NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Project ID# TV001

Controlled Hydrogen Fleet and Infrastructure Analysis

2010 DOE Annual Merit Review and Peer Evaluation Meeting

Keith Wipke, **Sam Sprik, Jennifer Kurtz, Todd Ramsden**

June 10, 2010
Washington, DC

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Fuel Cell Vehicle Learning Demonstration Project Objectives, Relevance, and Targets

- Objectives
  - Validate H_2 FC Vehicles and Infrastructure in Parallel
  - Identify Current Status and Evolution of the Technology
- Relevance
  - Objectively Assess Progress Toward Technology Readiness
  - Provide Feedback to H_2 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 H_2 vehicle and FC system data

B. **Storage** – technology does not yet provide necessary 300+ mile range

C. **Hydrogen Refueling Infrastructure** – cost and availability

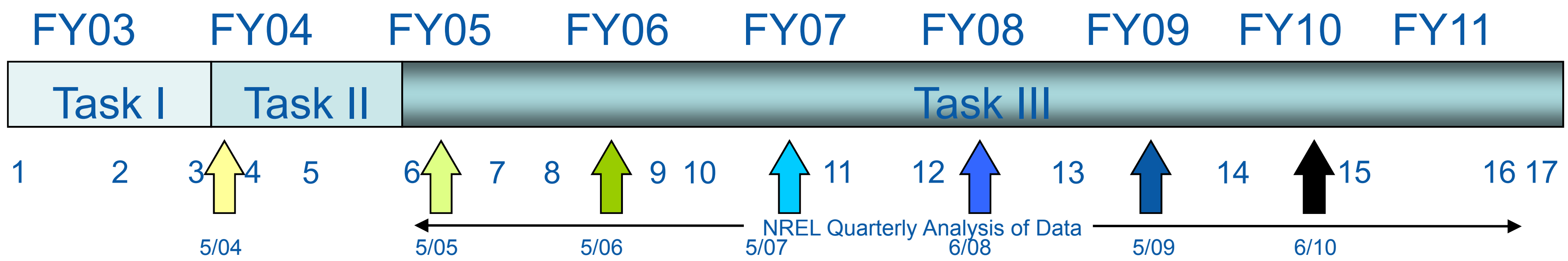
D. **Maintenance and Training Facilities** – lack of facilities and trained personnel

E. **Codes and Standards** – lack of adoption/validation

H. **Hydrogen Production from Renewables** – need for cost, durability, efficiency data for vehicular application

I. **H_2 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 H_2 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

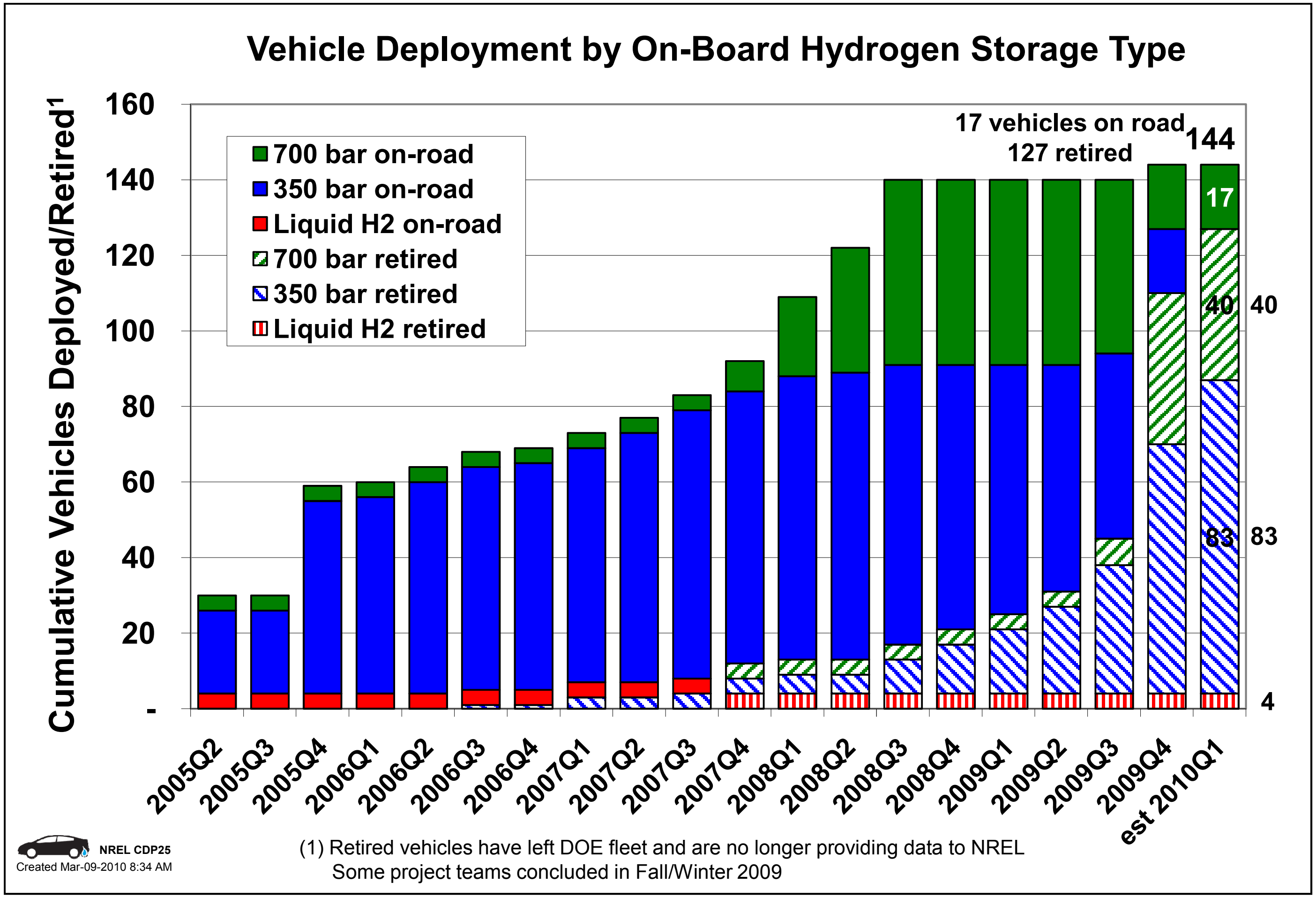
- Publish/present progress of project to public and stakeholders (composite data products)

Industry Partners Include Automakers and Energy-Suppliers

DAIMLER bp

GM Shell

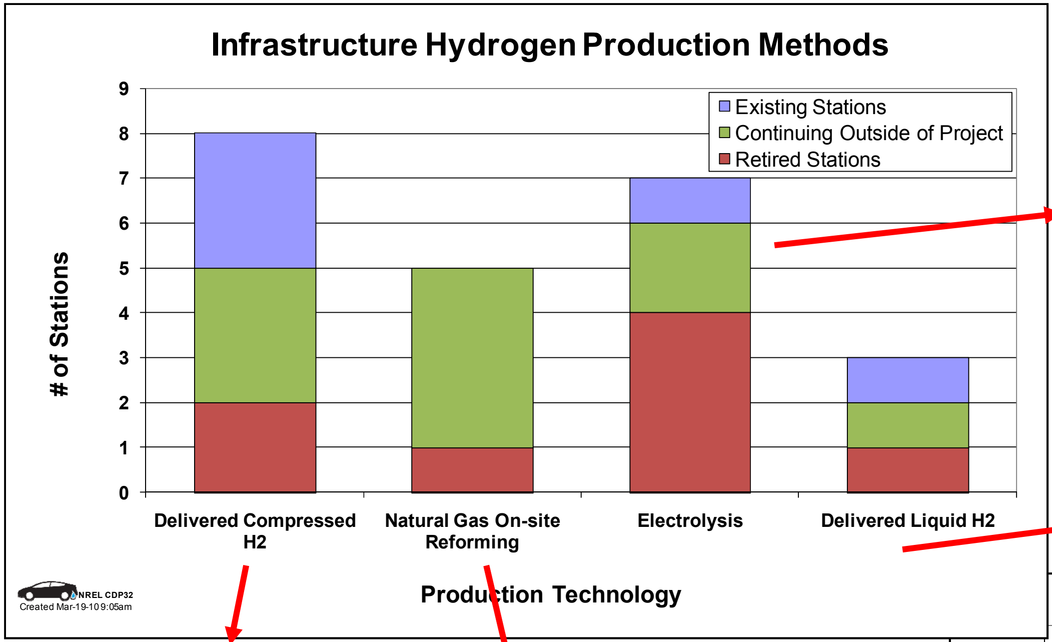
AIR PRODUCTS (CHIP)



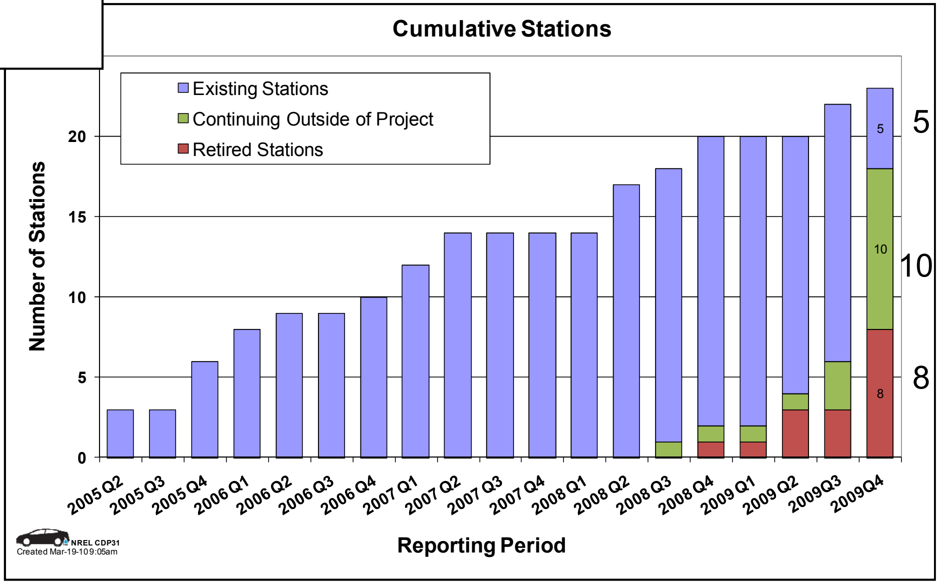
Chevron UTC Power A United Technologies Company HYUNDAI KIA

Ford bp

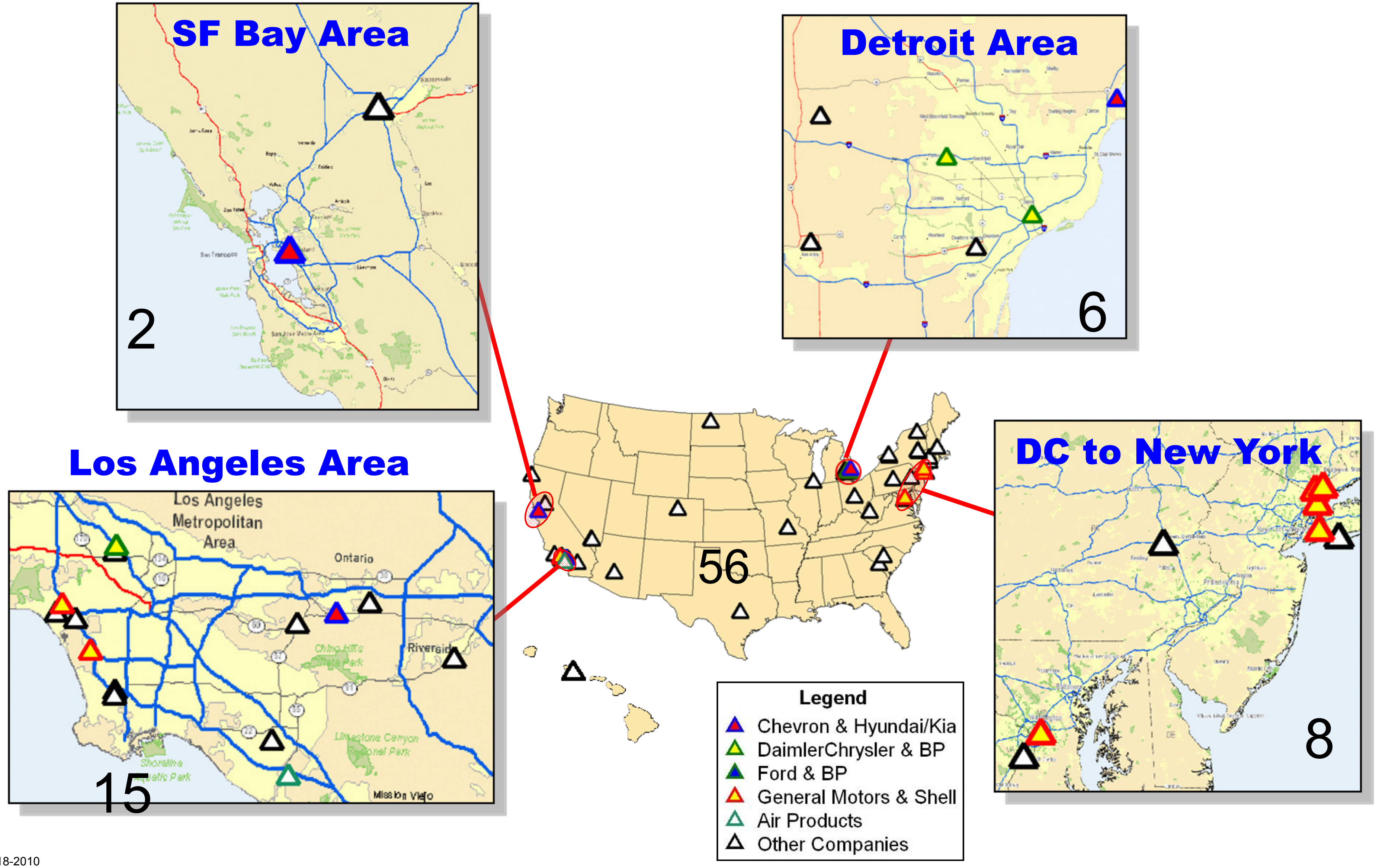
Status: >1/2 Learning Demo Stations Still in Operation; Remainder Decommissioned



Total of 130,000 kg H_2 produced or dispensed from the 23 stations

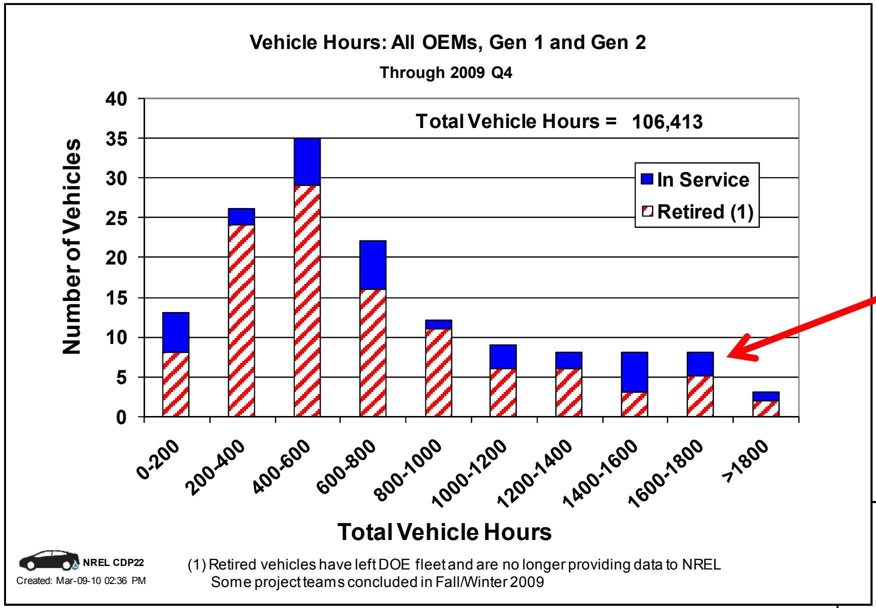


Status: Learning Demo & CHIP Stations Still Serving as Critical Backbone of H_2 Infrastructure in LA and Northeast

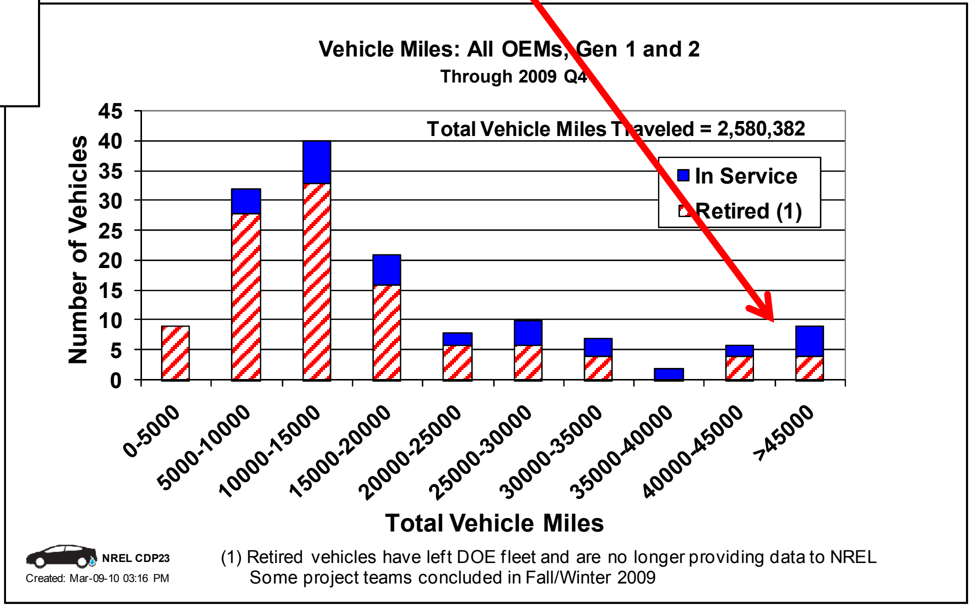


Feb-18-2010

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

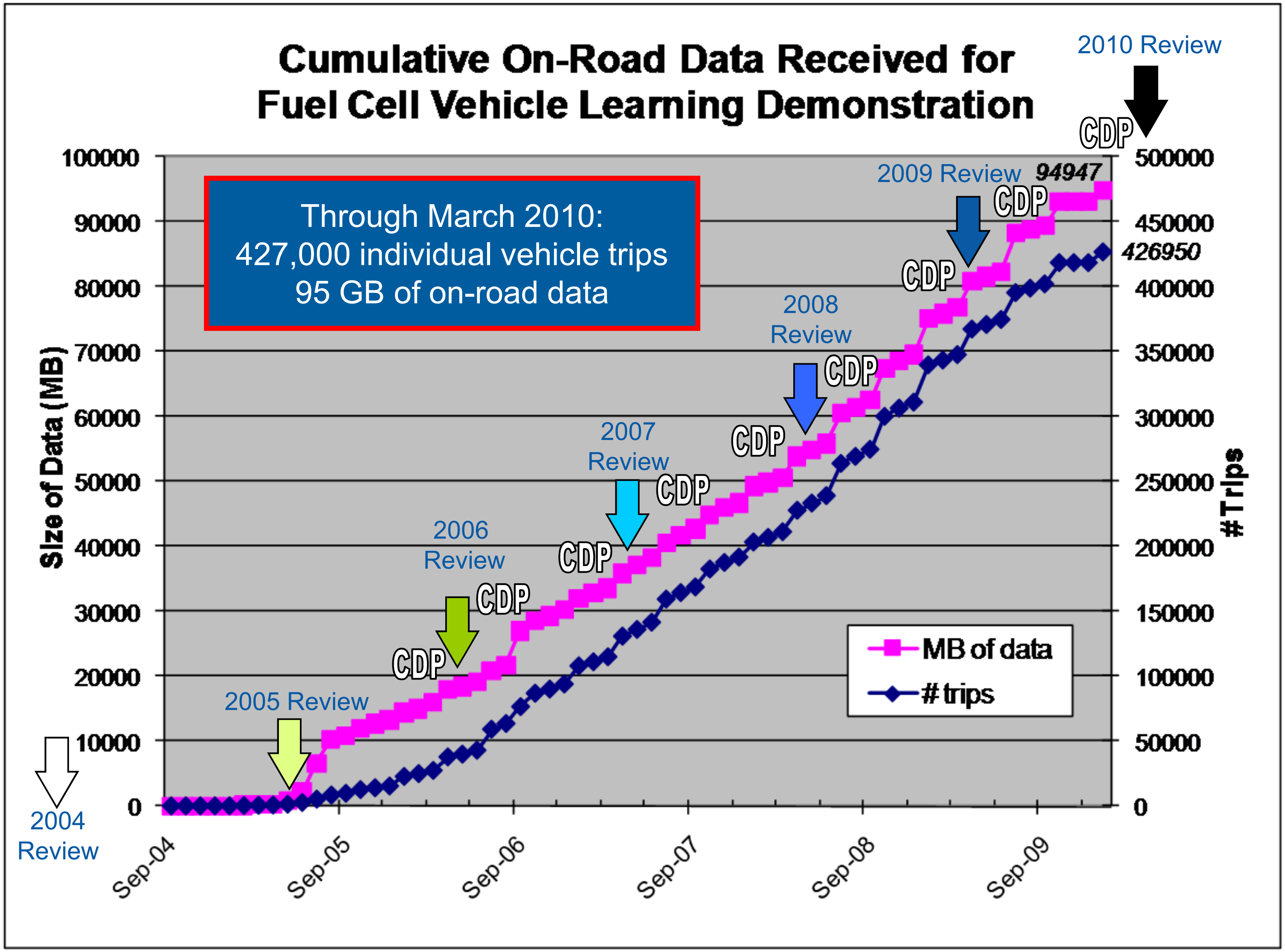


Some Gen 1 vehicles achieved very high miles and hours



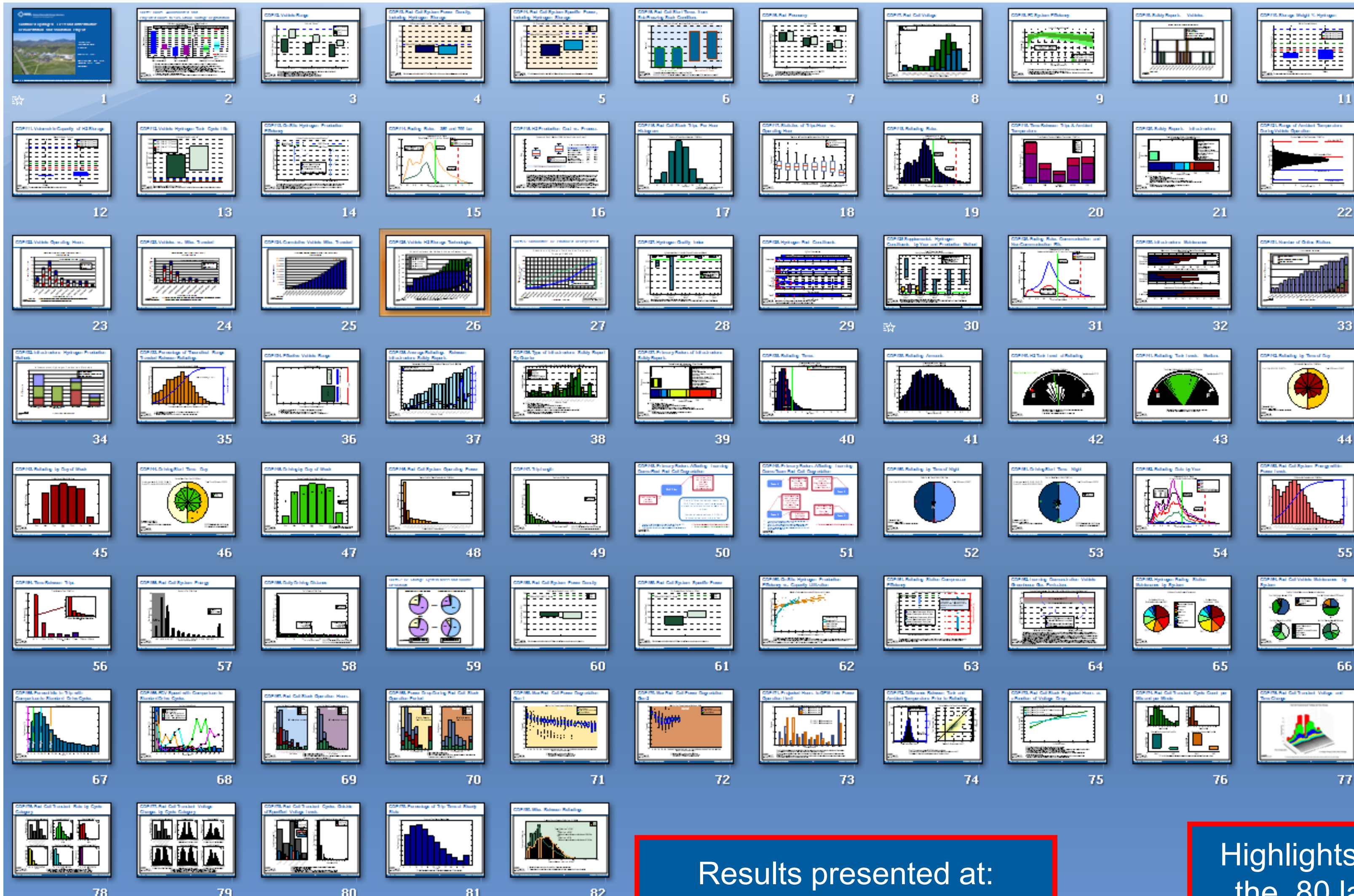
All vehicles continuing in the project will all be Gen 2 vehicles

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



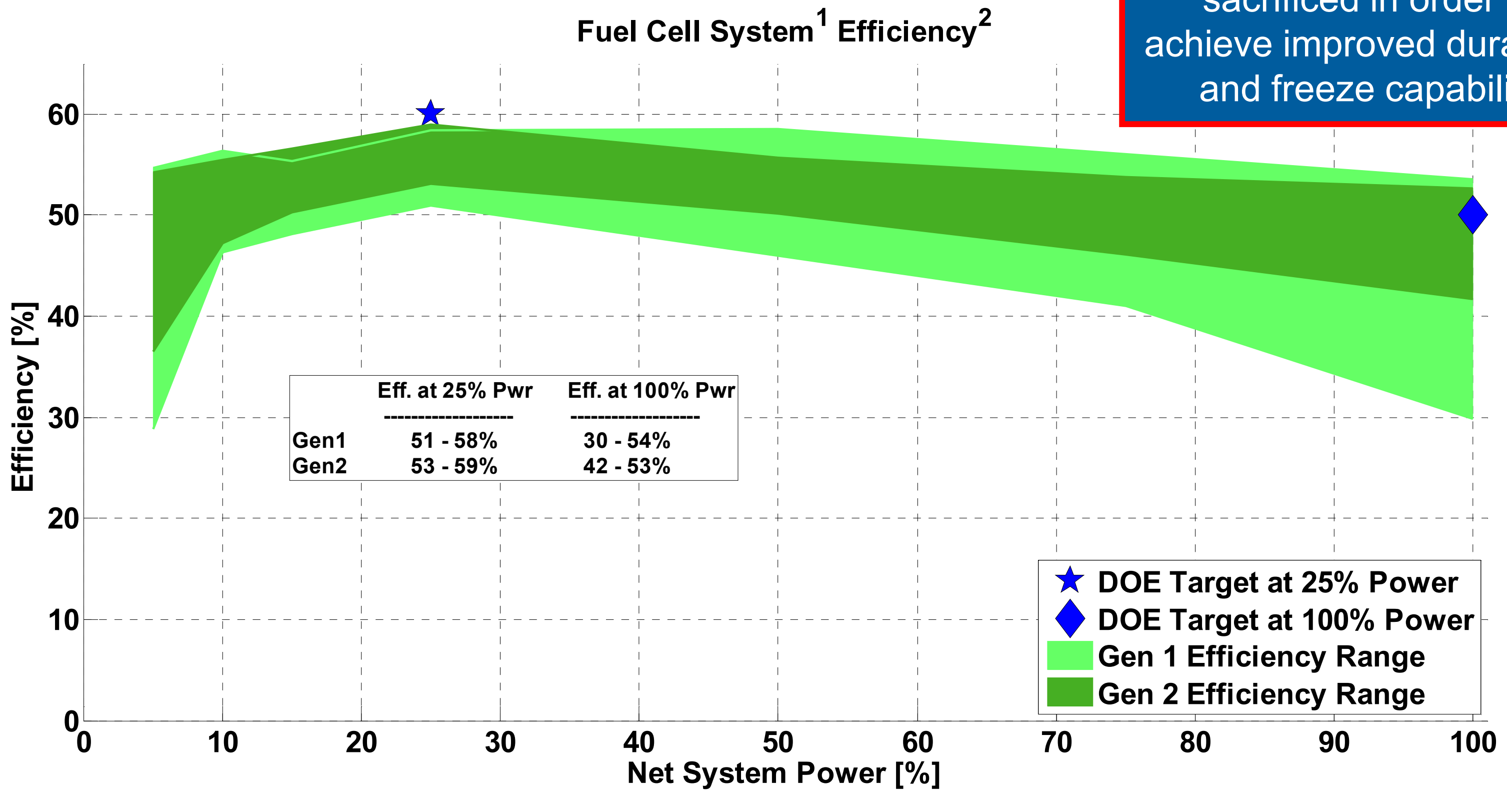
Results presented at:
FC Seminar, NHA, EVS

Highlights from the 80 latest results follow…

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

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

Critical result: Efficiency not sacrificed in order to achieve improved durability and freeze capability



[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.

NREL CDP08

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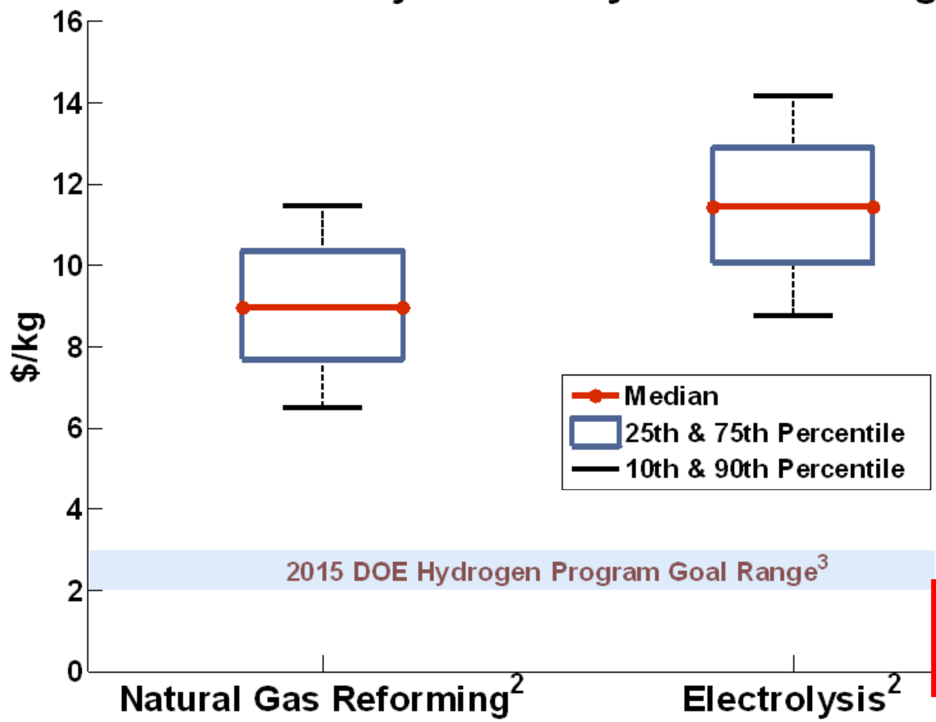
Accomplishment: Projected Early Market H_2 Production Cost from Learning Demo Energy Partners' Inputs

Projected Early Market 1500 kg/day Hydrogen Cost[1] *



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.

NREL CDP15
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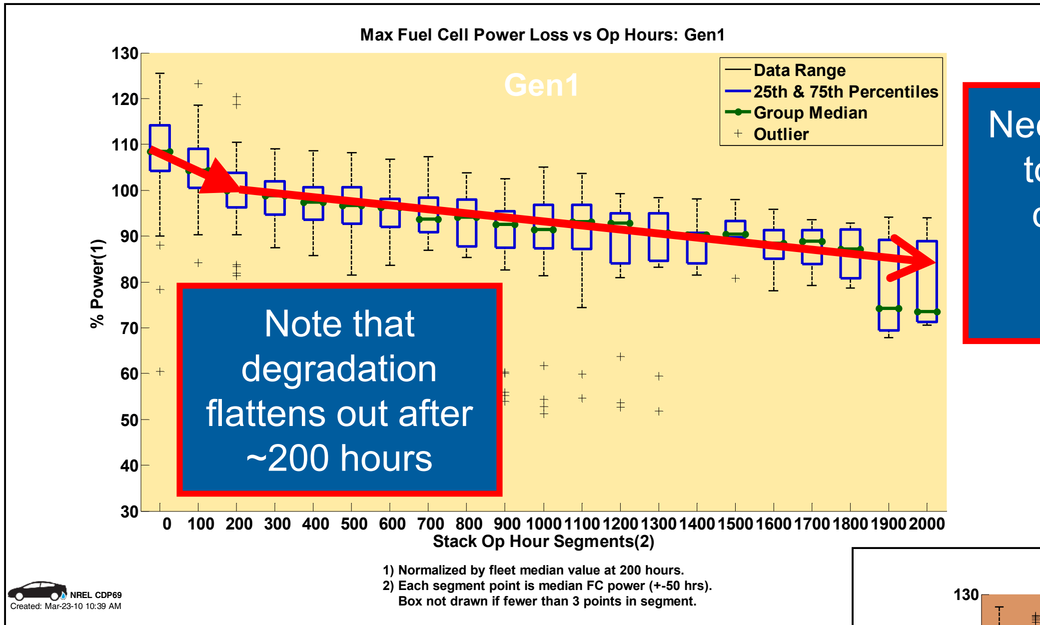
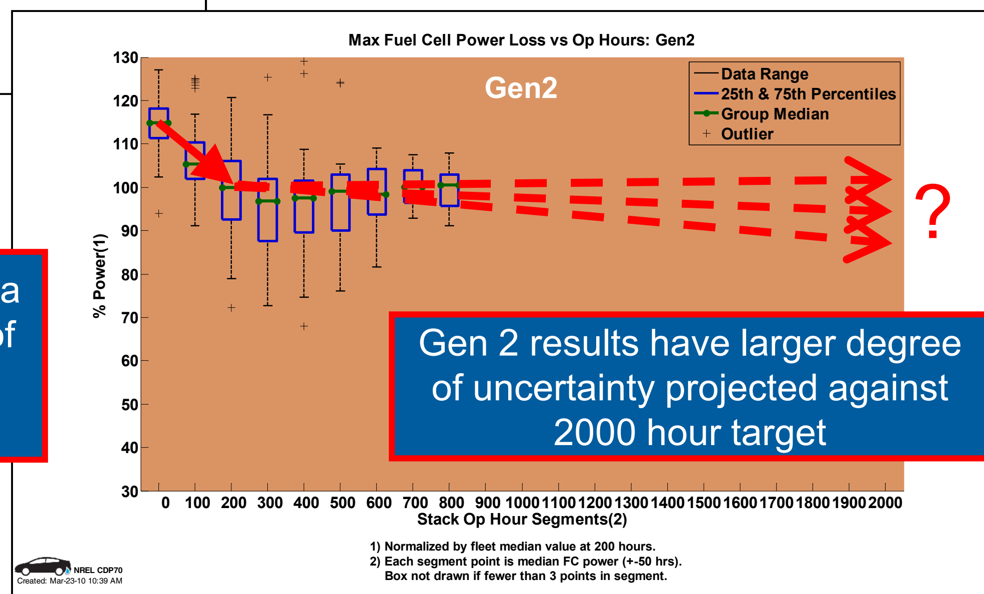
Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
Distributed natural gas reformation at 1500 kg/day: **$2.75-$3.50/kg** (2006)
Distributed electrolysis at 1500kg/day: **$4.90-$5.70** (2009)

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



Note that degradation flattens out after ~200 hours

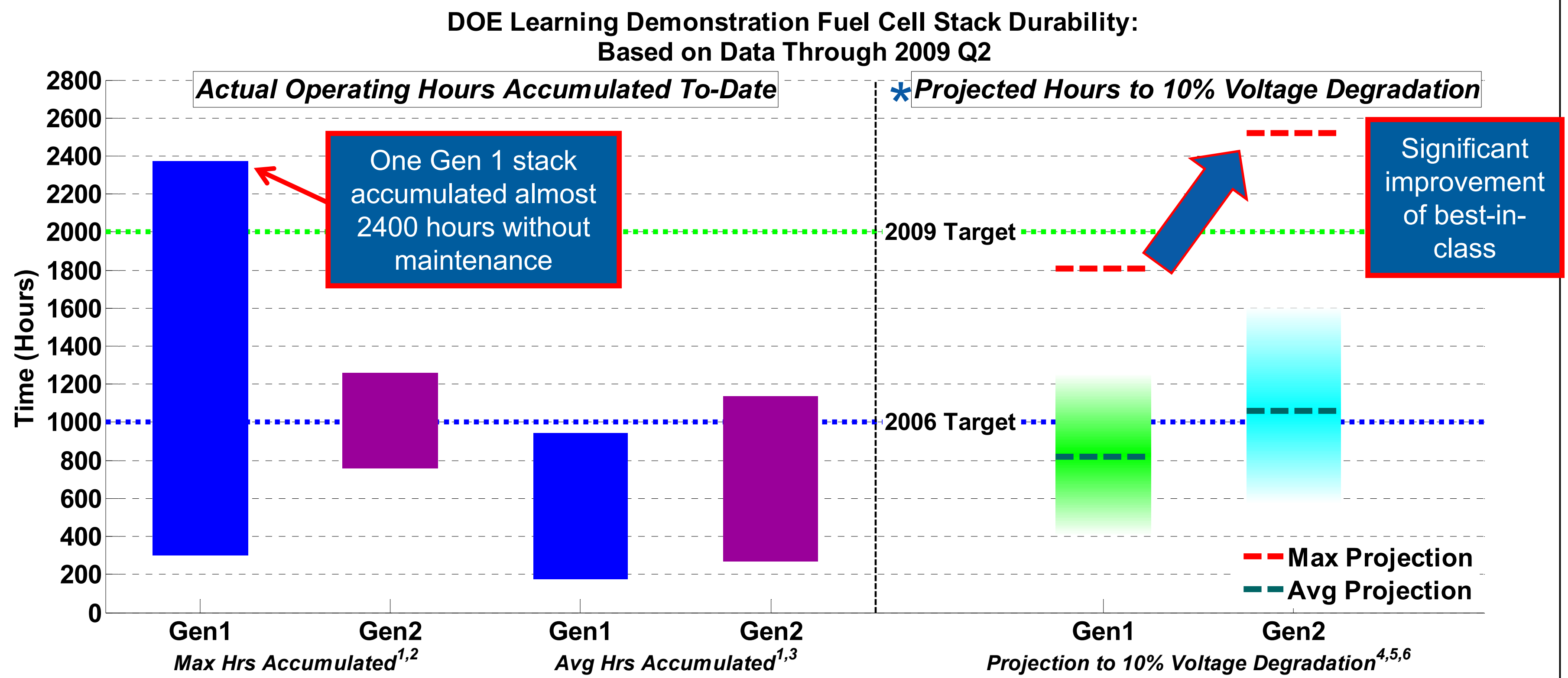
Need ~1000 hours to have higher confidence in slope of degradation



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 projec The shaded projection bars represents an engineering judgment of the uncertainty on the "Avg Projection" due to data and metho 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 hour

NREL CDP01
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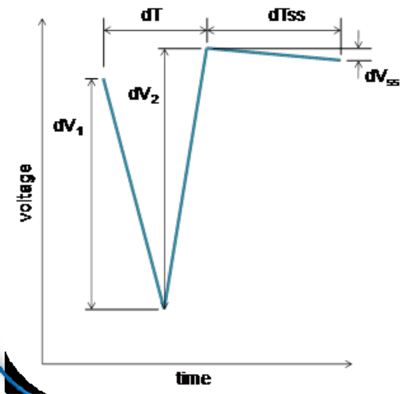
See last year's AMR for details of how voltage degradation is calculated

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

Accomplishment: Developed Methodology for Tracking FC System Voltage Transients

1) Define a voltage transient cycle



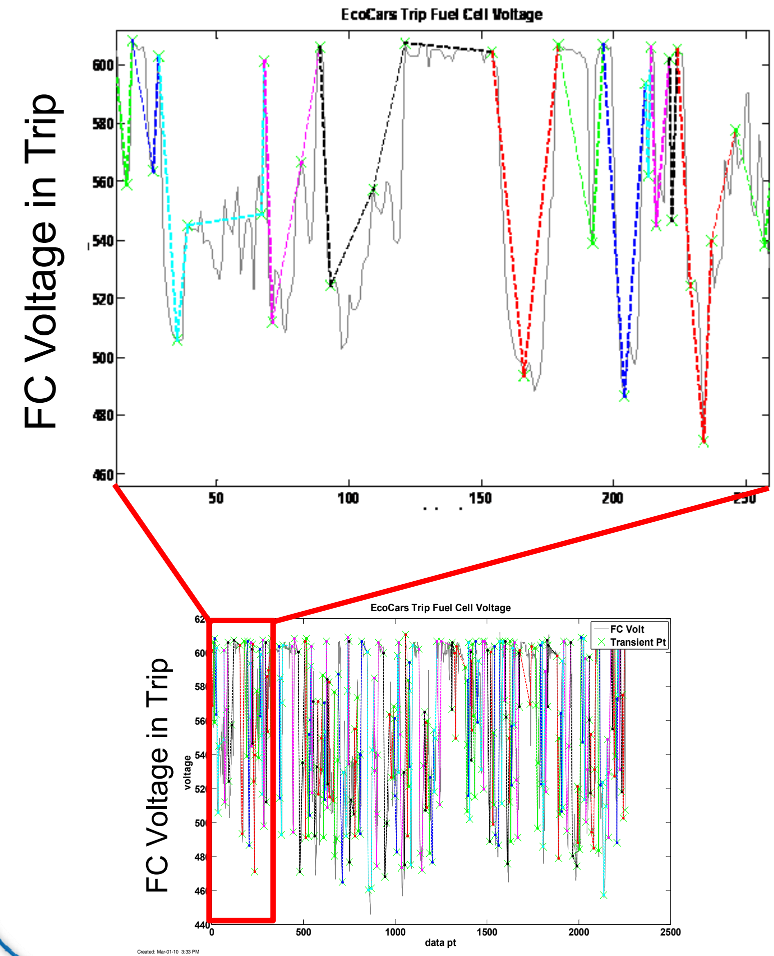
Cycle Definition:

dV >= 10% Nom Stack V

dTss >= 10 sec

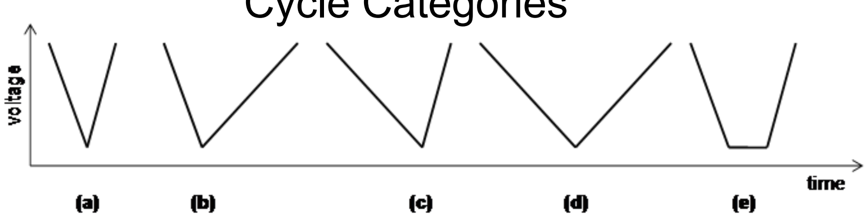
dVss <= 5% Nom Stack V

2) Find voltage transient cycles

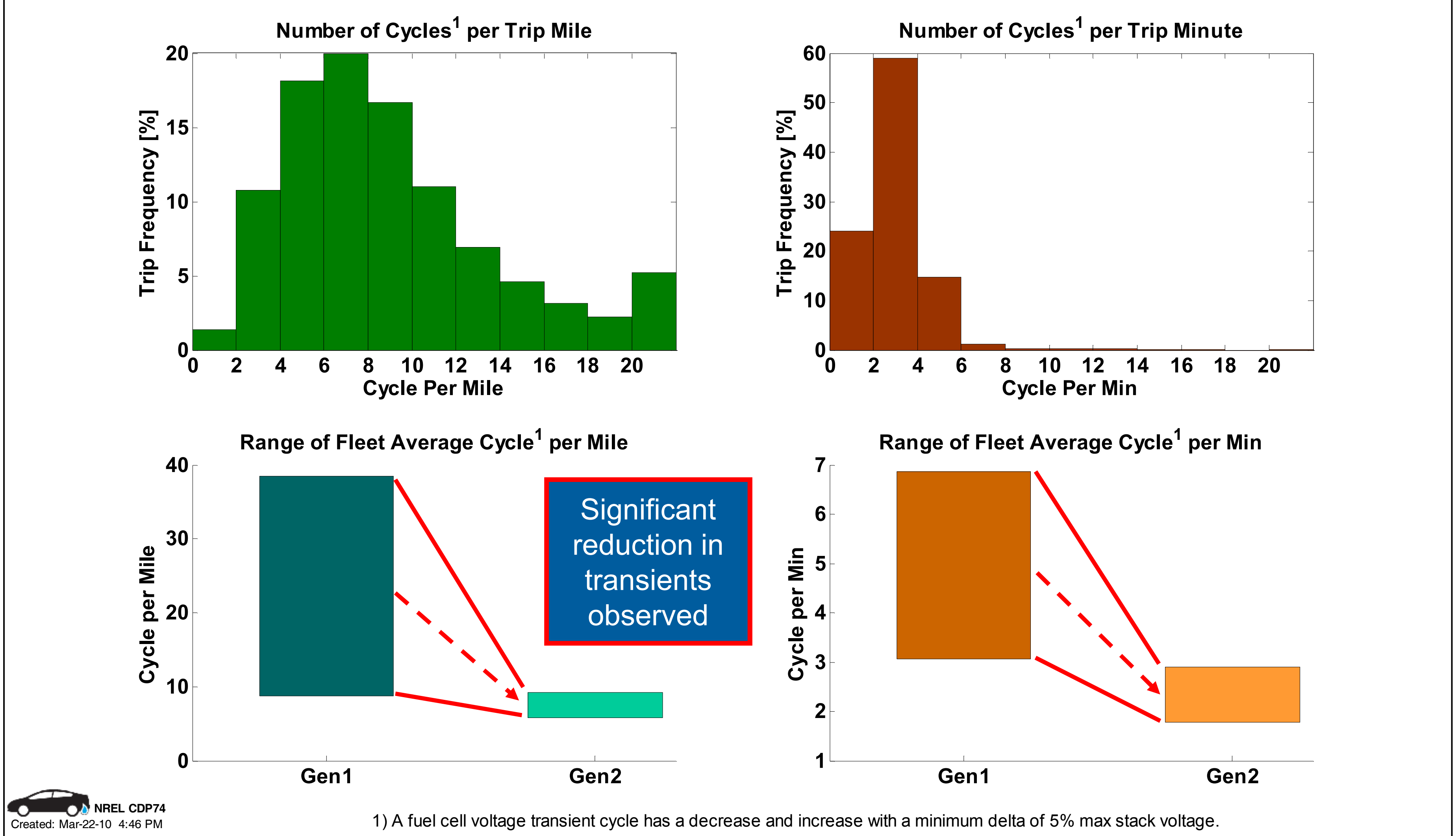


3) Categorize and collect voltage transient cycle details

Cycle Categories

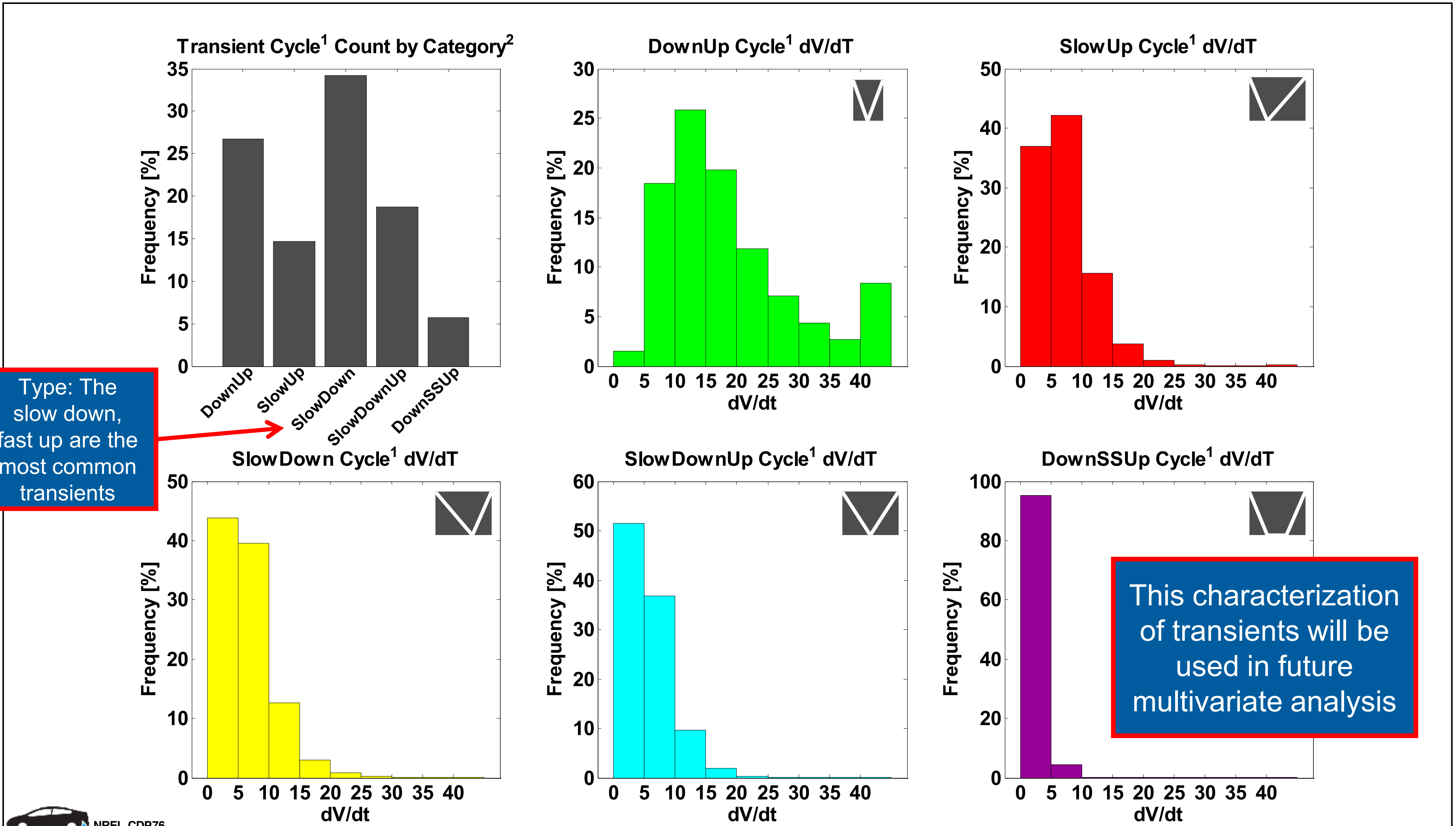


Accomplishment: Quantified Transient Cycle Reduction Between Gen 1 and Gen 2 FC Systems



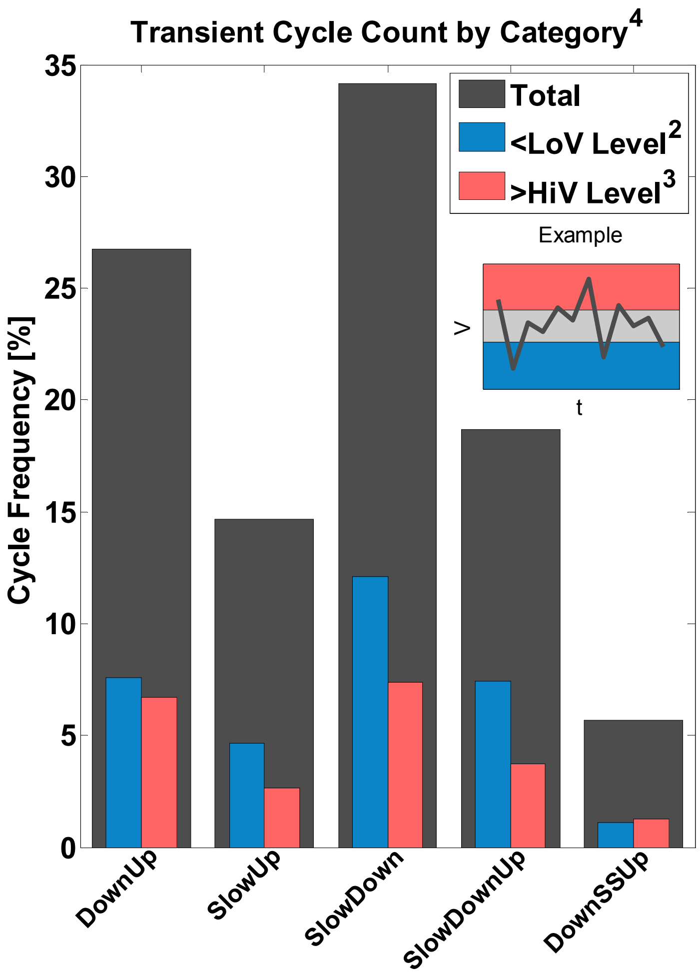
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

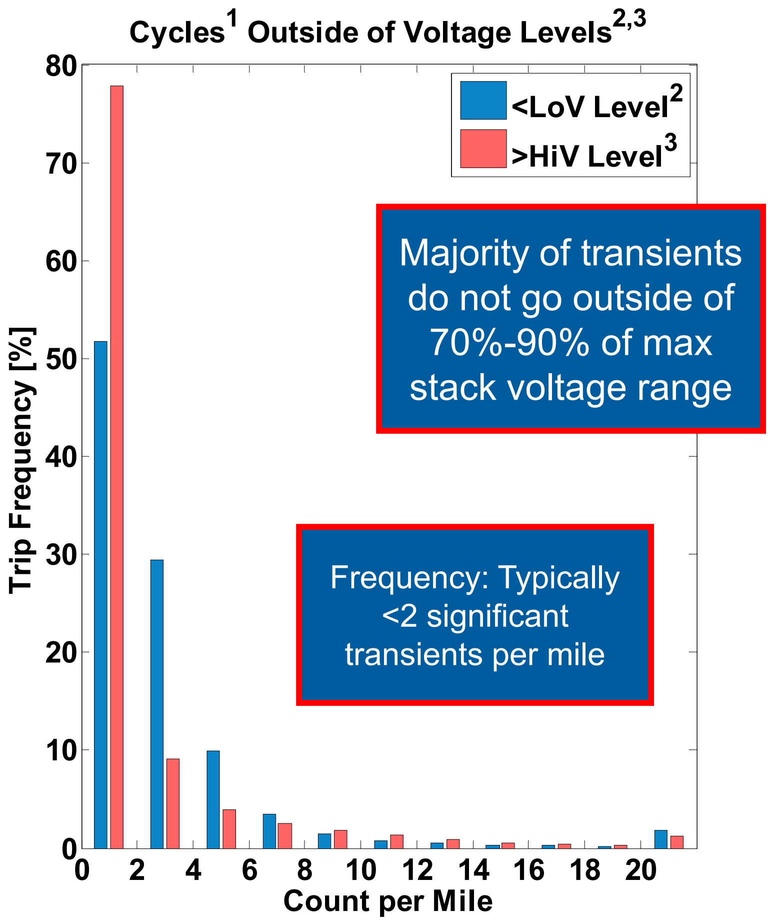
Accomplishment: Characterized Fuel Cell Transient Rates by Cycle Category



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.

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 <= 2.5% max stack voltage.

NREL CDP78
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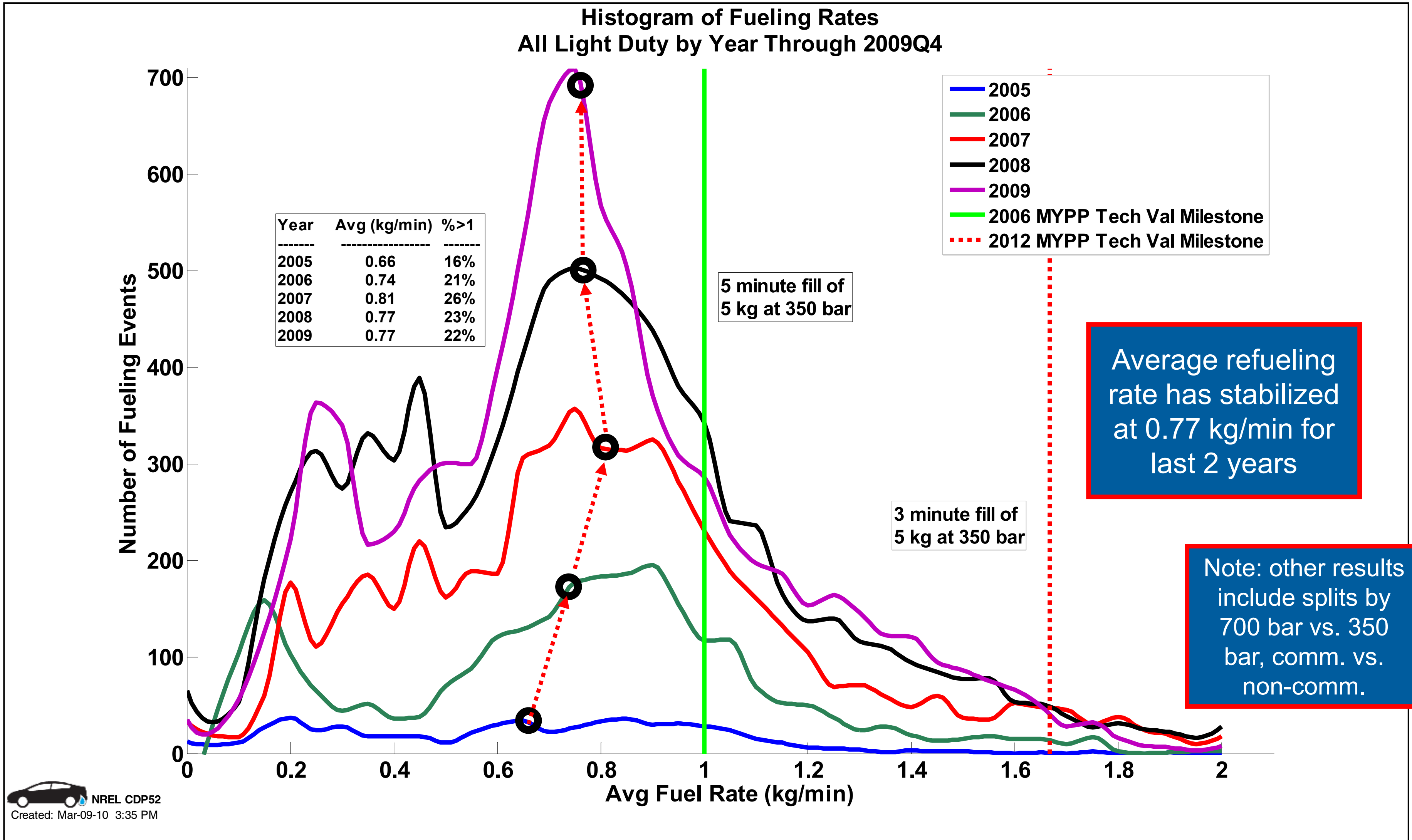
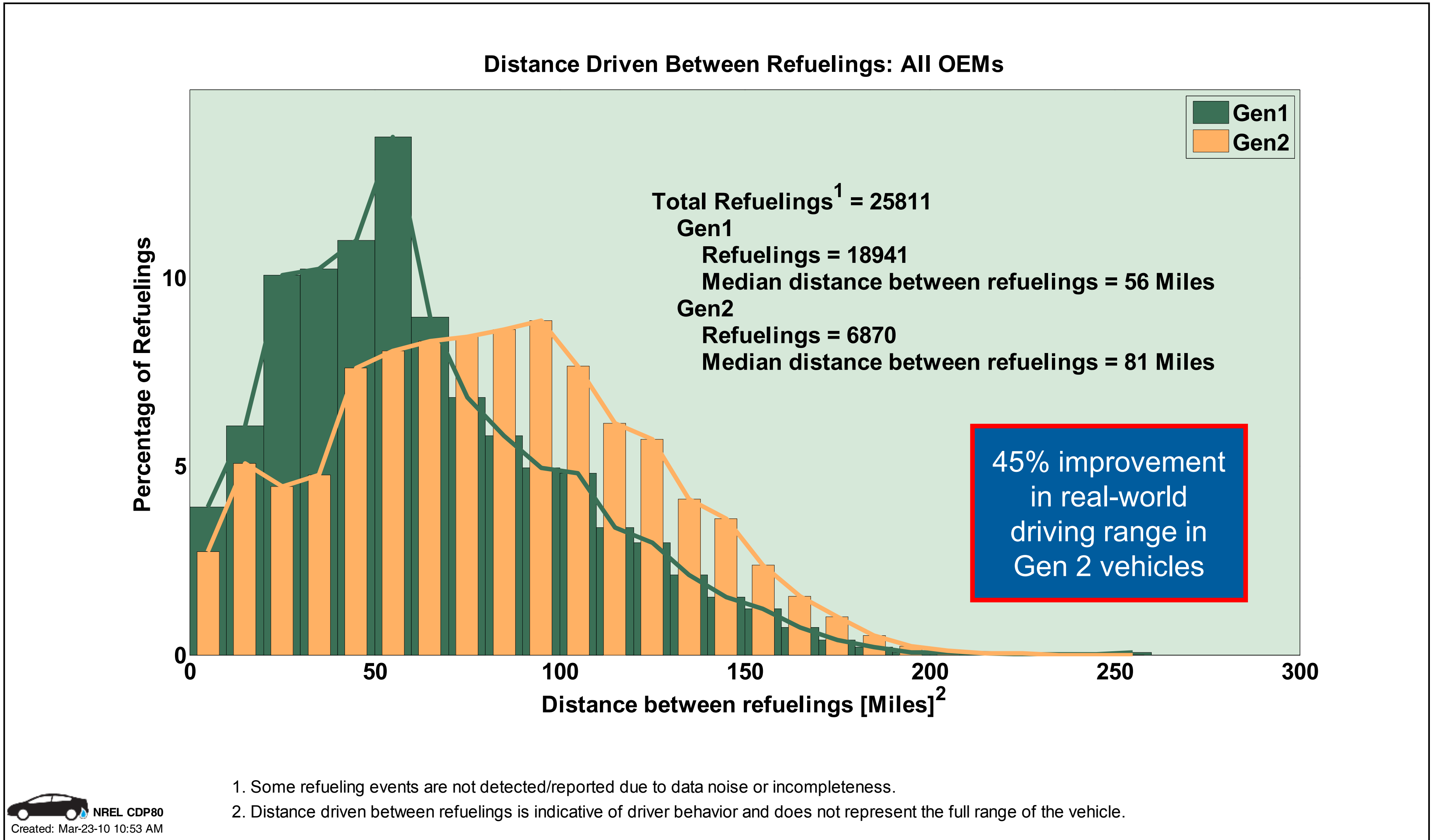
Accomplishment: Tracked Refueling Rates Over 5 Year Period of Project



Average refueling rate has stabilized at 0.77 kg/min for last 2 years

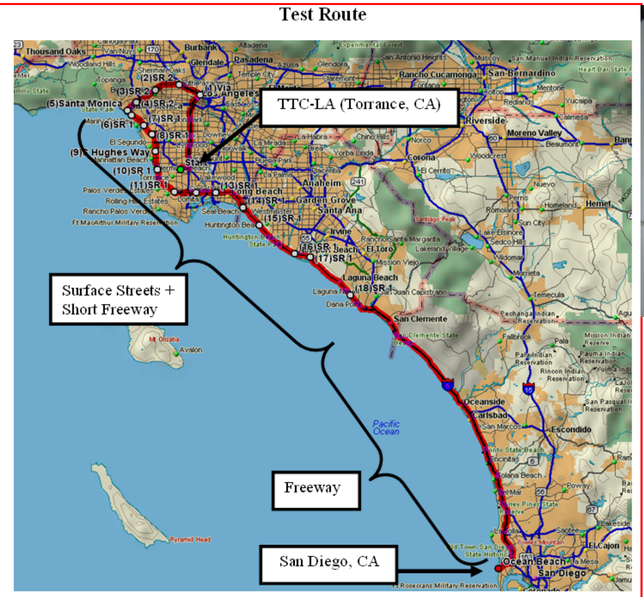
Note: other results include splits by 700 bar vs. 350 bar, comm. vs. non-comm.

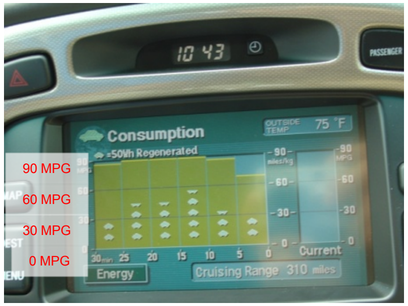
Accomplishment: Quantified Real-World Improvement in Driving Range Between Gen 1 and Gen 2 Vehicles



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.

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 Wipke[1], Donald Anton[2], Sam Sprik[1]

ver. 2.1

July 10, 2009

PTS-05 of SRNS CRADA No. CR-04-003

SRNL

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

[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 H_2 Storage (4/10) Tech Teams

US Fuel Cell Council Technical Working Groups

- Transportation Working Group
- Joint H_2 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 H_2 requirement); ZEV Tech Forum

Early FC Market Evaluations: DOD (DLA) and ARRA

- Leveraging experience to evaluate FC forklifts and backup power
- Assisted with DOD H_2 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

Future Work

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  - 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**	**2521 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**	**196-254 miles**	**250 miles**
Fuel Economy (Window Sticker)	42 – 57 mi/kg	43 – 58 mi/kg	no target
Fuel Cell Efficiency at ¼ Power	51 - 58%	53 - 59%	60%
Fuel Cell Efficiency at Full Power	30 - 54%	42 - 53%	50%

Infrastructure Performance Metrics			2009 Target
H_2 Cost at Station (early market)*	On-site natural gas reformation **$7.70 - $10.30**	On-site Electrolysis **$10.00 - $12.90**	**$3/gge**
Average H_2 Fueling Rate	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

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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