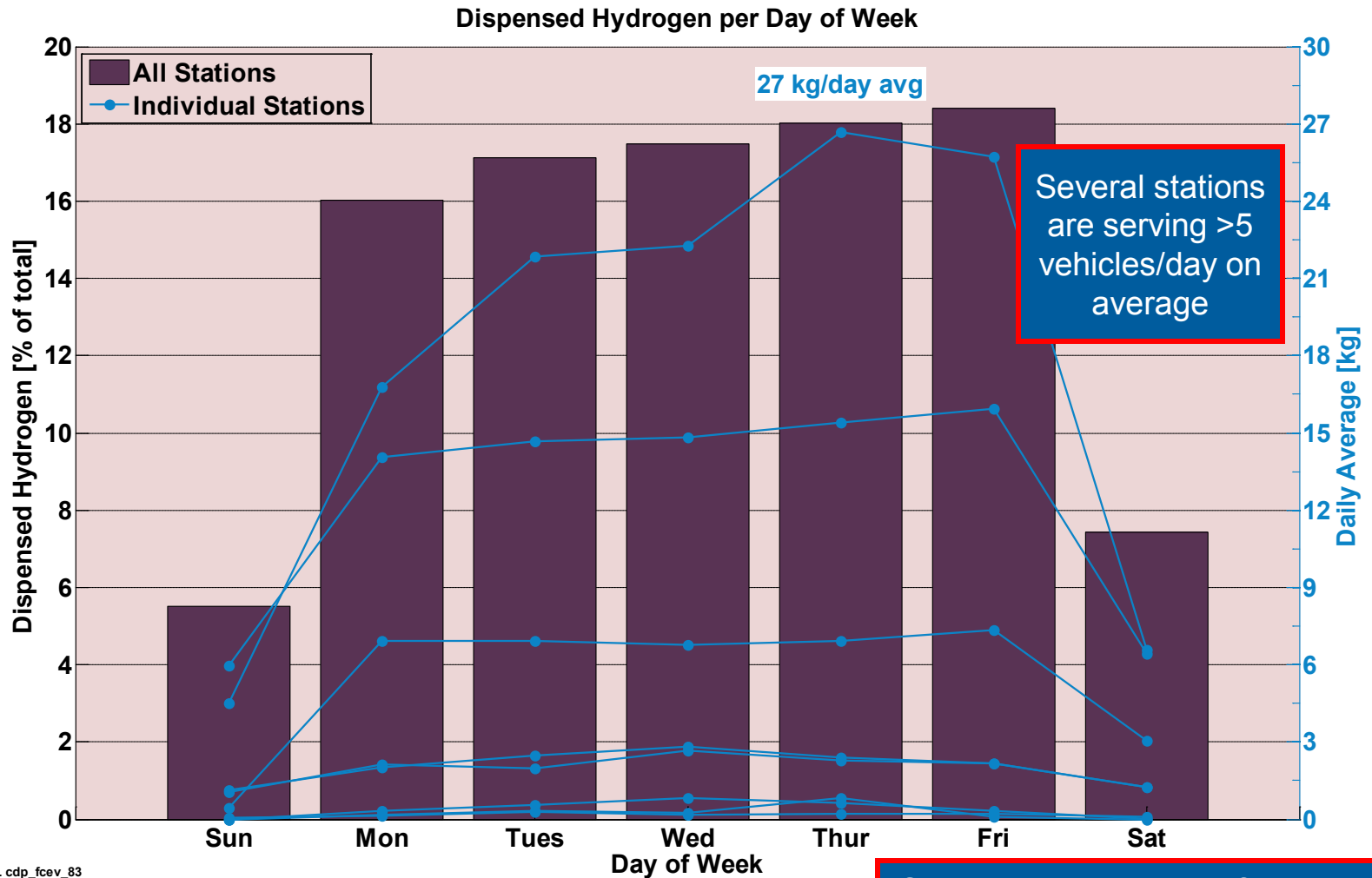
Even with demonstration systems, FCEVs show significant GHG reduction potential

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 1330 g/mile.

# INFRASTRUCTURE: Station Capacity Utilization

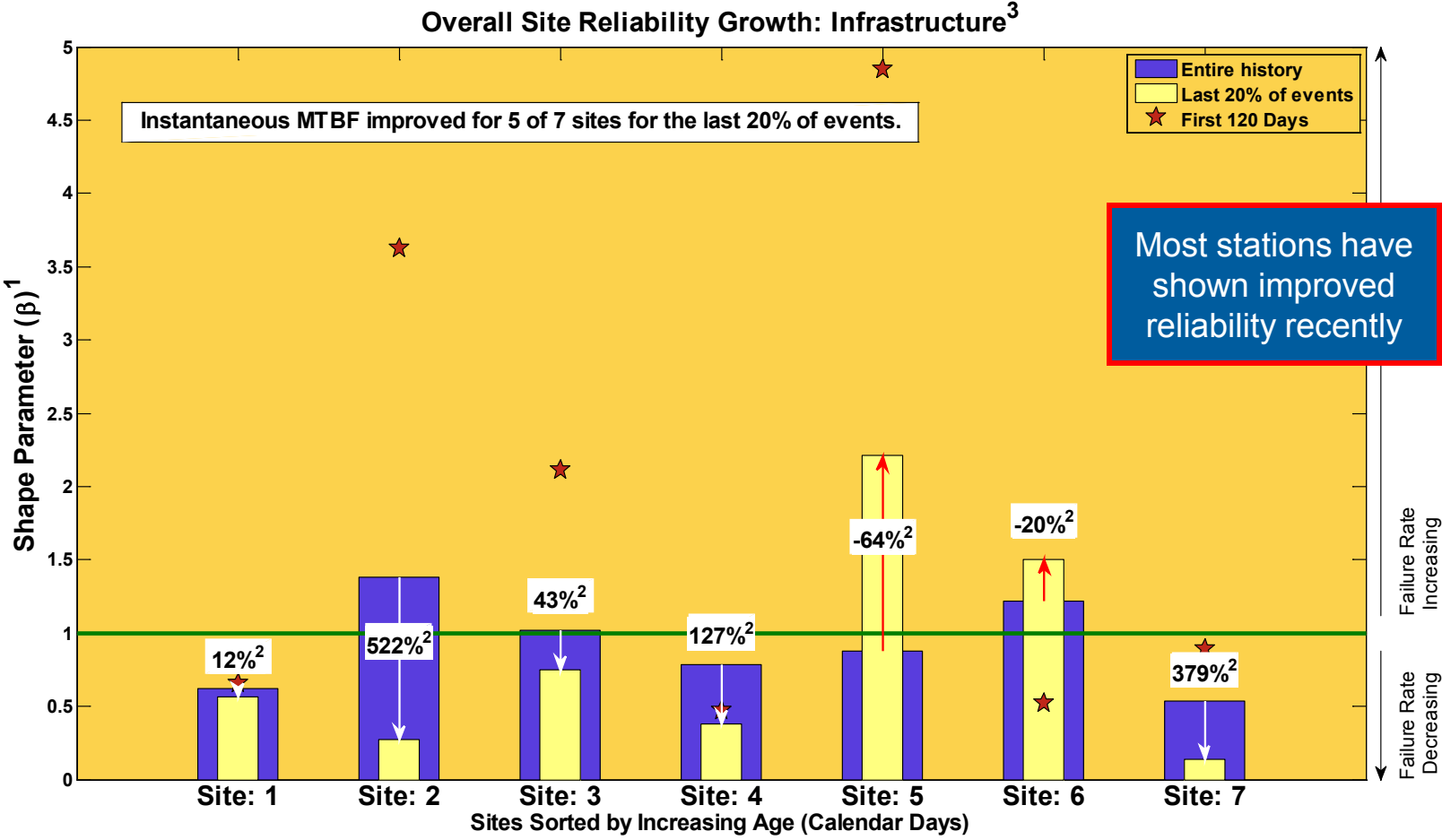


# INFRASTRUCTURE: Some CDPs Are Now Looking at the Transition from Demo to Early Market – Utilization is Important



Some stations still significantly under-utilized but helping provide coverage

# INFRASTRUCTURE: Infrastructure Reliability Growth

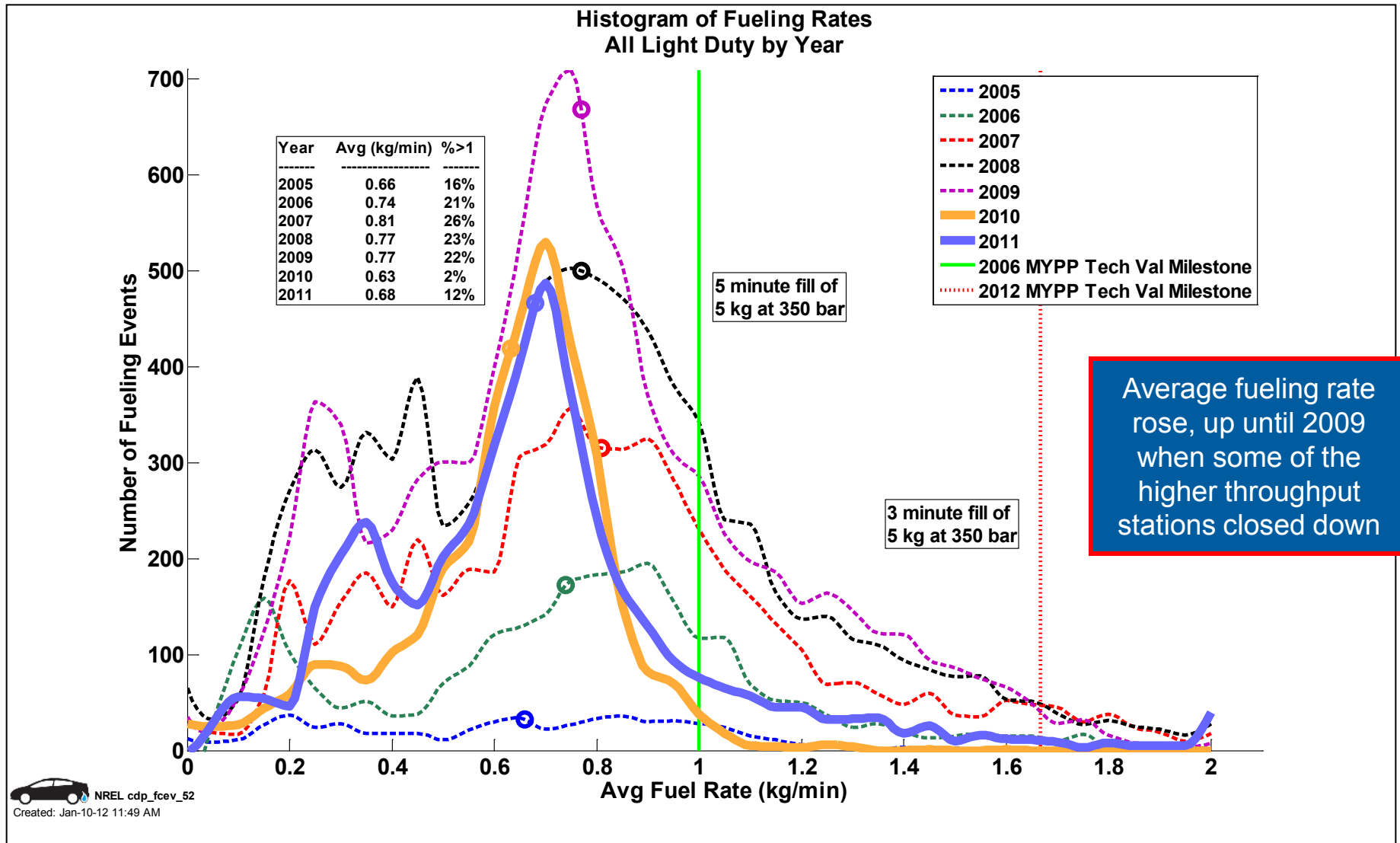


1. IEC 61164:2004(E), Reliability Growth - Statistical Test and Evaluation Methods, IEC. 2004.

2. % change in instantaneous MTBF

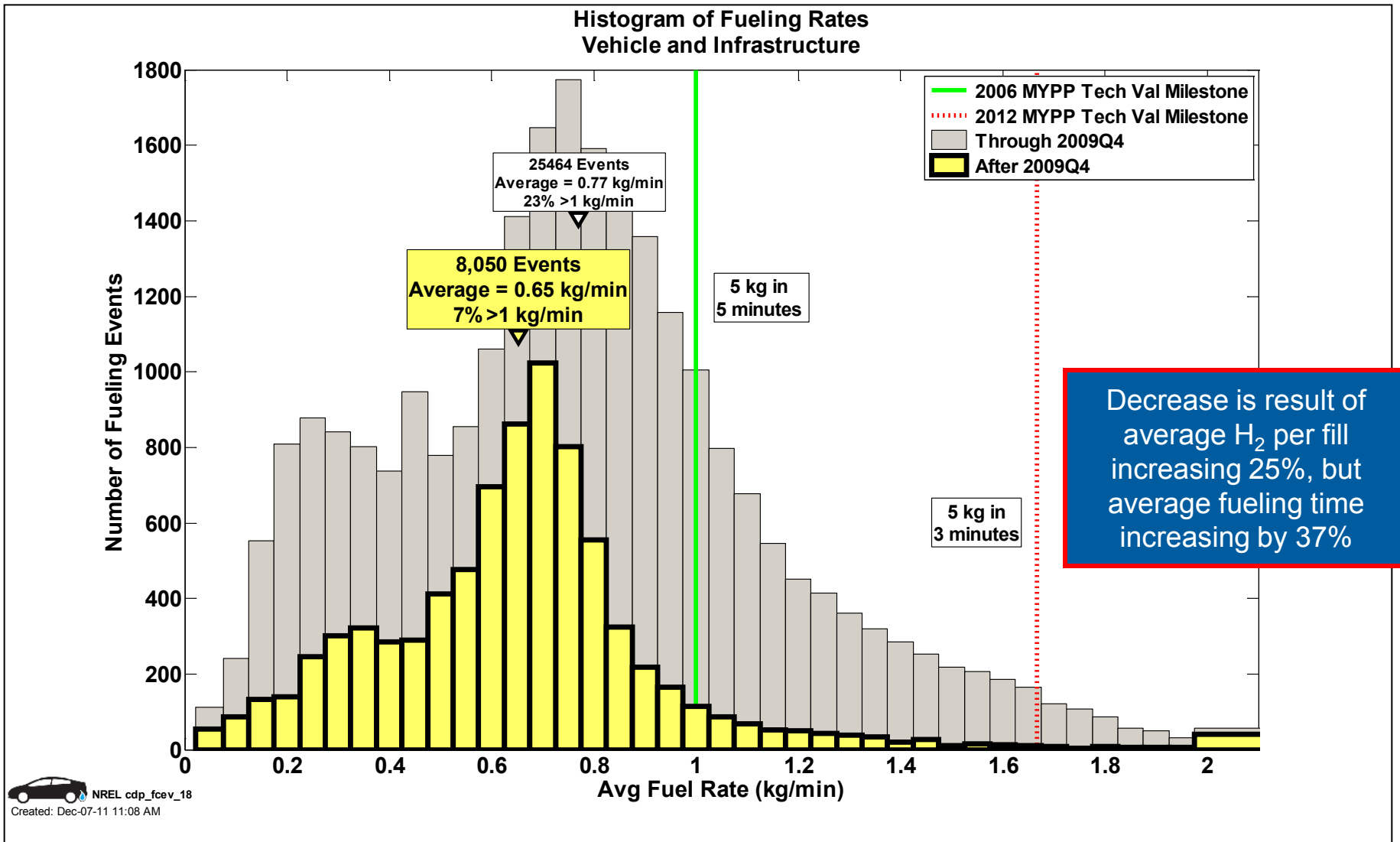
3. Includes data from stations operating after 2009 Q4.

# FUELING: Tracking Fueling Rates by Year

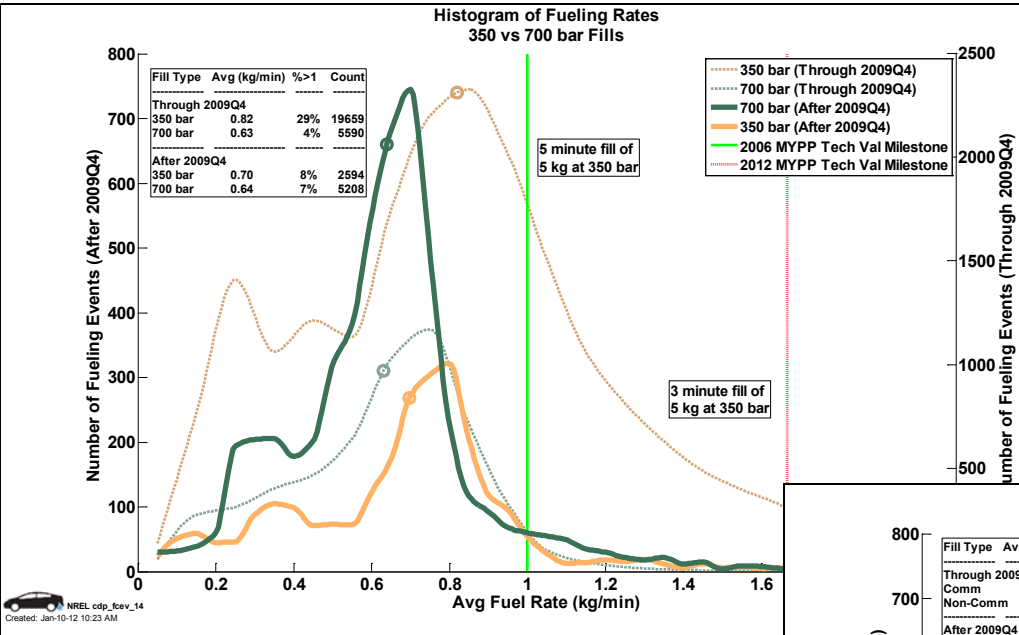




# FUELING: Changes in Refueling Rate Trends – Average Refueling Rate Decreased 16%

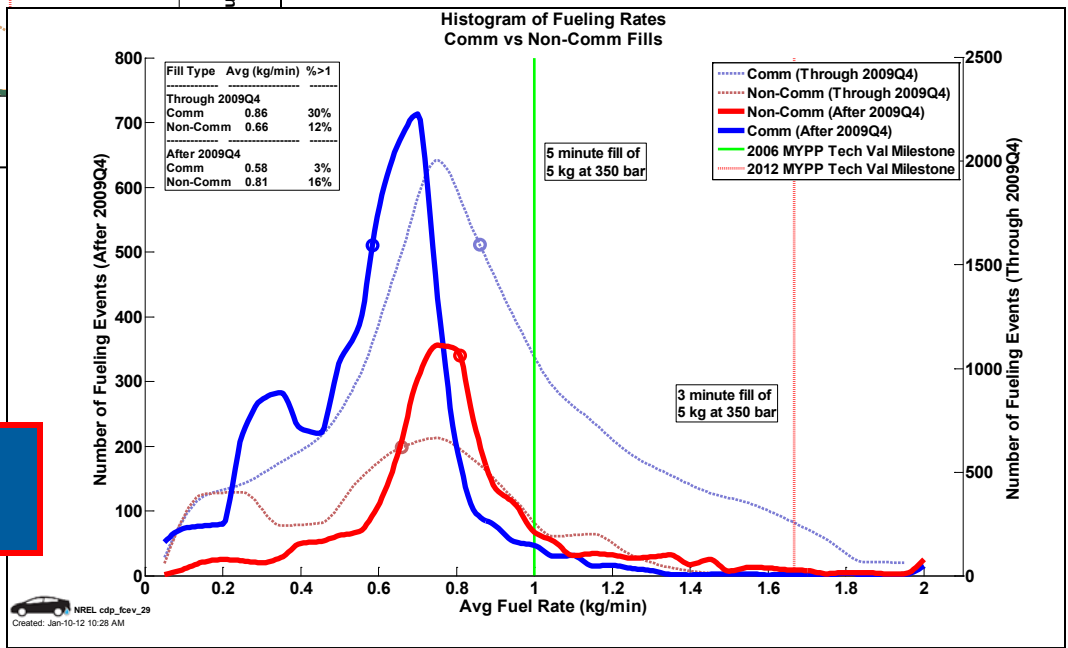


# FUELING: Fueling Rates by Fill Pressure and Communication vs. Non-communication – Fueling infrastructure in transition



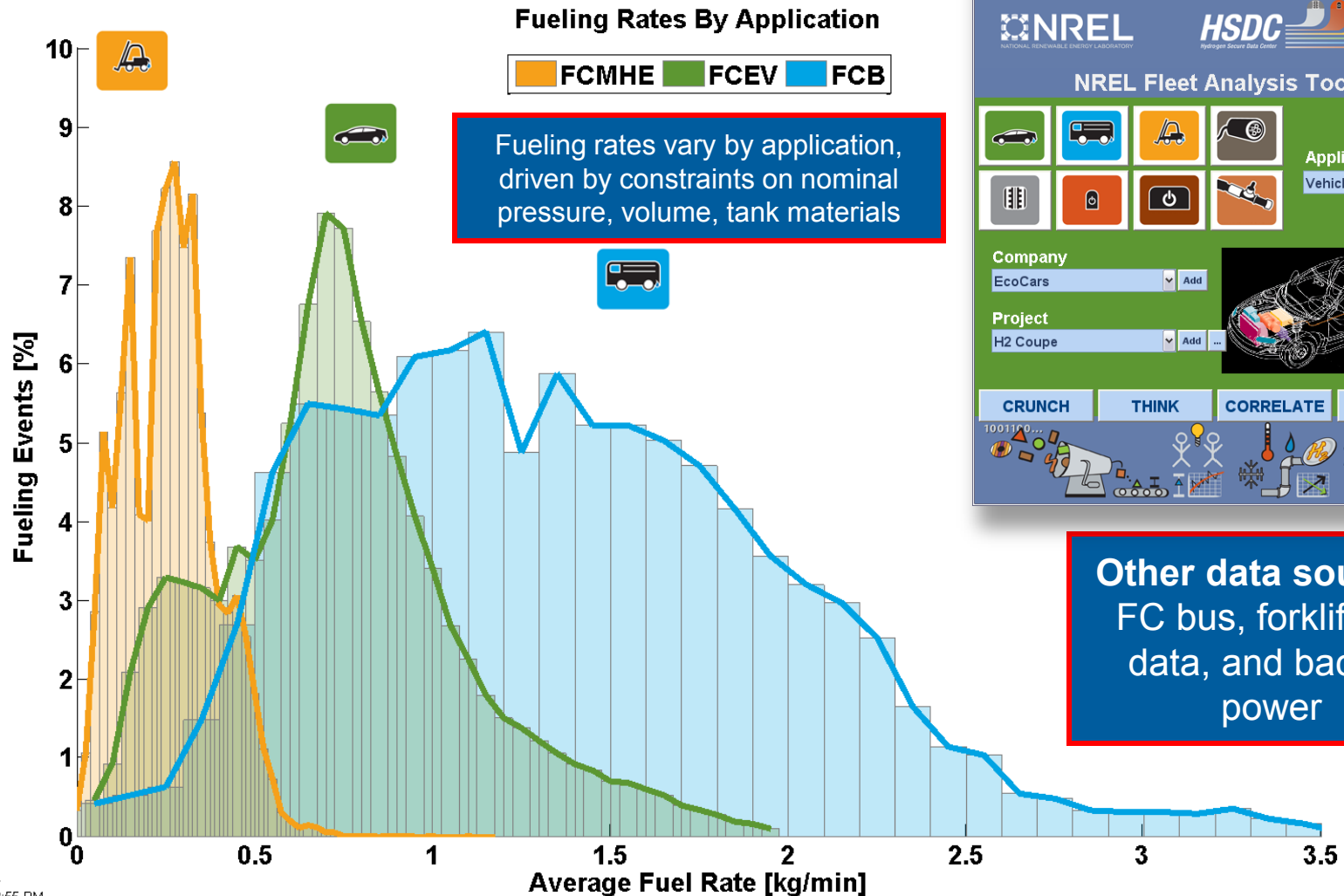
700 bar fueling rates holding constant at ~0.63 kg/min

350 bar fueling rates dropped from 0.82 to 0.70 kg/min



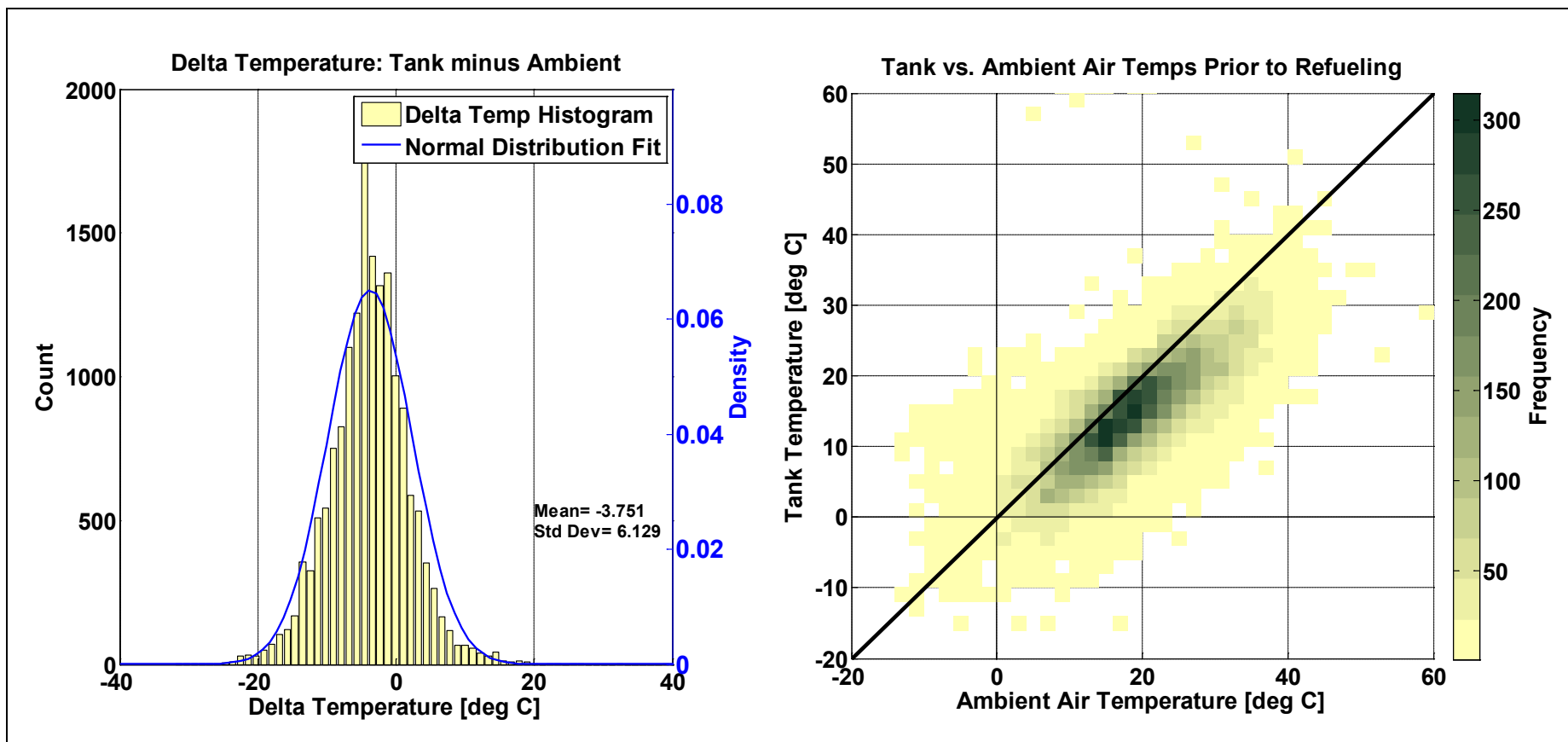
Comm. fill rates dropped while non-comm. fill rates increased

# Analysis at NREL Leveraged Across Applications; Being Applied to Compare Similarities/Differences



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# Example of Analysis Results Informing R&D Activities and Codes and Standards Development



- This CDP created in support of SAE J2601 related to refueling
- Temperatures are prior to refueling and exclude data within 4 hours of a previous refueling
- The plot to the left excludes ambient temperatures less than -5 deg C

FCEVs arrive at station with a tank temperature that is 3.8 degrees C colder than ambient temp

# Technical Summary

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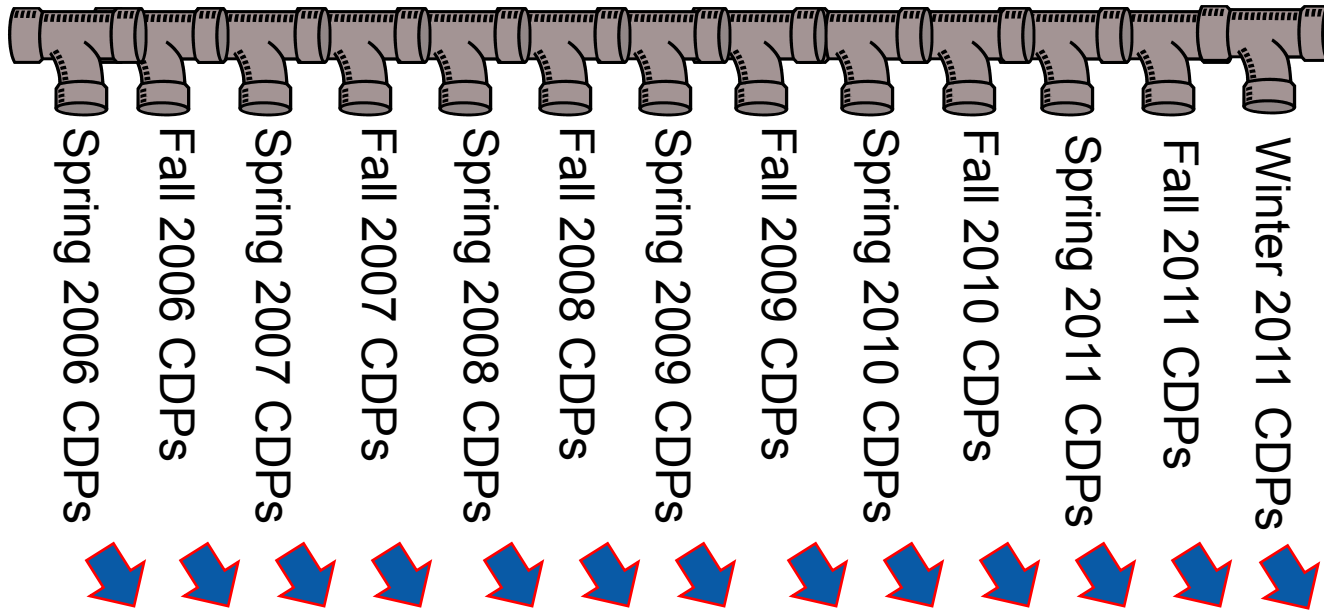
- Project has completed ~7 years of real-world validation
- Vehicle operation: 183 vehicles, 154,000 hours, 3.5 million miles, 500,000 trips
- H<sub>2</sub> station operation: 25 stations, 151,000 kg produced or dispensed, 33,000 fuelings
- DOE Key Technical Targets Validated and Met:
  - FC Durability >2,000 hours and Range >250 miles

# Learning Demo Project Wrap-Up

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- Winter 2011 CDPs just posted on NREL web site
- Draft final report in March 2012, to be published in April
- Continuing to receive data on H2 infrastructure with support from DOE (primarily in CA: stations funded by CEC and ARB). New results to follow.
- In discussions with how to continue to assess FCEV progress in the coming years
- This project is the 1<sup>st</sup> time such comprehensive data was collected by an independent 3<sup>rd</sup>-party and consolidated for public dissemination
  - Successful framework being used for other projects

# NREL Has Built the Infrastructure and Framework for Other Projects to Follow



Learning Demo  
Conclusion

Final  
Public Report

**OBJECTIVE CREDIBLE EVALUATIONS  
HELPED LEAD TO INFORMED DECISIONS**



# To Learn More on Your Own... It's All Online on NREL's web site

The screenshot shows a web browser window displaying the NREL website. The browser's address bar shows the URL: [http://www.nrel.gov/hydrogen/proj\\_learning\\_demo.html](http://www.nrel.gov/hydrogen/proj_learning_demo.html). The NREL logo is visible at the top left, and the navigation menu includes links for 'ABOUT NREL', 'ENERGY ANALYSIS', 'SCIENCE & TECHNOLOGY', 'TECHNOLOGY TRANSFER', and 'APPLYING TECHNOLOGIES'. The main heading is 'Hydrogen & Fuel Cells Research'. A sidebar on the left lists various categories like 'Capabilities', 'Projects', 'Research Staff', and 'Facilities'. The main content area features a section titled 'Hydrogen Fuel Cell Vehicle and Infrastructure Learning Demonstration' with a detailed description of the project. Below this, there is a section for 'Composite Data Products' and a 'Publications' section listing recent work from 2012 and 2011. A colorful circular graphic is also present on the right side of the page.

**Hydrogen & Fuel Cells Research**

**Hydrogen Fuel Cell Vehicle and Infrastructure Learning Demonstration**

Initiated in 2003, DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project is the largest project in the world to validate fuel cell vehicles and the supporting refueling infrastructure in parallel under real-world conditions.

The project identifies and tracks the status of technologies as they evolve, assesses the progress of technology readiness, and provides feedback for hydrogen research and development activities. This six-year project through 2010 uses multiple geographic locations and climates with a variety of hydrogen sources, including renewables.

NREL's role is to receive and analyze the technical data from the fuel cell vehicles and the hydrogen refueling infrastructure. Learn more about NREL's role in [validation of hydrogen fuel cell vehicle and infrastructure technology](#). As nations around the world pursue a variety of sustainable transportation solutions, [hydrogen fuel cell electric vehicles \(FCEVs\)](#) present a promising opportunity for American consumers and automakers. FCEVs offer a sustainable transportation option, provide a cost-competitive alternative for drivers, reduce dependence on imported oil, and enable global economic leadership and job growth.

**Composite Data Products**

The raw data for this project is protected in NREL's Hydrogen Secure Data Center, but the public may access results through composite data products (CDPs). The results are presented in three ways:

- [CDPs by topic](#)
- [CDPs by date](#)
- [CDPs by number](#)

**Publications**

This page is a repository for NREL's technical analysis results, papers, and presentations generated for this project.

**2012**

- [All Composite Data Products: National FCEV Learning Demonstration, with Updates through January 18, 2012](#). K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, G. Saur. (January 2012)

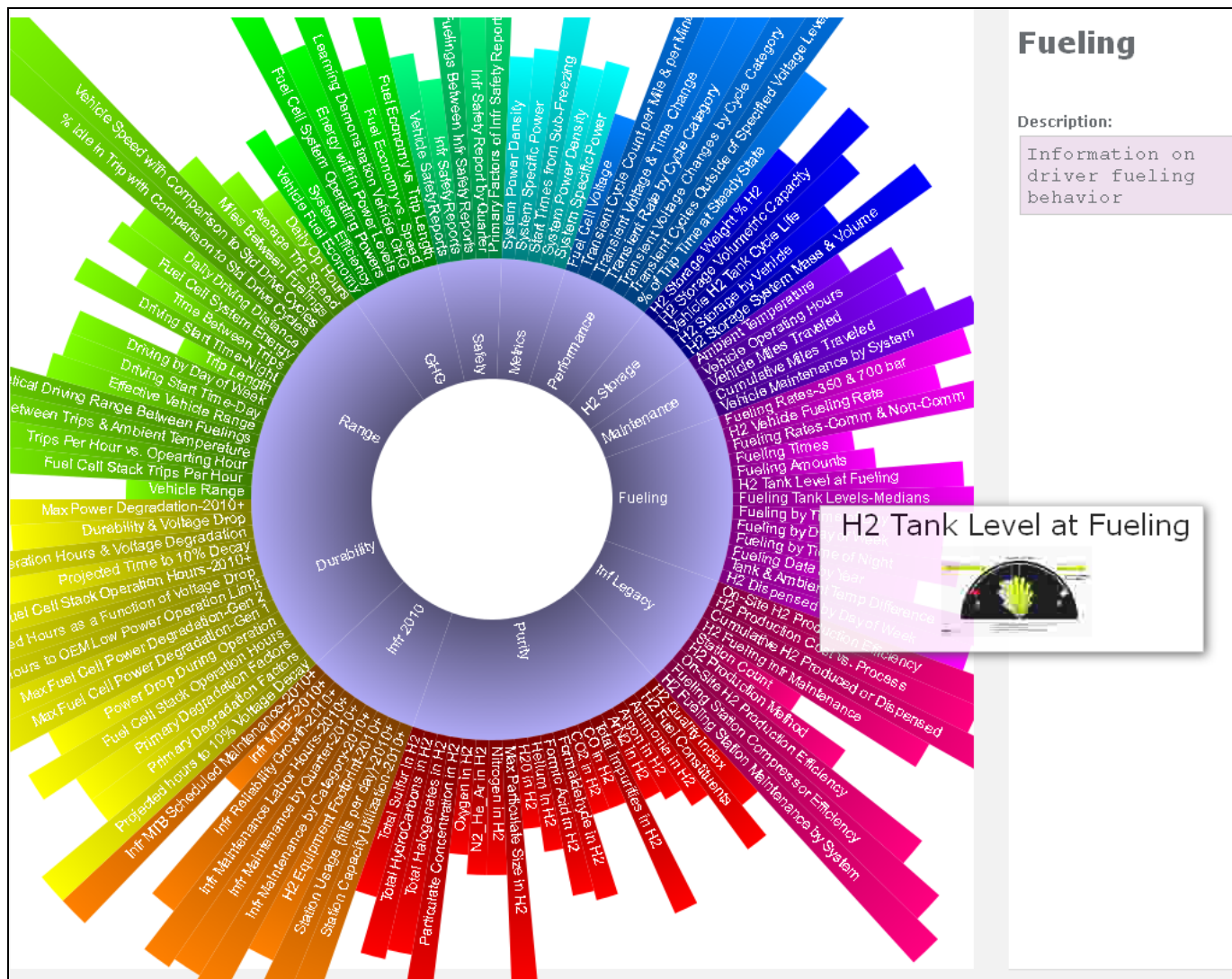
**2011**

- [Conclusion of the National FCEV Learning Demonstration Project](#). K. Wipke, S. Sprik, J. Kurtz, T.

Web link



# New Graphical Way of Viewing Results Will Soon Be Online



Sunburst temporarily located at [http://nreldev.nrel.gov/hydrogen/\\_noctp/demo/source/sunburst.html](http://nreldev.nrel.gov/hydrogen/_noctp/demo/source/sunburst.html)

Web demo

# 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](http://www.nrel.gov/hydrogen/proj_tech_validation.html)

DOE FCT Program website:  
<http://www1.eere.energy.gov/hydrogenandfuelcells/index.html>