

Controlled Hydrogen Fleet and Infrastructure Analysis



**2010 DOE Annual Merit
Review and Peer
Evaluation Meeting**

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Jennifer Kurtz, Todd
Ramsden***

**June 10, 2010
Washington, DC**

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

Fuel Cell Vehicle Learning Demonstration 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

Key Targets

Performance Measure	2009	2015
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	\$3/gge	\$2-3/gge

Outside review panel



Burbank, CA station. Photo: NREL

Project Overview

Timeline

- Project start: FY03
- Project end: FY11
- ~85% of Task III complete (see timeline slide)

Budget

- NREL funding prior to FY09 : \$3942K
- NREL FY09 funding: \$925K
- NREL FY10 funding: \$650K

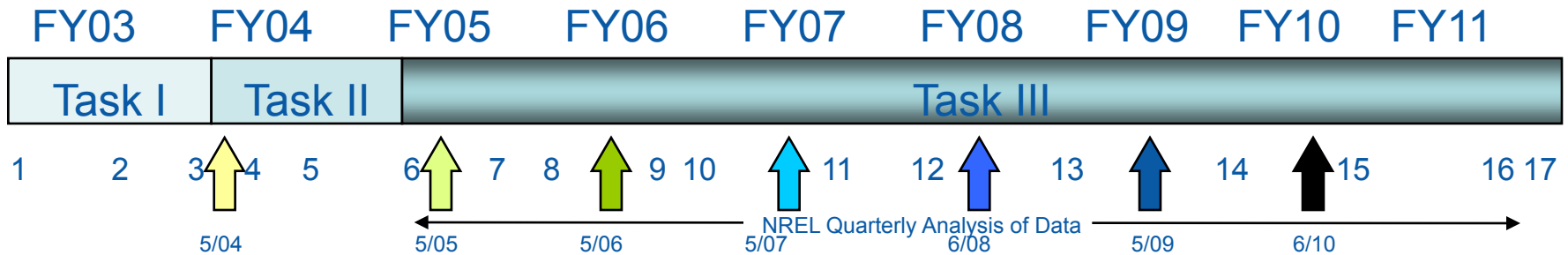
Partners

- See partner slide

Tech. Val. Barriers

- A. **Vehicles** – lack of controlled & on-road H₂ vehicle and FC system data
- B. **Storage** – technology does not yet provide necessary 300+ mile range
- C. **Hydrogen Refueling Infrastructure** – cost and availability
- D. **Maintenance and Training Facilities** – lack of facilities and trained personnel
- E. **Codes and Standards** – lack of adoption/validation
- H. **Hydrogen Production from Renewables** – need for cost, durability, efficiency data for vehicular application
- I. **H₂ and Electricity Co-Production** – cost and durability

Approach and Accomplishments: Project Timeline and Major Milestones



Task I – Project Preparation [100% Complete]

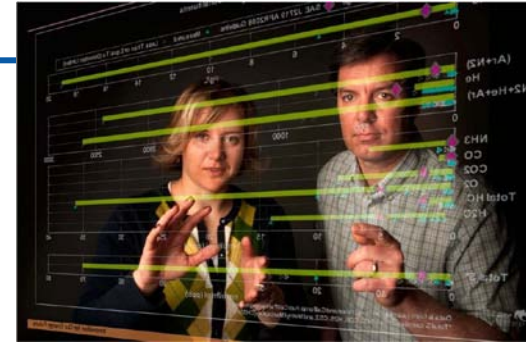
Task II – Project Launch [100% Complete]

Task III – Data Analysis and Feedback to R&D activities (partial list) [85% Complete]

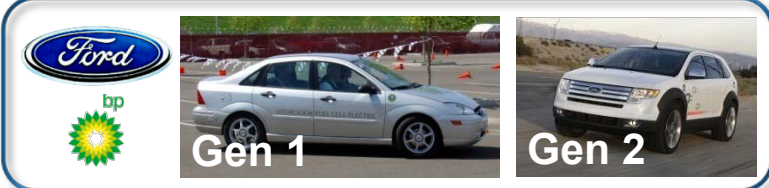
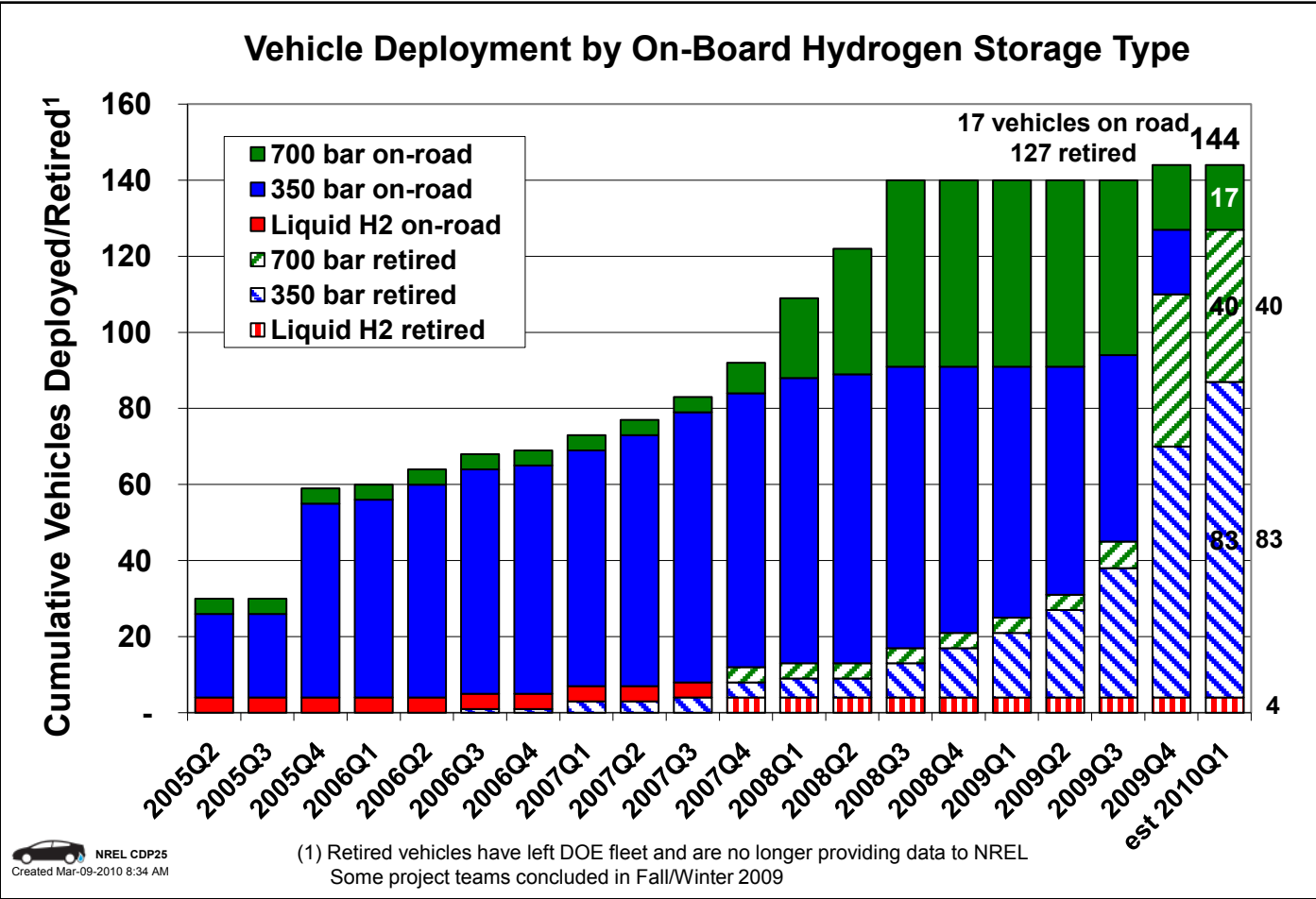
- 6 Preliminary data collection, analysis, and first quarterly assessment report
- 7 Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles
- 8 Publication of first “composite data products”
- 9 Evaluate FC stack time to 10% voltage degradation relative to 1000-hour target
- 10 Decision for purchase of additional vehicles based on performance, durability, cost
- 11 Preliminary evaluation of dominant real-world factors influencing FC degradation
- 12 Introduction of 2nd generation FC systems into vehicles begins
- 13 FCVs demonstrate 250-mile range without impacting passenger cargo compartment
- ➔ 14 **Validate FCVs with 2,000 hour durability and \$3.00/gge (based on volume production)**
- 15 Data analysis continues with data from 2 of the 4 OEM/Energy teams plus CHIP stations
- 16 Conclusion of data submission to NREL on pre-commercial FCVs
- 17 Final data analysis and report on Learning Demonstration

Project Approach

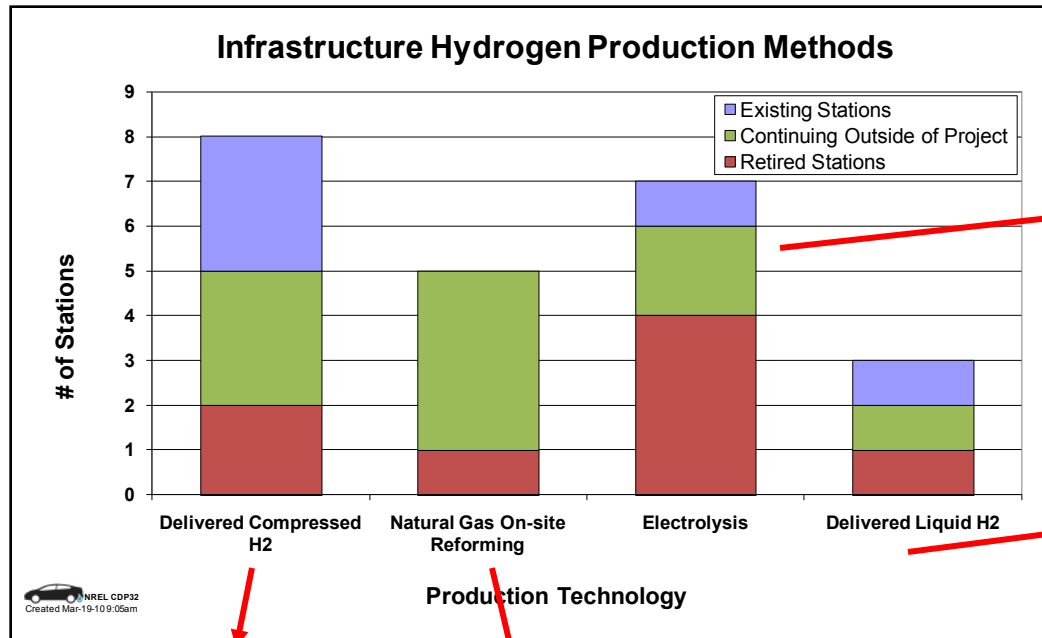
- Provide facility and staff for securing and analyzing industry sensitive data
 - NREL Hydrogen Secure Data Center (HSDC)
- Perform analysis using detailed data in HSDC to:
 - Evaluate current status and progress toward targets
 - Feed back current technical challenges and opportunities into DOE H₂ R&D program
 - Provide analytical results to originating companies on their own data (detailed data products)
 - Collaborate with industry partners on new and more detailed analyses
- Publish/present progress of project to public and stakeholders (composite data products)



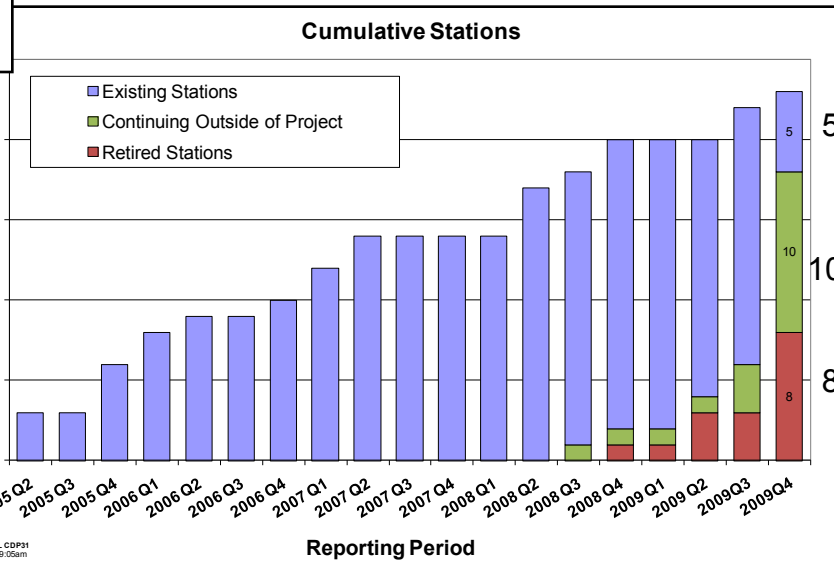
Industry Partners Include Automakers and Energy-Suppliers



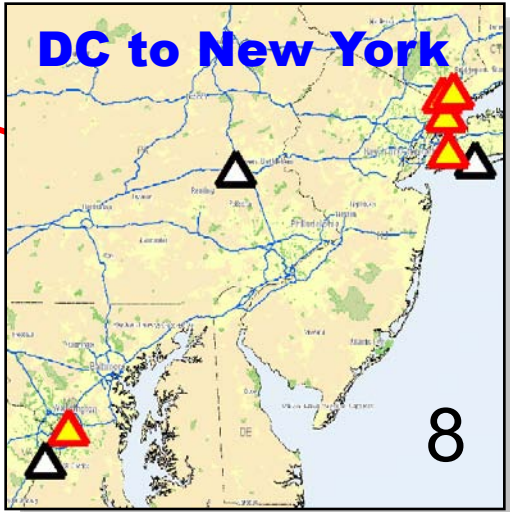
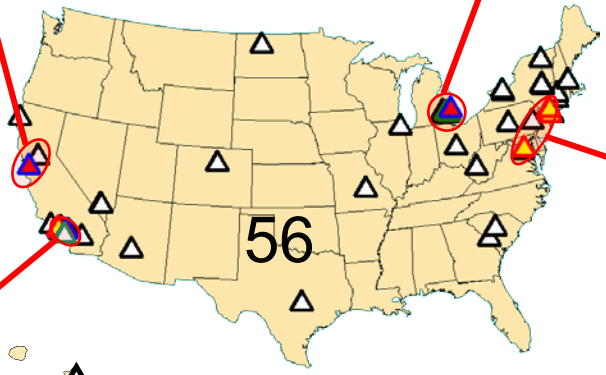
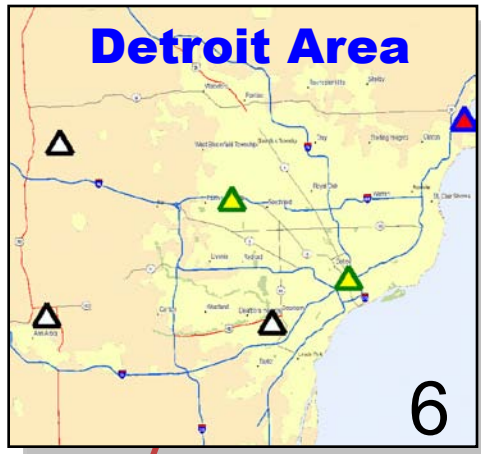
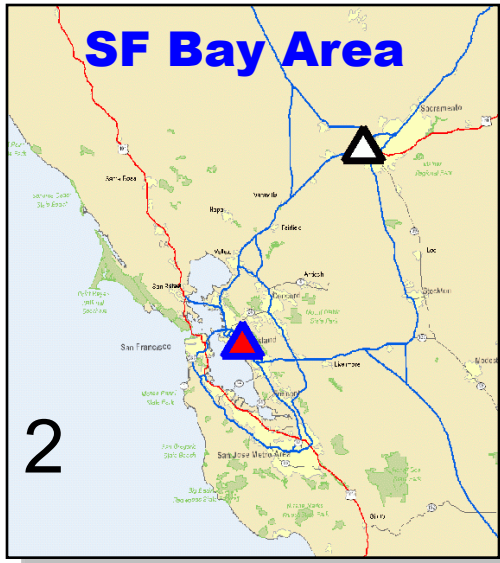
Status: >1/2 Learning Demo Stations Still in Operation; Remainder Decommissioned



Total of 130,000 kg H₂ produced or dispensed from the 23 stations

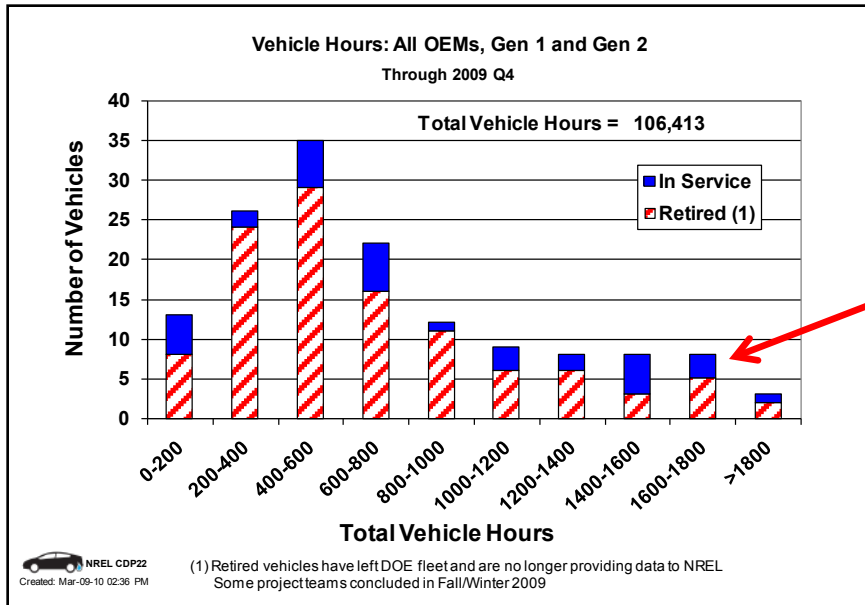


Status: Learning Demo & CHIP Stations Still Serving as Critical Backbone of H₂ Infrastructure in LA and Northeast



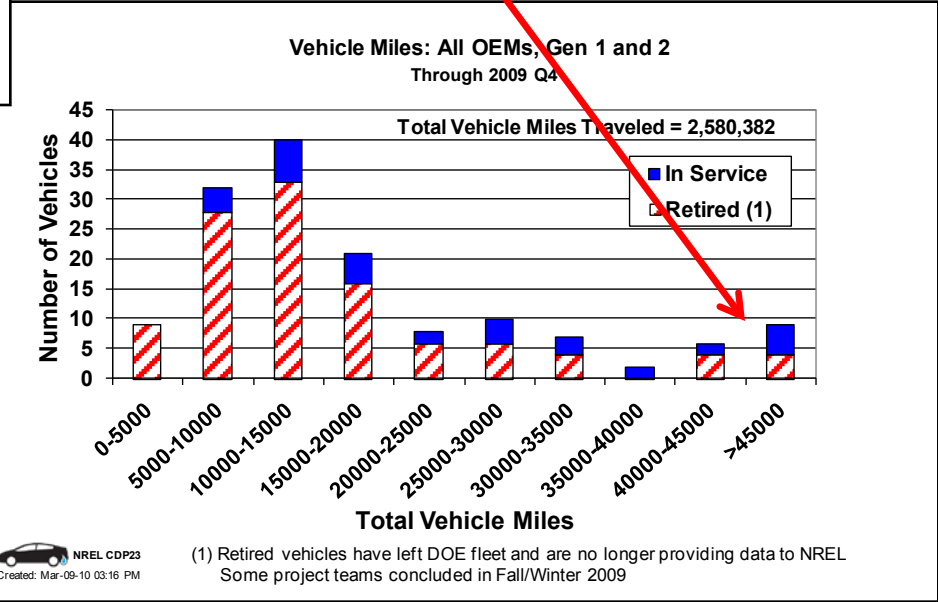
- Legend**
- ▲ Chevron & Hyundai/Kia
 - ▲ DaimlerChrysler & BP
 - ▲ Ford & BP
 - ▲ General Motors & Shell
 - ▲ Air Products
 - ▲ Other Companies

Accomplishment: NREL Has Analyzed Data from Over 100,000 Vehicle Hours and 2.5 Million Miles

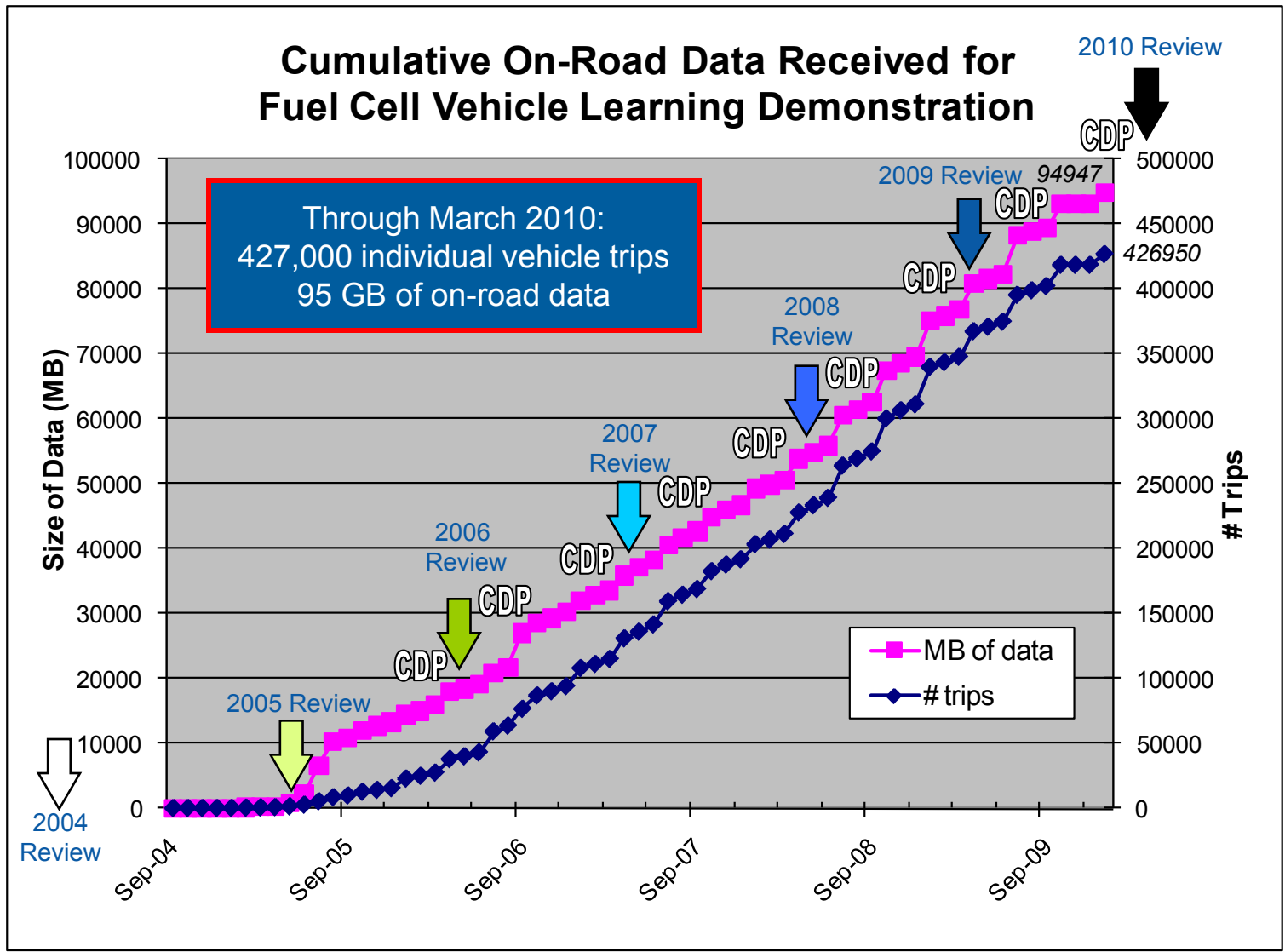


Some Gen 1 vehicles achieved very high miles and hours

All vehicles continuing in the project will all be Gen 2 vehicles

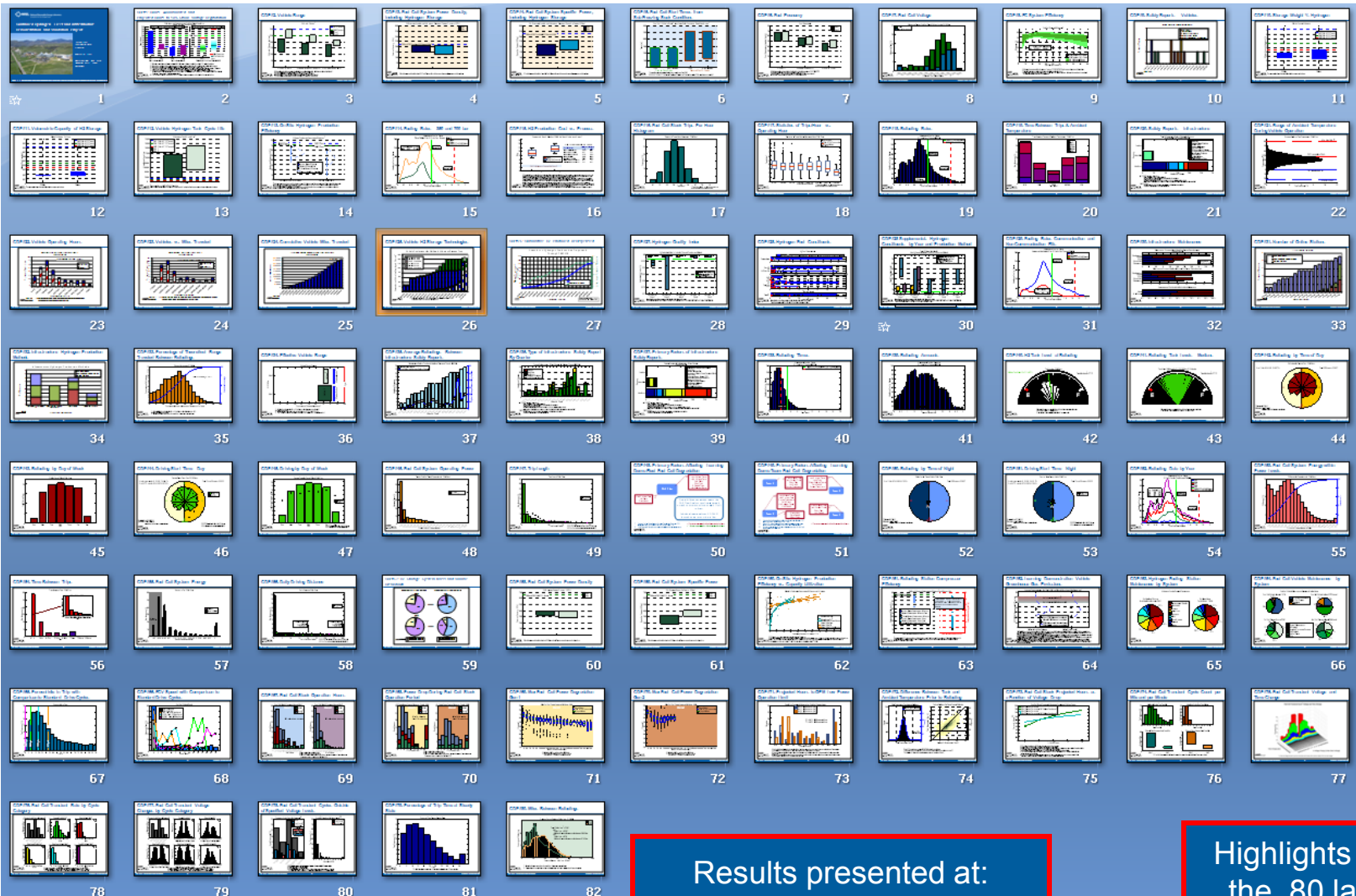


Accomplishment: 19 Quarters of Data Analyzed to Date, Two New Sets of Composite Data Products Published



CDP = Composite Data Products Published

Accomplishment: 80 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months

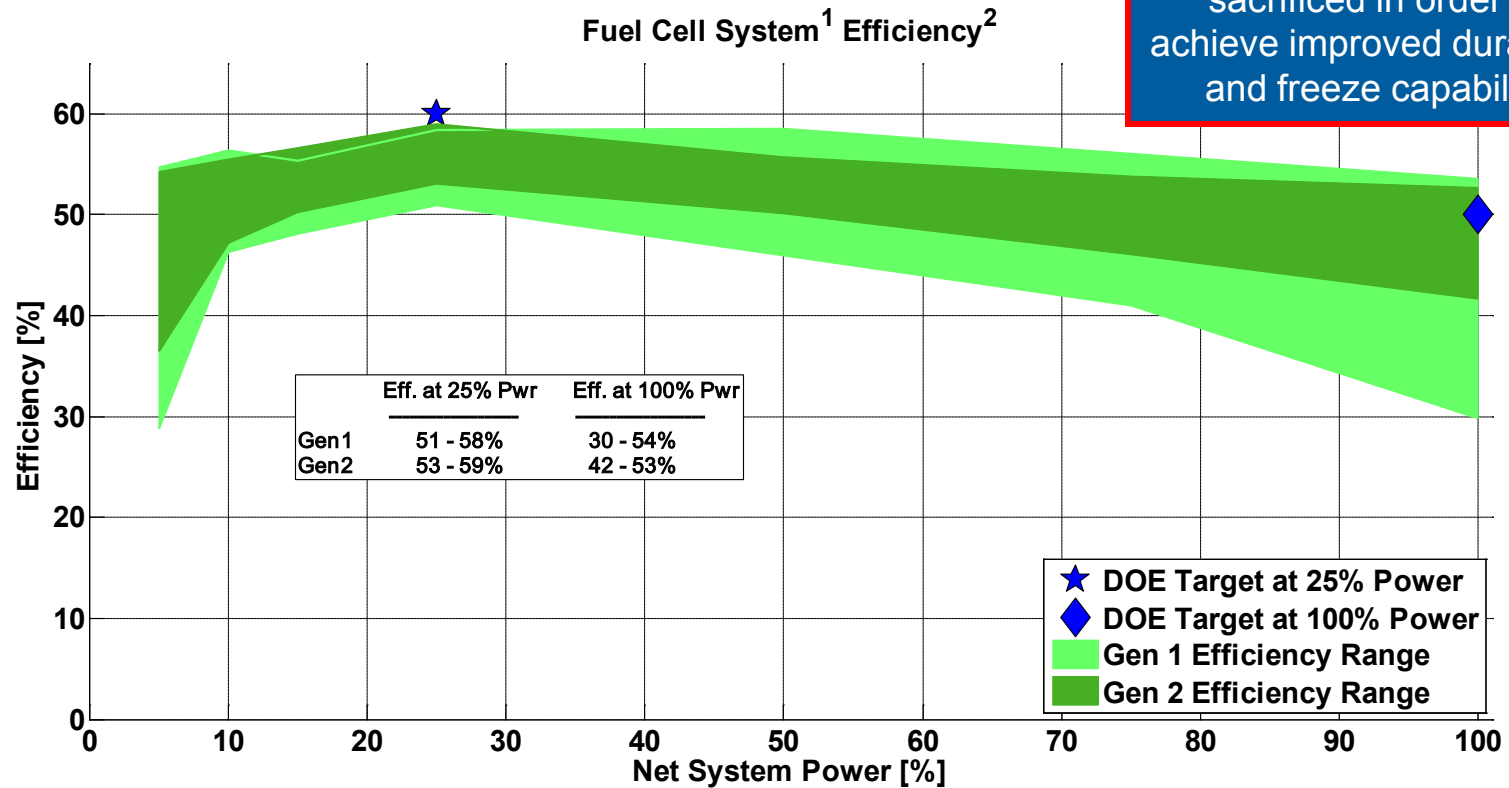


Since last AMR:
20 new + 52 updated + 8 static = 80 results

Results presented at:
 FC Seminar, NHA, EVS

Highlights from
 the 80 latest
 results follow...

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



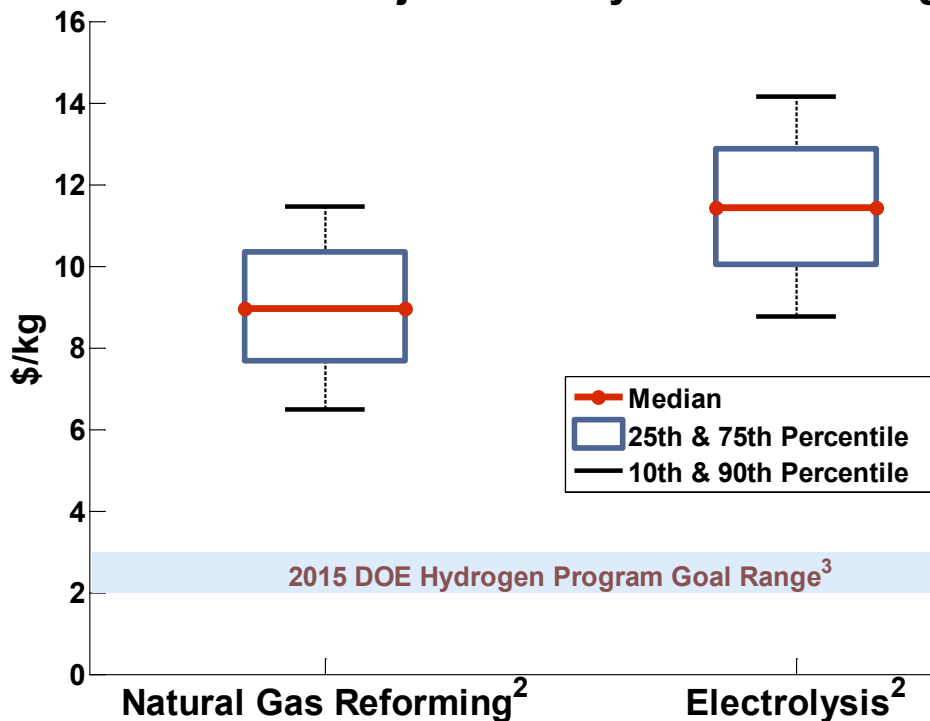
¹ Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.

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.

Accomplishment: Projected Early Market H₂ Production Cost from Learning Demo Energy Partners' Inputs

Projected Early Market 1500 kg/day Hydrogen Cost^{1 *}



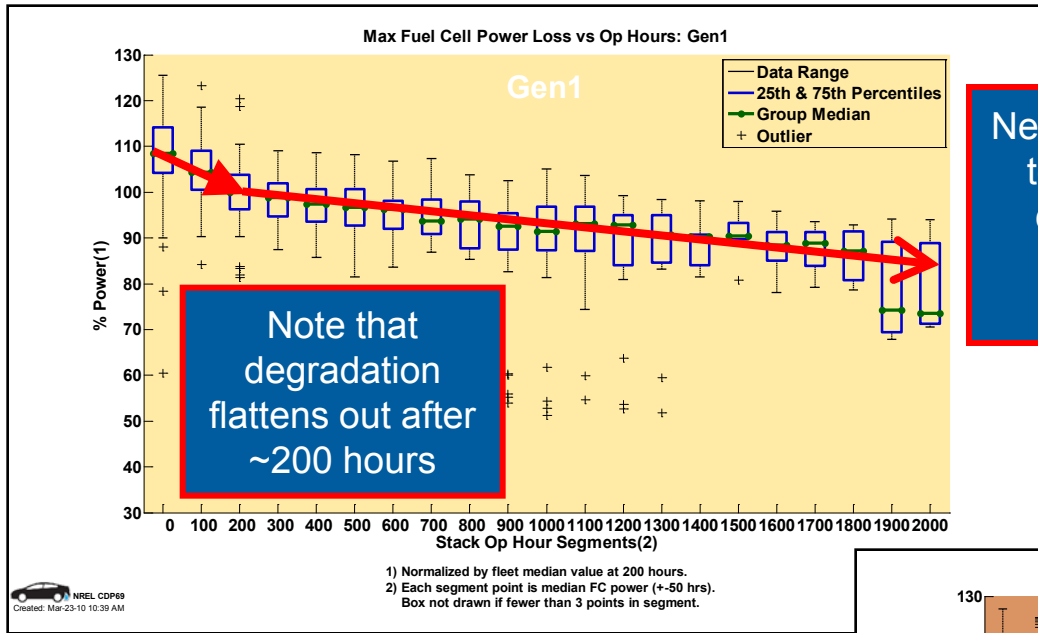
Input Parameter	Minimum (P10)	Maximum (P90)
Facility Direct Capital Cost	\$10M	\$25M
Facility Capacity Utilization	85%	95%
Annual Maintenance & Repairs	\$150K	\$600K
Annual Other O&M	\$100K	\$200K
Annual Facility Land Rent	\$50K	\$200K
Natural Gas Prod. Efficiency (LHV)	65%	75%
Electrolysis Prod. Efficiency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

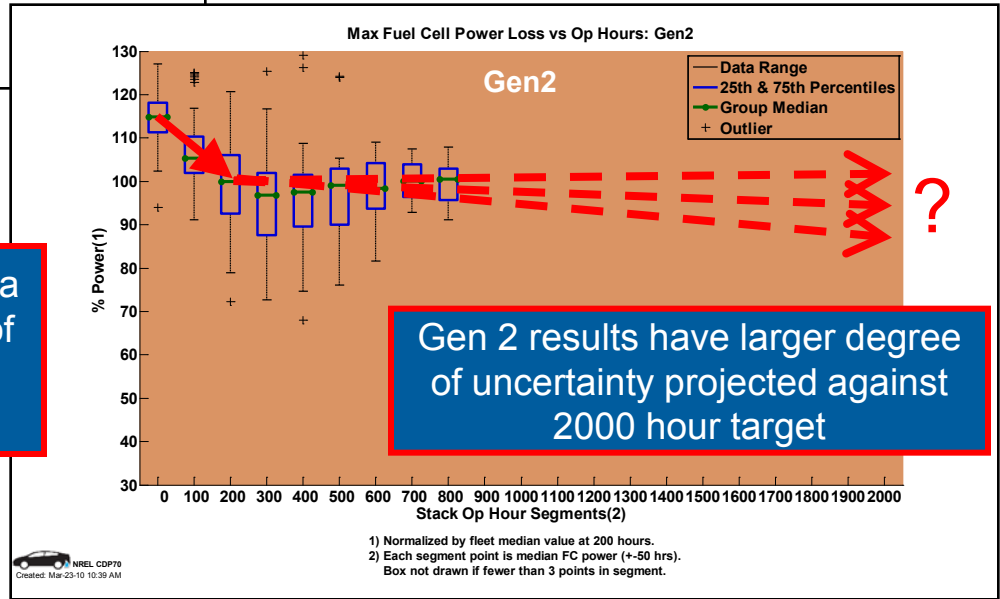
Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
 Distributed natural gas reformation at 1500 kg/day: **\$2.75-\$3.50/kg (2006)**
 Distributed electrolysis at 1500kg/day: **\$4.90-\$5.70 (2009)**

Accomplishment: Completed Final Analysis of Gen 1 Fuel Cell System Power Degradation



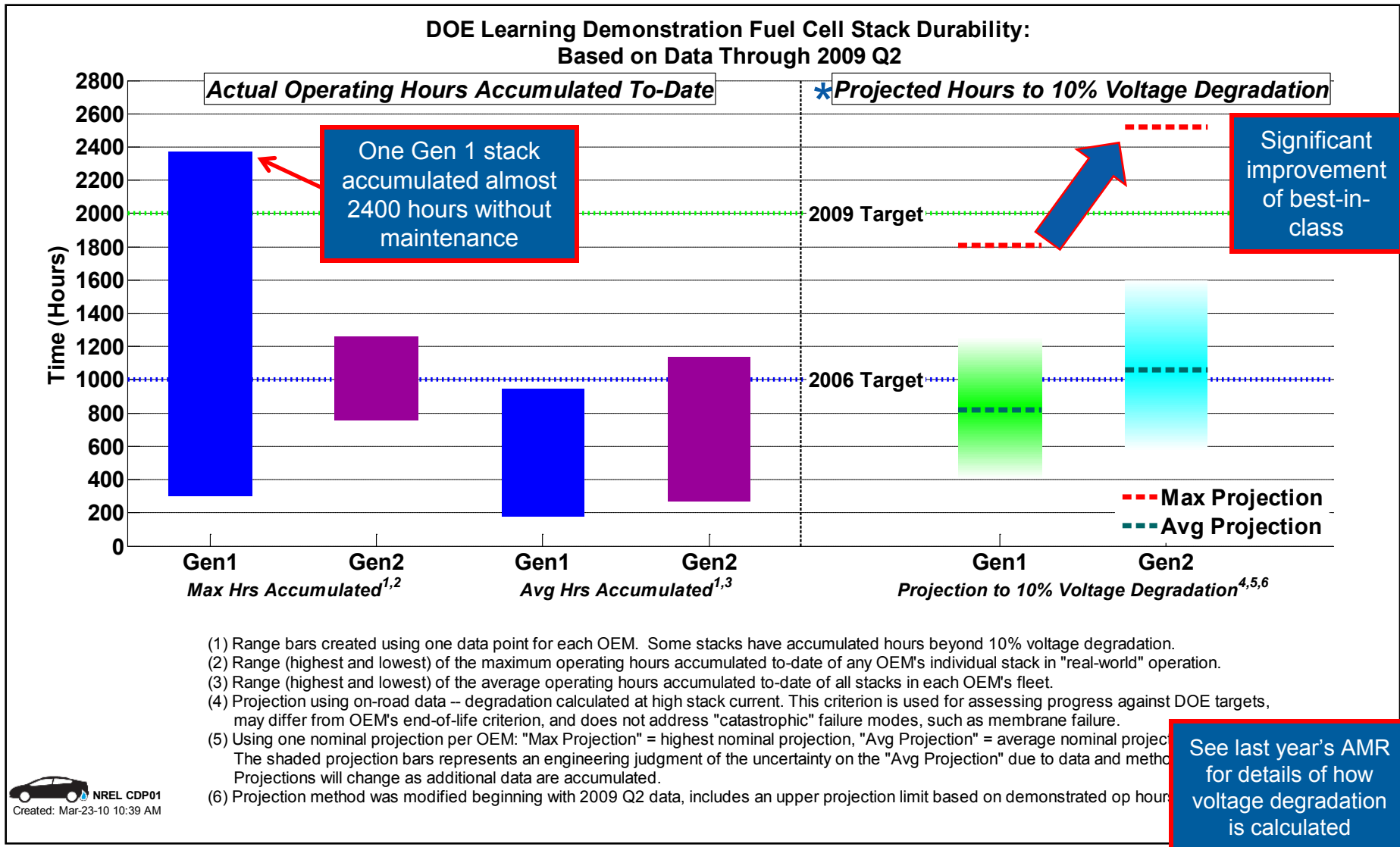
Need ~1000 hours to have higher confidence in slope of degradation

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

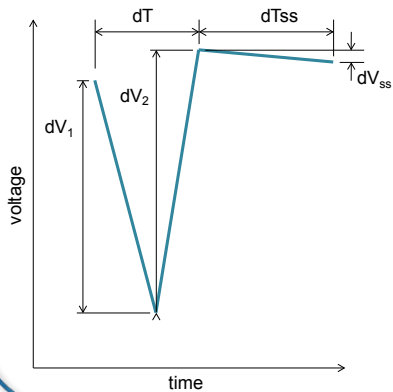
Accomplishment: Quantified Gen 2 Fuel Cell System Durability* Improvement from Gen 1



- (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 method. 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.

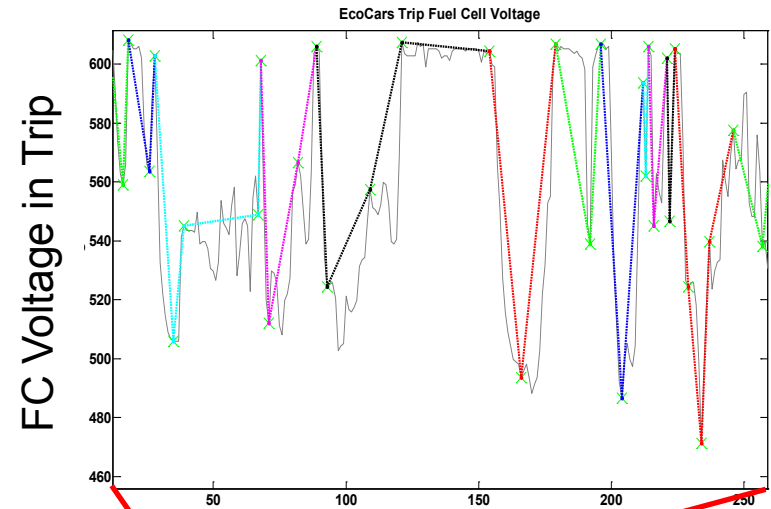
Accomplishment: Developed Methodology for Tracking FC System Voltage Transients

1) Define a voltage transient cycle

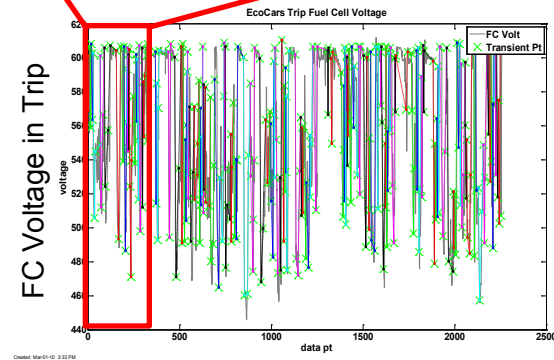
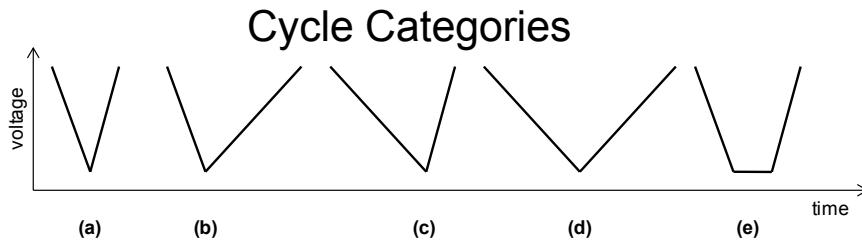


Cycle Definition:
 $dV \geq 10\% \text{ Nom Stack } V$
 $dT_{ss} \geq 10 \text{ sec}$
 $dV_{ss} \leq 5\% \text{ Nom Stack } V$

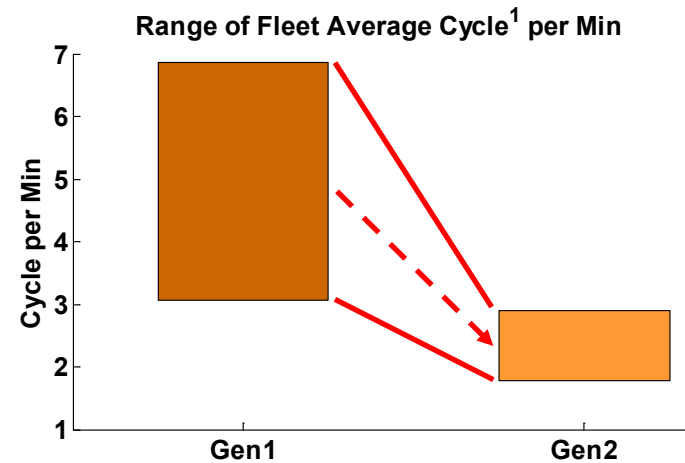
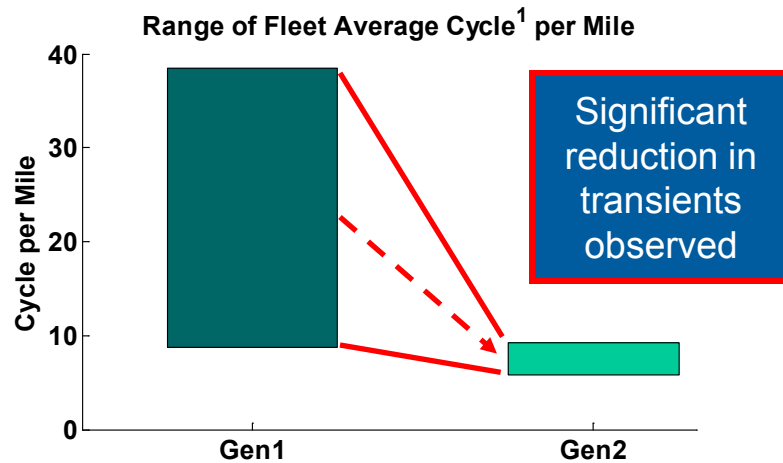
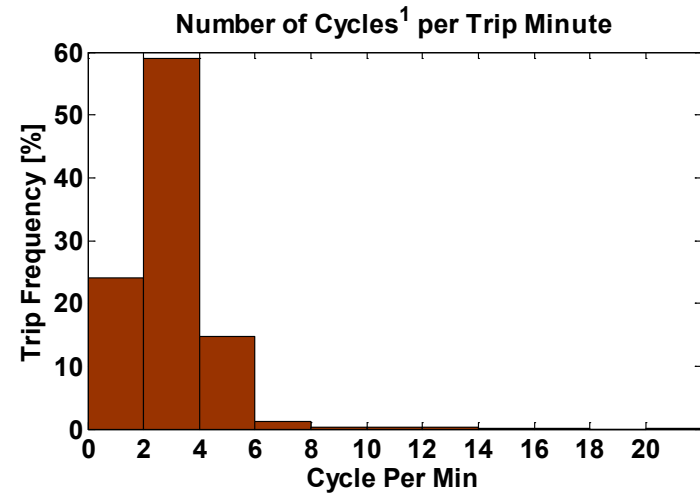
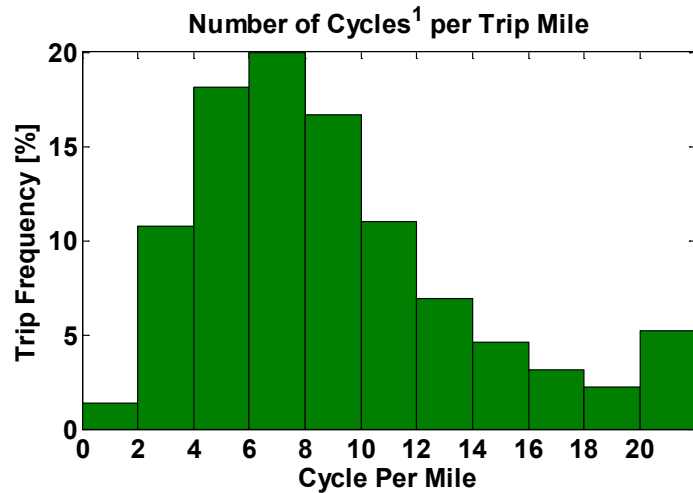
2) Find voltage transient cycles



3) Categorize and collect voltage transient cycle details



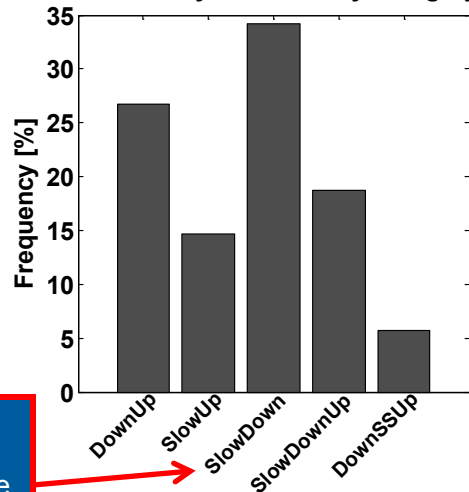
Accomplishment: Quantified Transient Cycle Reduction Between Gen 1 and Gen 2 FC Systems



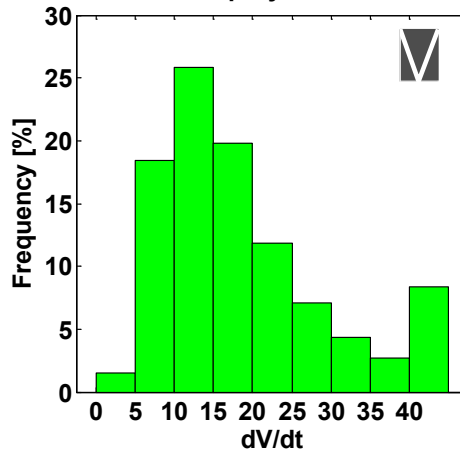
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

Accomplishment: Characterized Fuel Cell Transient Rates by Cycle Category

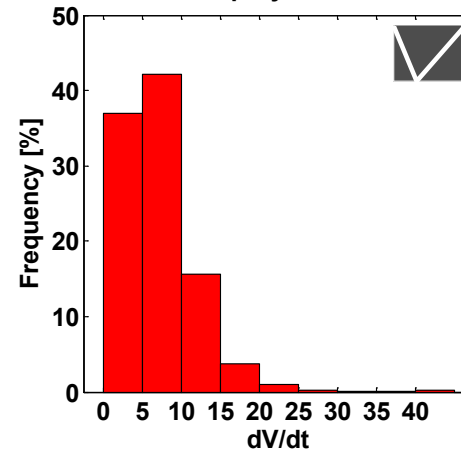
Transient Cycle¹ Count by Category²



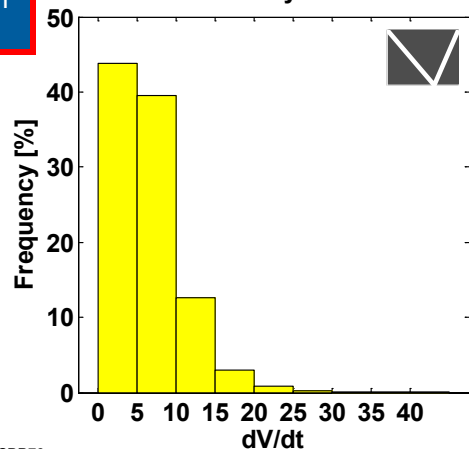
DownUp Cycle¹ dV/dT



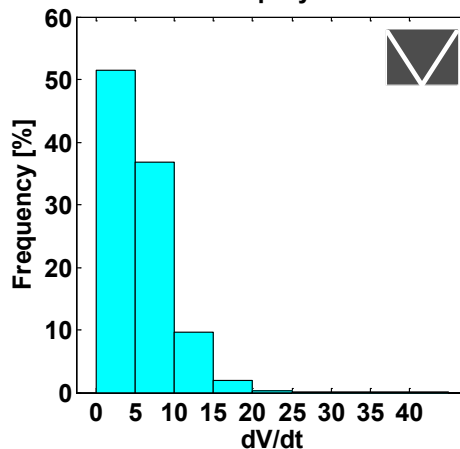
SlowUp Cycle¹ dV/dT



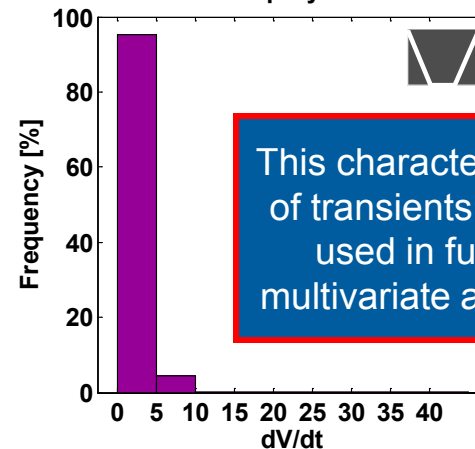
SlowDown Cycle¹ dV/dT



SlowDownUp Cycle¹ dV/dT



DownSSUp Cycle¹ dV/dT

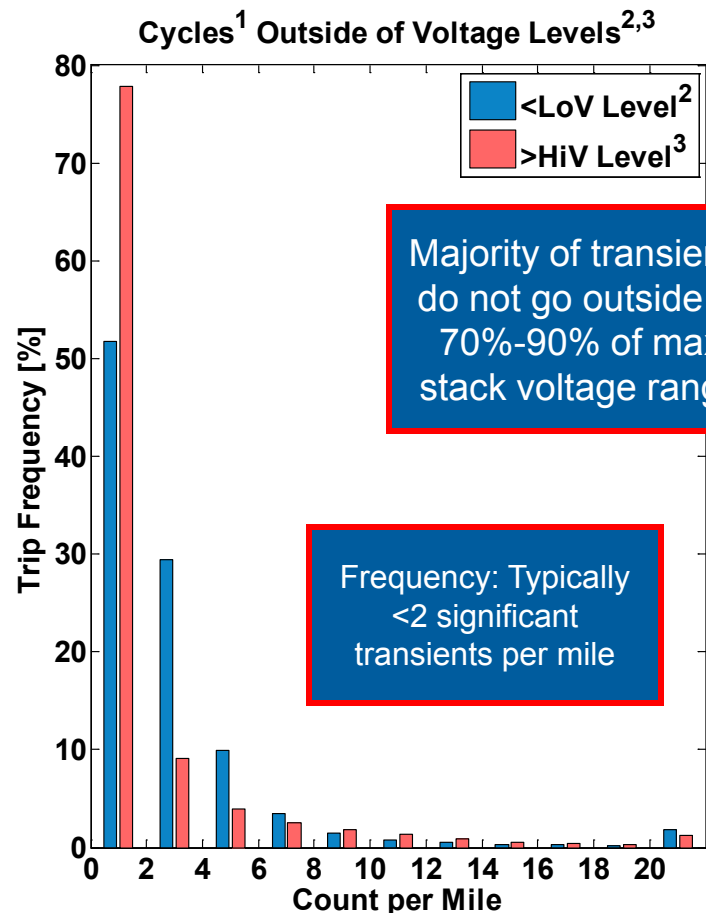
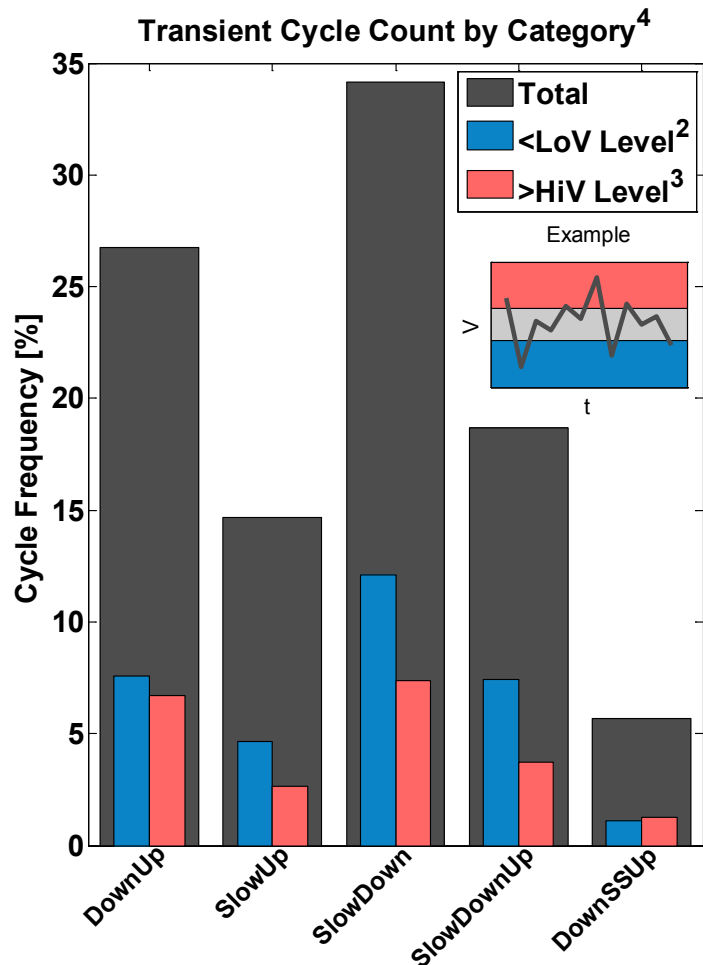


Type: The slow down, fast up are the most common transients

This characterization of transients will be used in future multivariate analysis

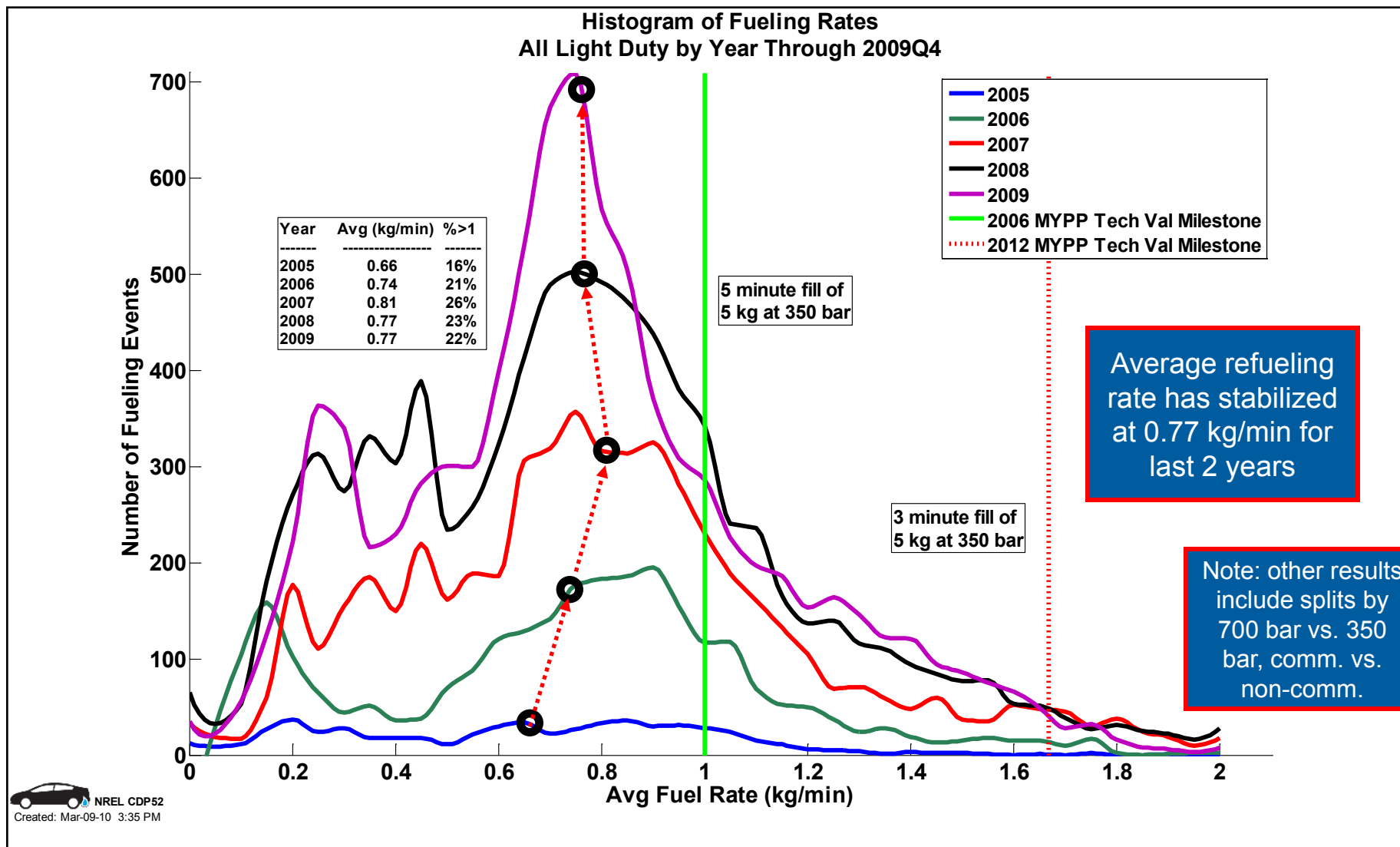
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change ≥ 5 seconds. SS = Steady State, where the time change is ≥ 10 seconds and the voltage change is $\leq 2.5\%$ max stack voltage.

Accomplishment: Characterized Fuel Cell Transient Cycles Outside of Specified Voltage Levels

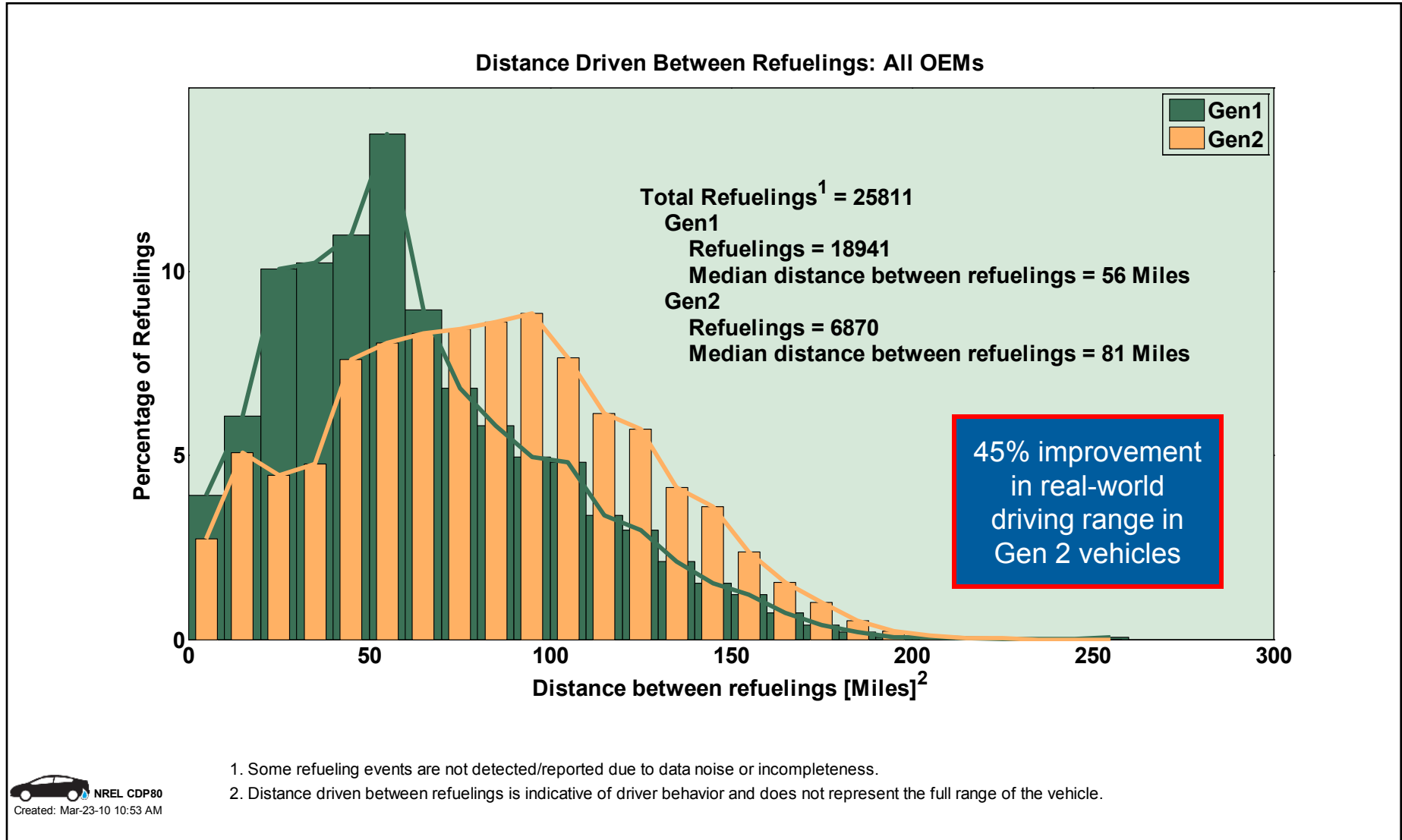


- 1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
- 2) The low voltage level is 70% Max Stack Voltage
- 3) The high voltage level is 90% Max Stack Voltage
- 4) Cycle categories based on cycle up and down times. A slow up or down transient has a time change ≥ 5 seconds.
SS = Steady State, where the time change is ≥ 10 seconds and the voltage change is $\leq 2.5\%$ max stack voltage.

Accomplishment: Tracked Refueling Rates Over 5 Year Period of Project



Accomplishment: Quantified Real-World Improvement in Driving Range Between Gen 1 and Gen 2 Vehicles



Accomplishment: NREL/SRNL Verified Toyota FCHV-adv Driving Range >400-Mile (Without Refueling) on June 30, 2009



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

DRAFT

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

Keith Wipke¹, Donald Anton², Sam Sprick¹

ver. 2.1
July 10, 2009
PTS-05 of SRNS CRADA No. CR-04-003




¹ National Renewable Energy Laboratory
² Savannah River National Laboratory

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Highlights of Interactions and Collaborations in the Last Year

Auto/Energy Industry Partners

- Detailed discussion of NREL results and methodology
- Focused on 2-way sharing of voltage degradation calculations and transient analyses
- Completed 3rd-party evaluation of FCV on-road driving range

FreedomCAR and Fuel Technical Teams

- Fuel Cell (4/10) and H₂ Storage (4/10) Tech Teams

US Fuel Cell Council Technical Working Groups

- Transportation Working Group
- Joint H₂ Quality Task Force

California Organizations

- CaFCP and CHBC: NREL actively participating as member
- CARB: New stations to provide data to NREL, assisting with SB 1505 feedback (renewable H₂ requirement); ZEV Tech Forum

Early FC Market Evaluations: DOD (DLA) and ARRA

- Leveraging experience to evaluate FC forklifts and backup power
- Assisted with DOD H₂ roadmap generation and review



Future Work

Remainder of FY10:

- Create new and updated composite data products (CDPs) based on data through June 2010 (Fall 2010 CDPs)
 - Prepare results for publication at 2010 Fuel Cell Seminar
- Collaborate even more closely with remaining auto OEM teams to make analyses useful for technology evolution and preparation for 2014-2015 market entry
- Support OEMs, energy companies, and state organizations in coordinating early infrastructure plans

FY11:

- Continue focused analyses with industry partners
- Publish new Spring 2011, Fall 2011 composite data products as the last anticipated results from the project
- Write final summary report for the project
- Continue to leverage analyses to early market FC demonstrations

Summary – Key Performance Metrics

Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target
Fuel Cell Stack Durability			2000 hours
Max Team Projected Hours to 10% Voltage Degradation	1807 hours	<u>2521</u> hours	
Average Fuel Cell Durability Projection	821 hours	1062 hours	
Max Hours of Operation by a Single FC Stack to Date	2375 hours	1261 hours	
Driving Range	103-190 miles	196-<u>254</u> miles	250 miles
<i>Fuel Economy (Window Sticker)</i>	42 – 57 mi/kg	43 – 58 mi/kg	no target
<i>Fuel Cell Efficiency at ¼ Power</i>	51 - 58%	53 - <u>59</u> %	60%
<i>Fuel Cell Efficiency at Full Power</i>	30 - 54%	42 - <u>53</u> %	50%

Infrastructure Performance Metrics			2009 Target
H₂ Cost at Station (early market)*	On-site natural gas reformation \$7.70 - \$10.30	On-site Electrolysis \$10.00 - \$12.90	\$3/gge
<i>Average H₂ 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)

Summary – Wrap-up

- **Relevance**
 - Provided DOE and taxpayers strong return on investment made in large hardware demonstration/validation projects
 - Many system level DOE program targets validated by this project
- **Approach**
 - Collaborative relationship to analysis with industry partners; HSDC
- **Technical Accomplishments and Progress**
 - 80 CDP analysis results; publication at conferences every 6 months
- **Collaborations**
 - Work closely with industry partners to validate methodology and ensure relevance of results
- **Future Work**
 - Focused analyses to assist in pre-launch technology improvements

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