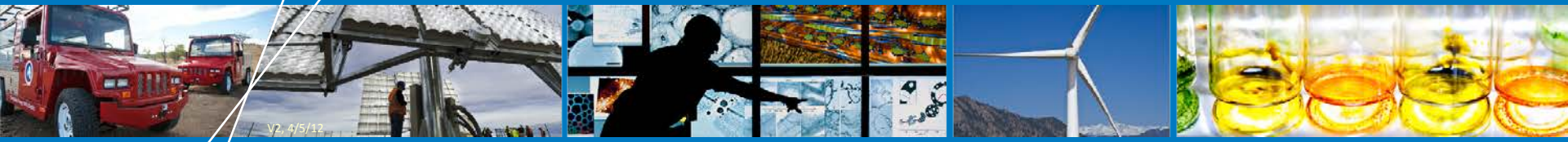
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

EVS26
GRANDES MENTES PENSAM ELETRICAMENTE
LAS MENTES BRILLANTES TIENEN IDEAS ELÉCTRICAS
GREAT MINDS THINK ELECTRIC
LES GRANDS ESPRITS S'ILLUMINENT
AGAR BUDDHIMAN HO BIJLI YAAD KARO
GROTE GEESTEN ZIJN VERLICHT KLUGE KÖPFE DENKEN ELETRISCH
26th International Electric Vehicle Symposium

Final Results from U.S. FCEV Learning Demonstration



EVS-26

Session B1

Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden, Chris Ainscough, Genevieve Saur

May 7, 2012: Los Angeles, CA

NREL/PR-5600-55347

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

Fuel Cell Electric Vehicle Learning Demo Project Objectives, Relevance, and Targets

- **Objectives**
  - Validate H_2 FC Vehicles and Infrastructure in Real-World Setting
  - Identify Current Status and Evolution of the Technology
  - Objectively Assess Progress Toward Targets and Market Needs
  - Provide Feedback to H_2 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 in technical backup slides (previous EVS)

APC/Shell Pipeline station, Torrance, CA.
Photo by Michael Penev, NREL

NREL's Technology Validation Approach

Supporting Both DOE/Public as Well as Technology Developers

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

Internal analysis completed quarterly

HSDC

NREL's Hydrogen Secure Data Center

DDPs

Confidential

Public

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[1]

Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data[2]

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)

Industry Partners: Collaborative Relationship, Working Through Details of Analysis, was Critical to Success

FY03	FY04	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12
RFP	Startup	Operation, Data Collection, and Analysis							

Collaboration with Daimler, GM, and Air Products;
Data in the Last Year (through Sept.) came from These 3 Companies

DAIMLER

GM

AIR PRODUCTS (CHIP)*

- Ford/BP and Chevron/Hyundai-Kia Participated Through 2009

Ford

bp

Chevron

UTC Power
A United Technologies Company

HYUNDAI

KIA

*CHIP = California Hydrogen Infrastructure Project

2nd Generation Vehicles Demonstrated Technology Improvements Over Gen 1

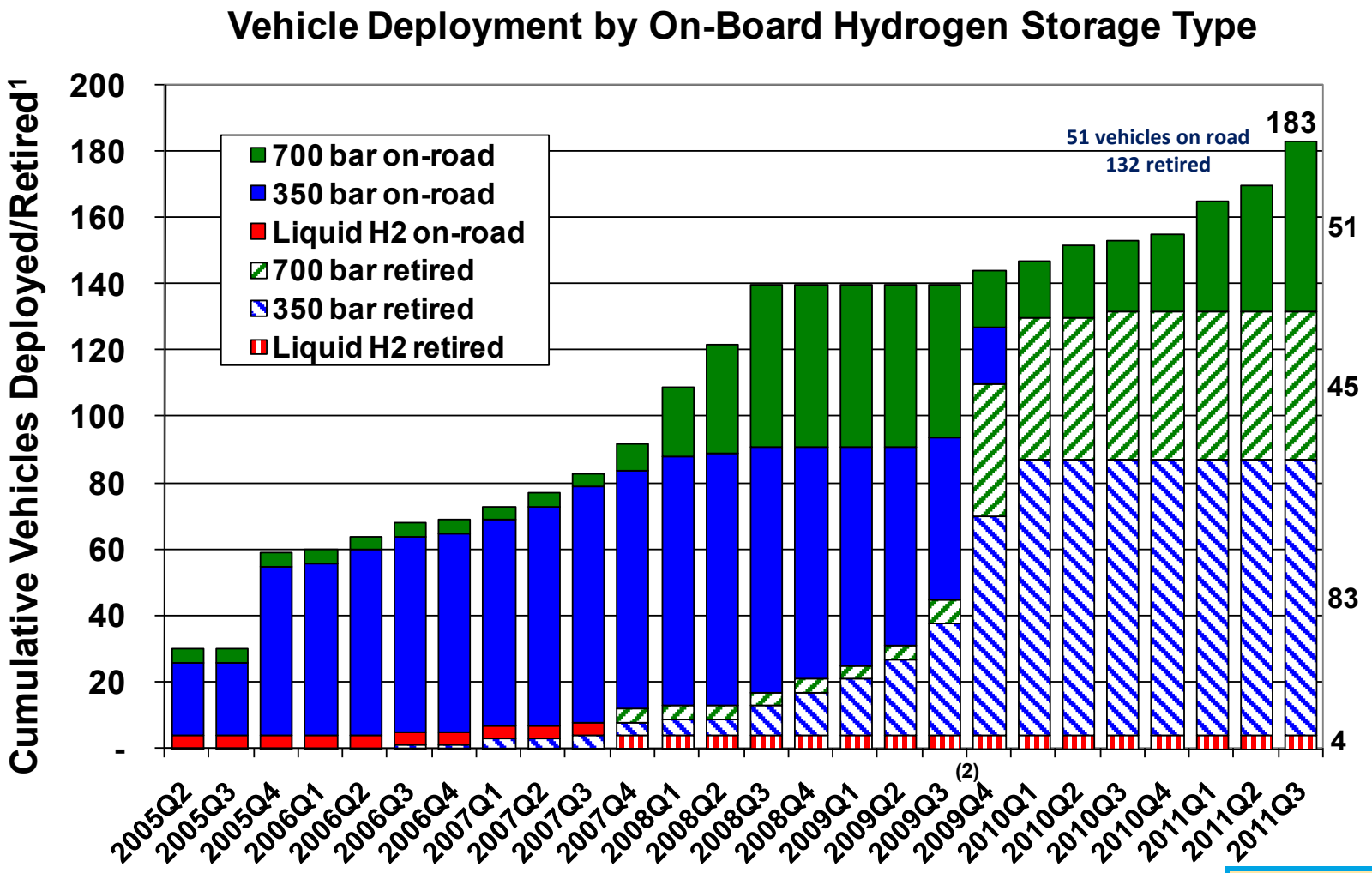
Generation 1 Vehicles

- FC not freeze-capable
- ~2003 stack technology
- Storage: liquid H2 & 350 and 700 bar
- Range: 100-200 miles
- Efficiency: 51-58% at ¼ power

Generation 2 Vehicles

- FC freeze-capable
- ~2007-2009 stack tech.
- Storage: All 700 bar
- Range: 200-250 miles
- Efficiency: 53-59% at ¼ power
- Longer FC durability

Vehicle Status: All Project Vehicles in the Last Two Years Were Using 700 bar Storage



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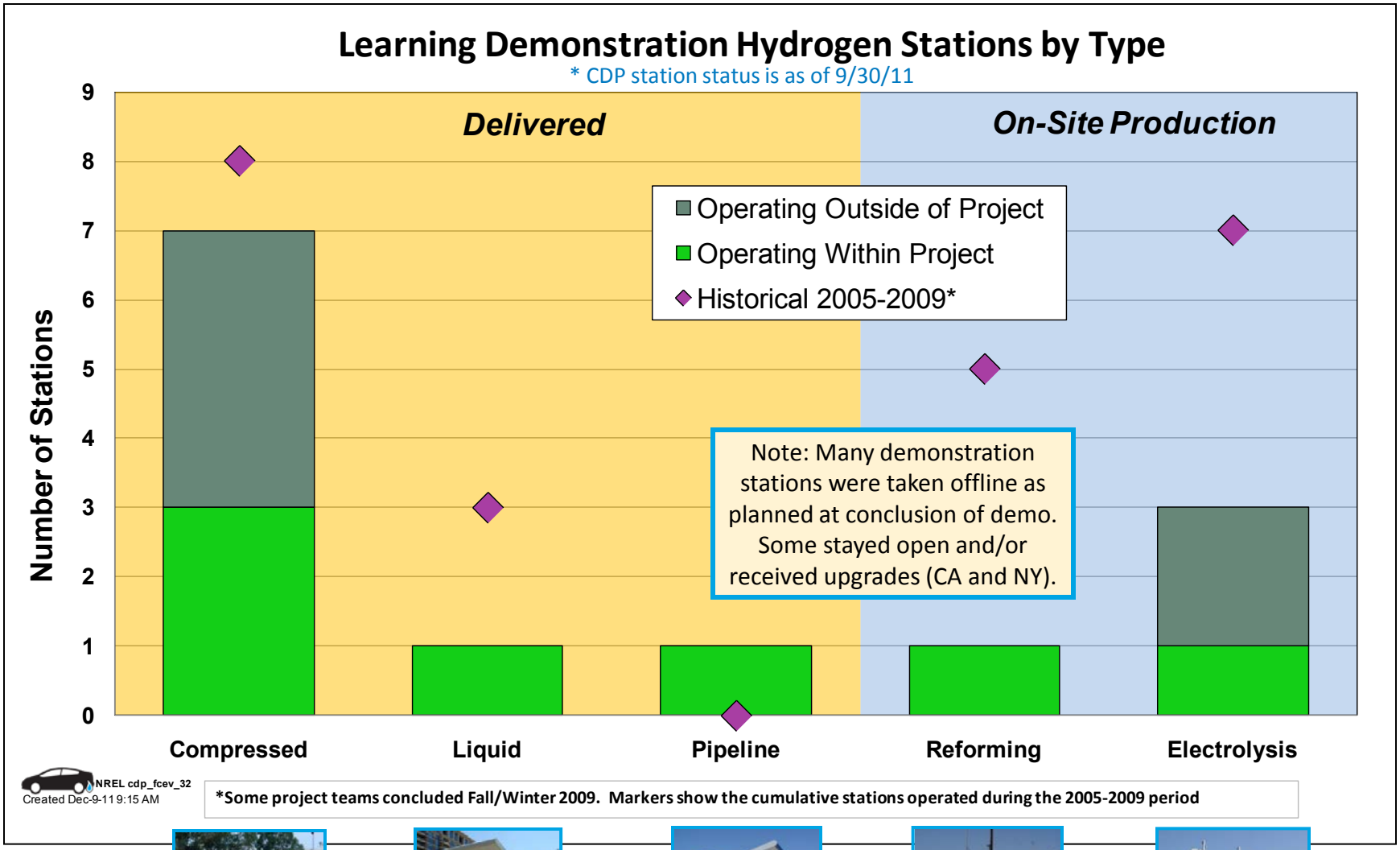
(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009

Large # vehicles required for statistical significance

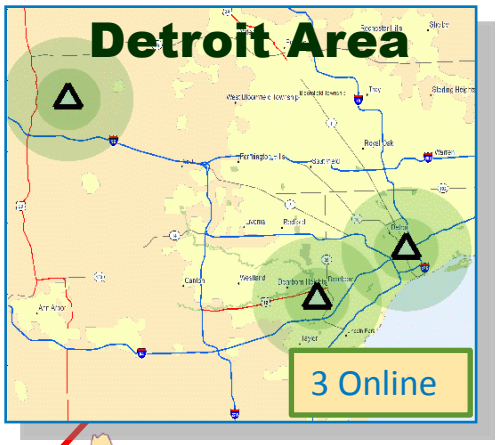
Five Types of Fueling Stations Evaluated

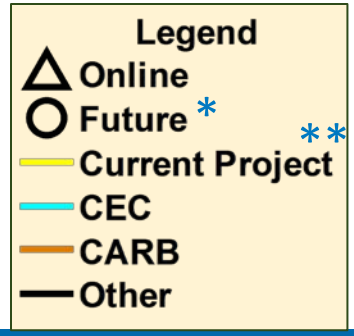






Infrastructure Status: Out of 25 Project Stations, 13 Were Still Operational at End of Project (6 outside of DOE project)

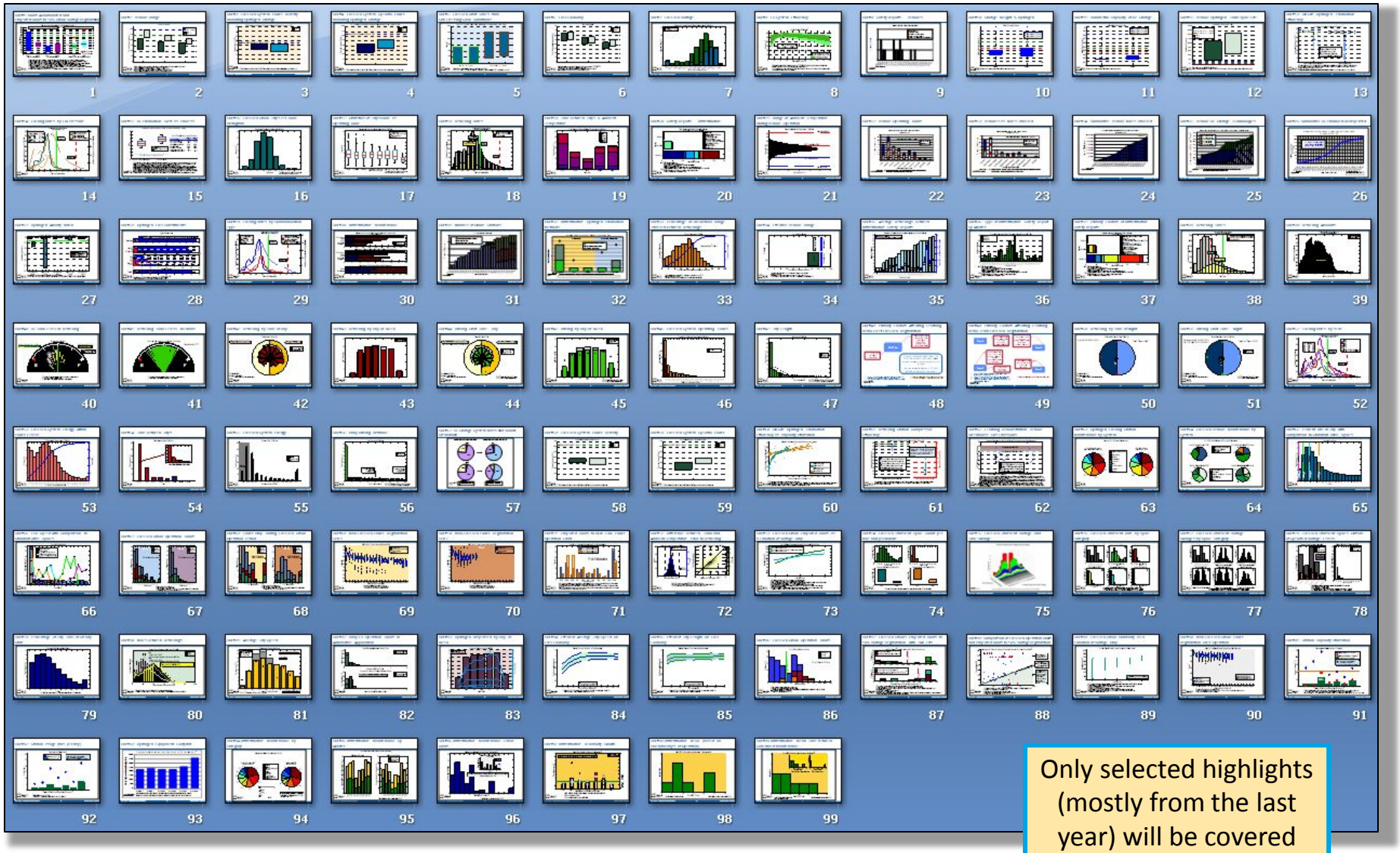




* Funded by state of CA or others, outside of this project

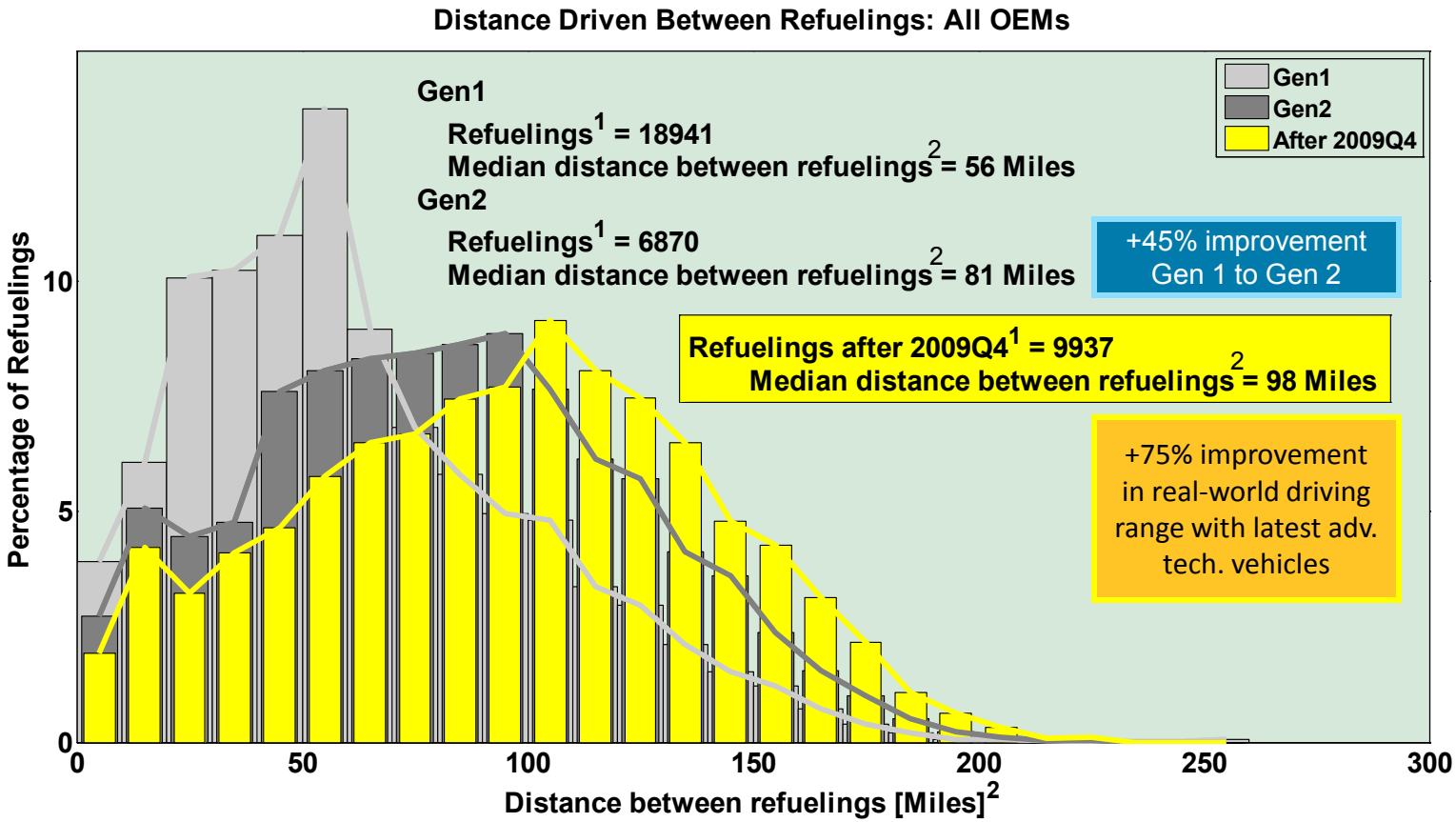
** Infrastructure project after Learning Demo

Total of 99 CDPs Published (40 Winter 2011 CDPs)



Only selected highlights (mostly from the last year) will be covered

Vehicles Show Continued Improvement in Distance Between Fuelings (Real-World)



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.

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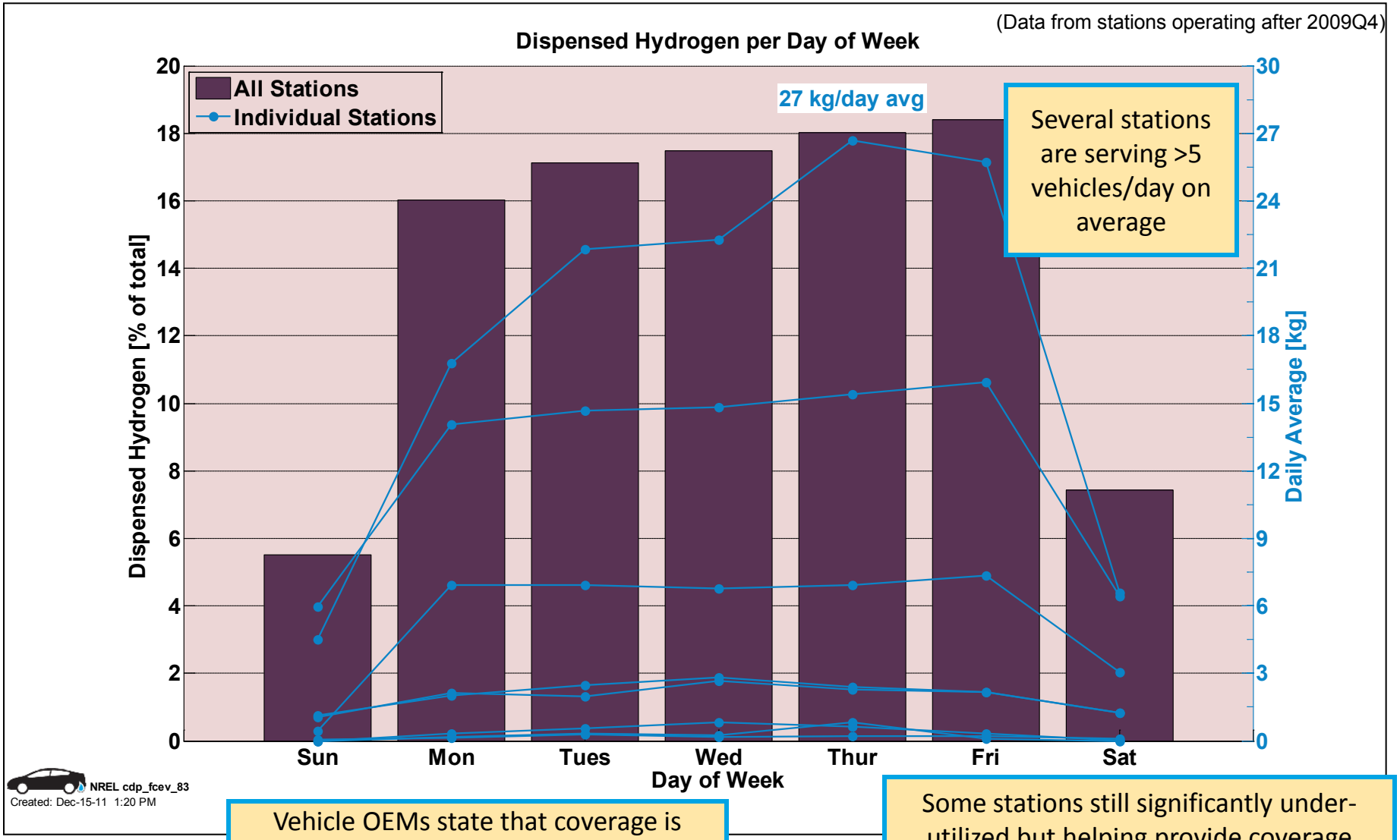
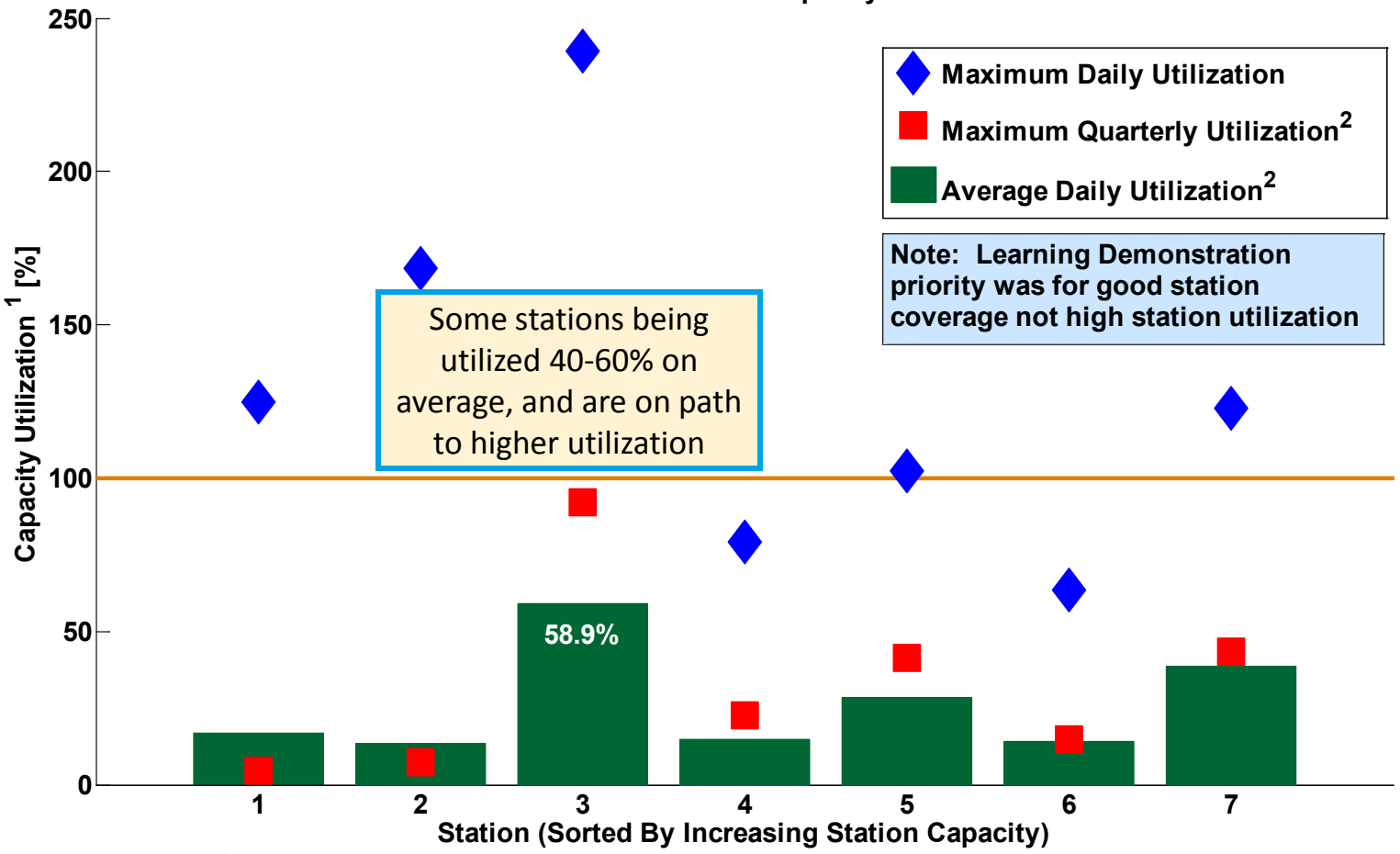
Note: Actual range possible >200 miles

INFRASTRUCTURE: New Infrastructure CDP Gives Insight Into Specific Fueling Usage Patterns



INFRASTRUCTURE: While Station Focus is on Coverage, We've Tracked Capacity Usage as Baseline for Future

(Data from stations operating after 2009Q4)



[1]Station nameplate capacity reflects a variety of system design consderations including system capacity, throughput, system reliability and durability, and maintenance. Actual daily usage may exceed nameplate capacity.

[2]Maximum quarterly utilization considers all days; average daily utilization considers only days when at least one filling occurred

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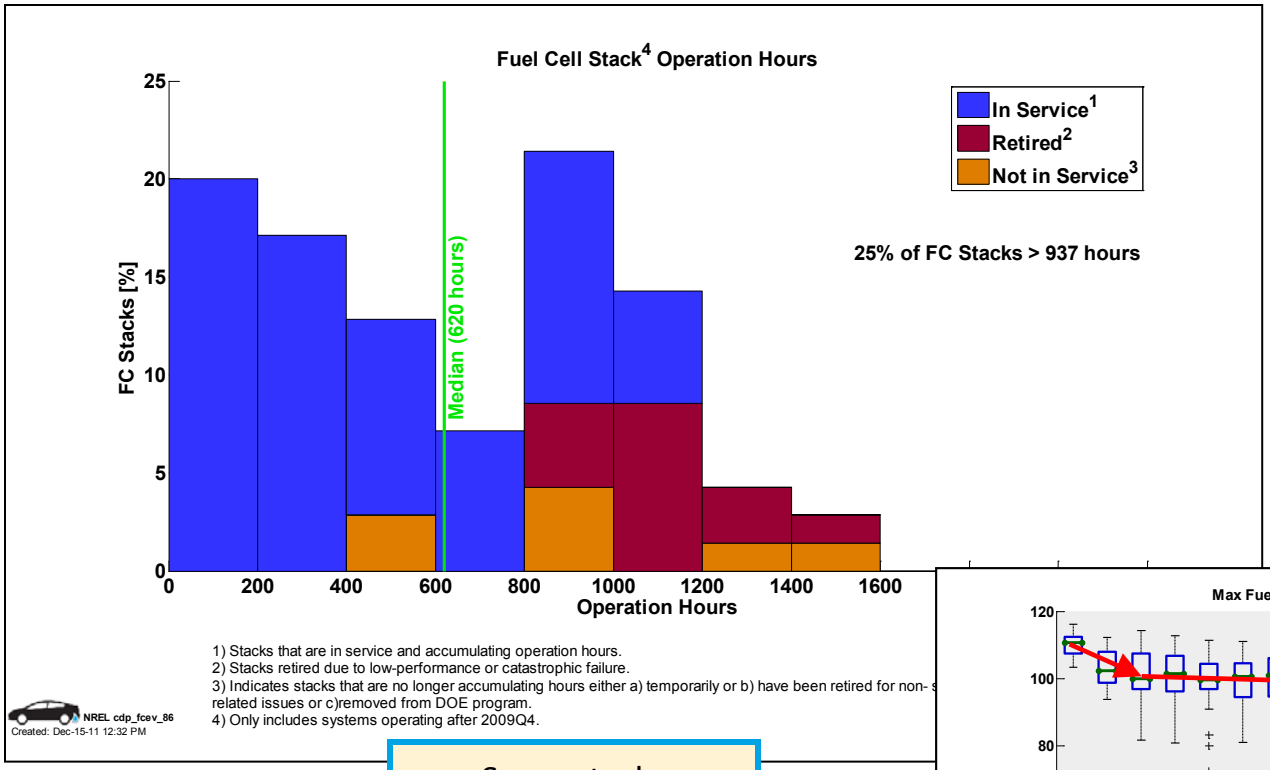
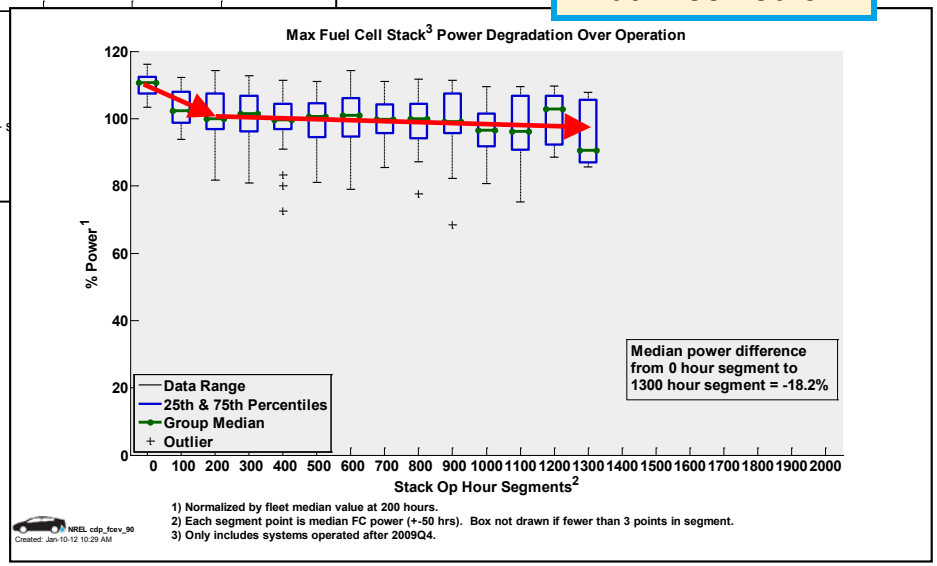
FC DURABILITY: Evaluated FC Durability Data from FCEVs After 2009Q4



Some stacks operated over 1,400 hours, but half were still below 600 hours

Recent data from stacks shows knee in FC power degradation curve at ~200 hours



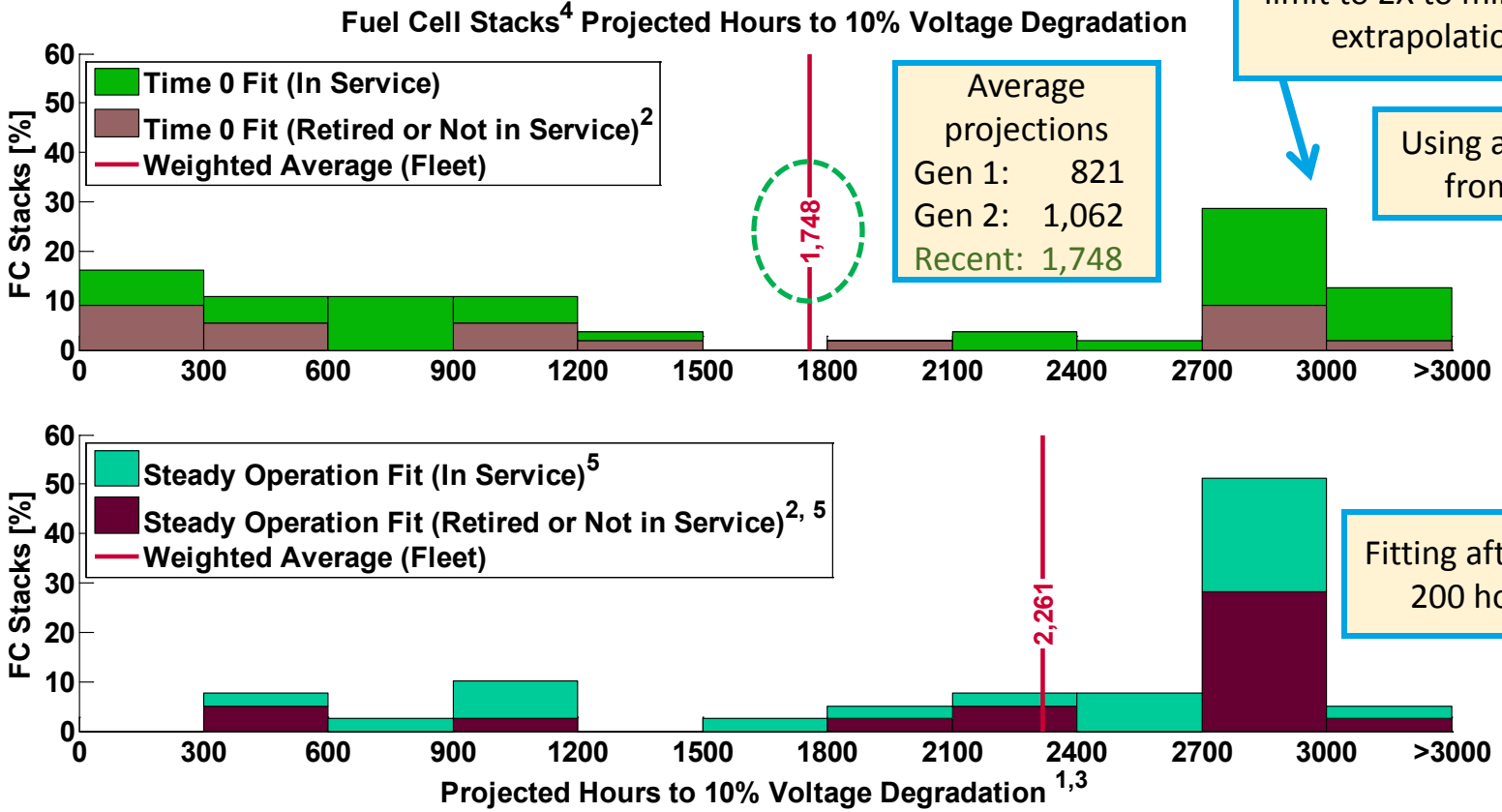
FC DURABILITY: Projected Fuel Stack Durability to 10% Voltage Degradation; Two Fits

Many stacks have projections that we limit to 2X to minimize extrapolation

Using all data from t0

Fitting after first 200 hours

See technical backup for additional details in scatter plot



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 hou the period after initial break-in where degradation levels to a more steady rate.

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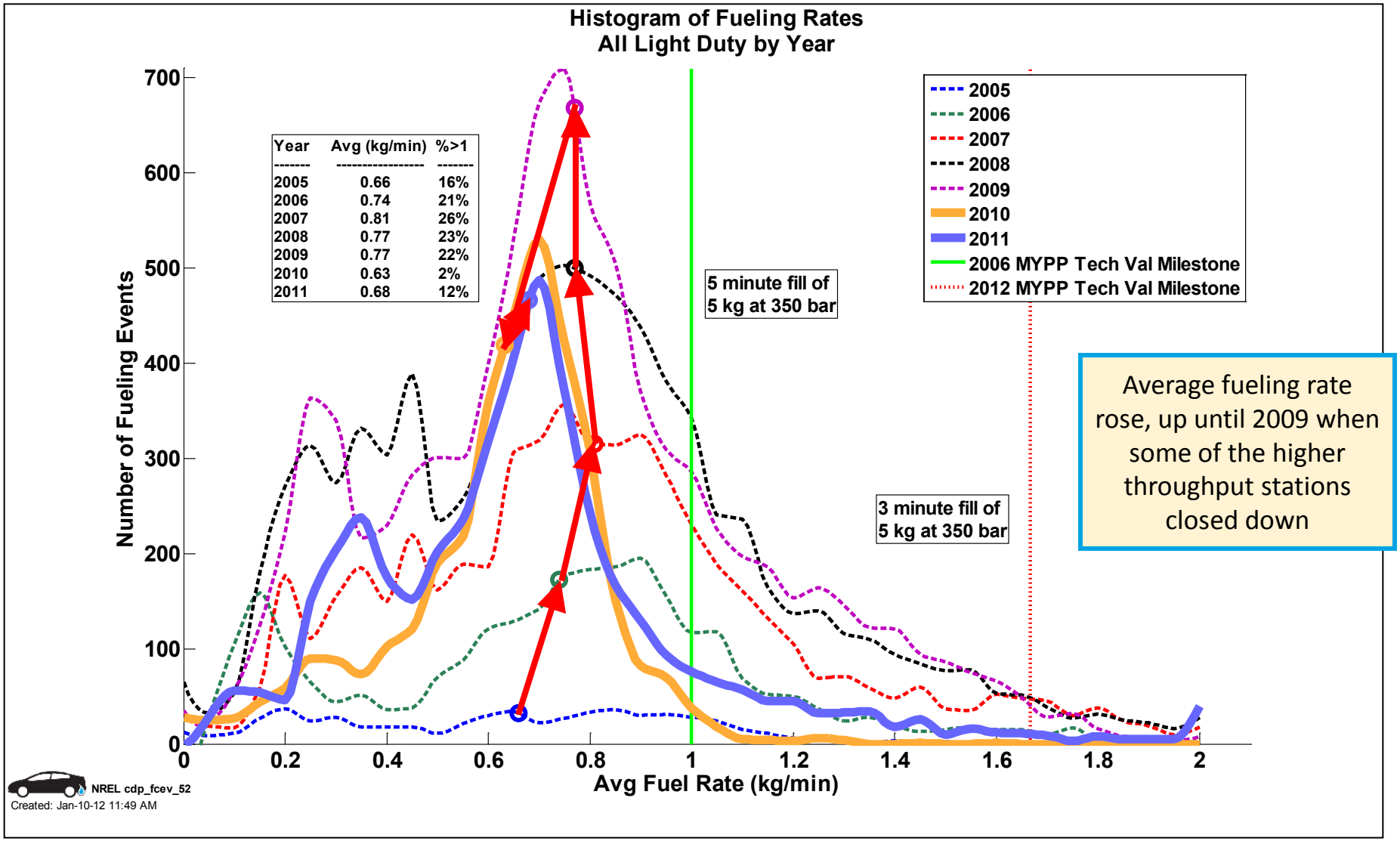
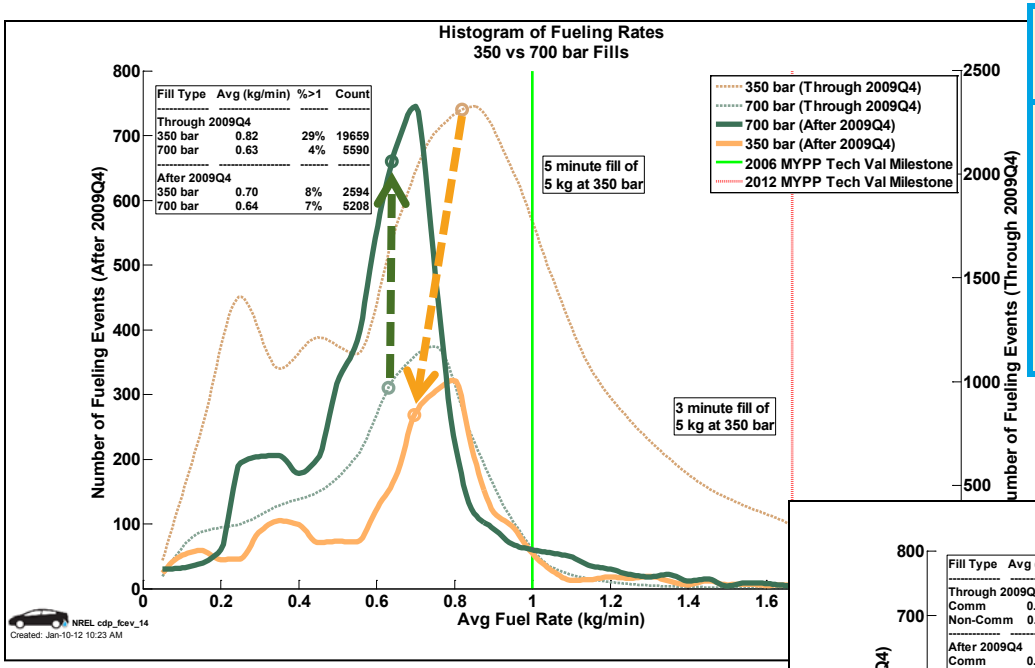
FUELING: Tracked Fueling Rates by Year – Analyzed Trends as Stations Move to 700 bar as Standard



Average fueling rate rose, up until 2009 when some of the higher throughput stations closed down

FUELING: Evaluated Fueling Rates by Fill Pressure and Communication vs. Non-Communication



350 vs. 700 bar

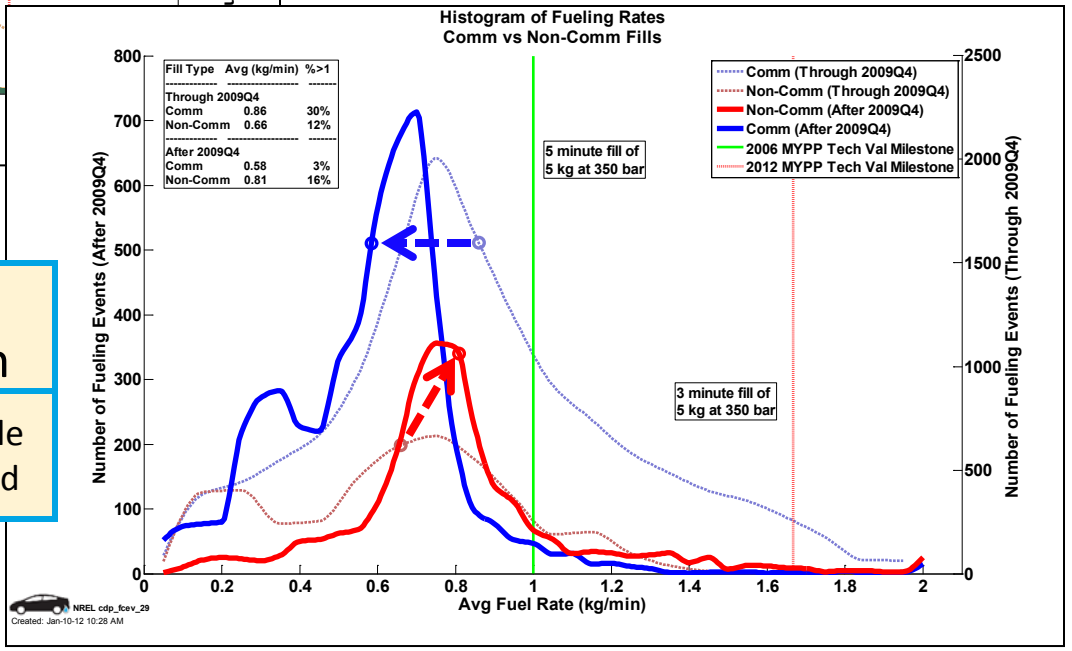
700 bar fueling rates holding constant at ~0.63 kg/min

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

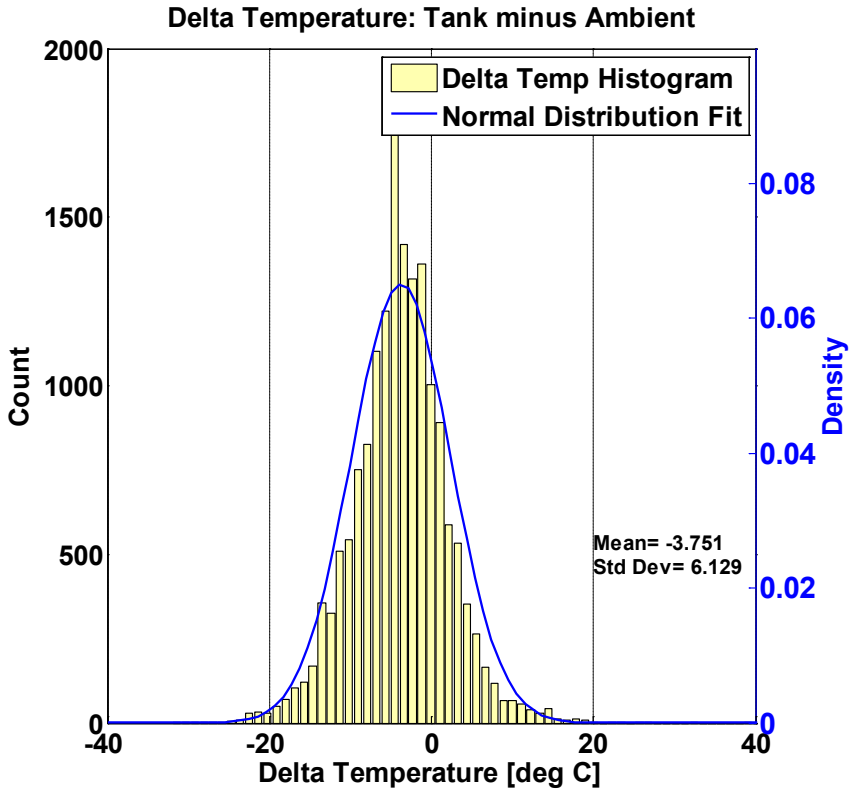
Fueling rates are still evolving due to changes in technology and protocols

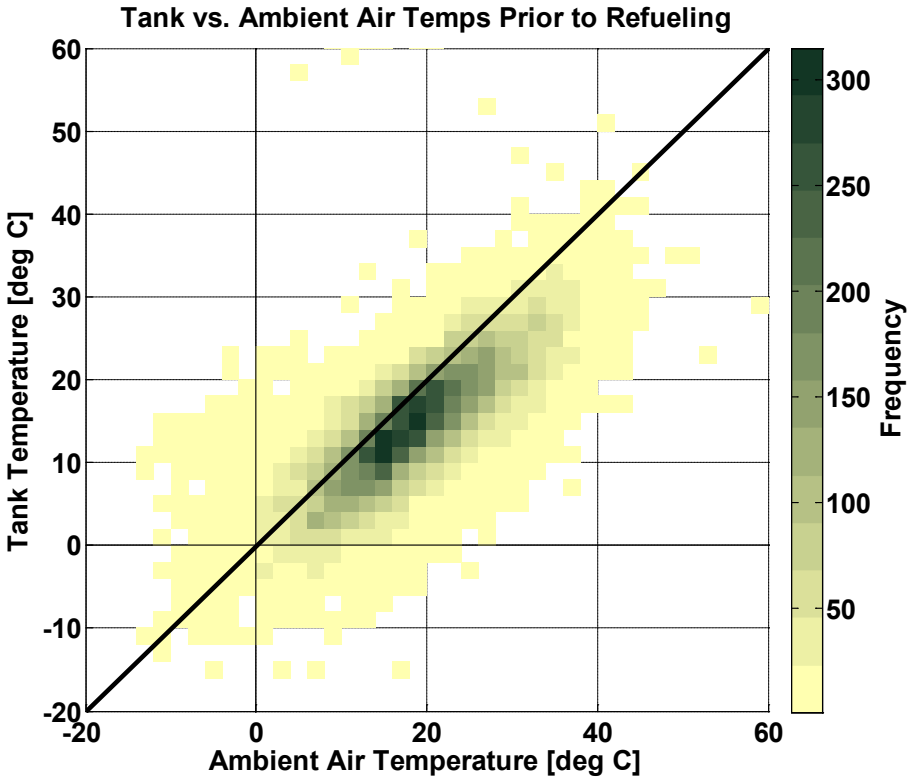
Communication vs. non-communication

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



STANDARDS: Analysis Results Informed R&D Activities and Codes and Standards Development





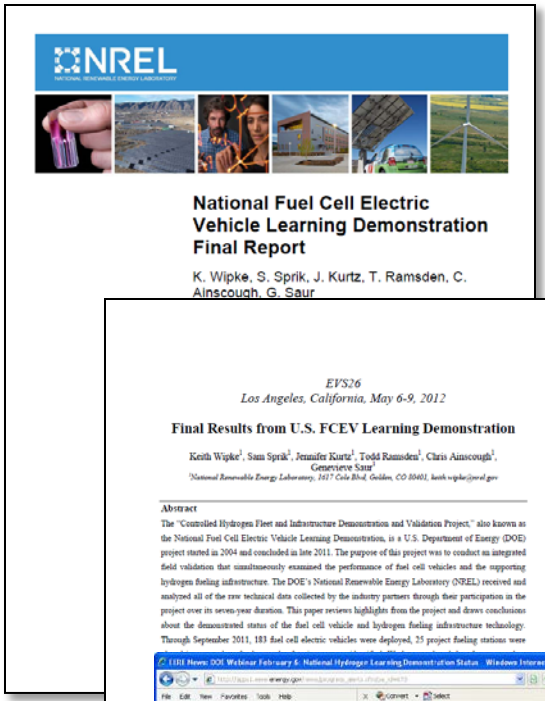
FCEVs arrive at station with a tank temperature that is 3.8 degrees C colder than ambient temp

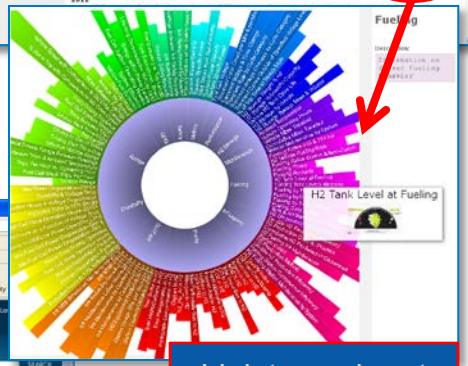
-This CDP created in support of SAE J2601 related to refueling
-Temperatures are prior to refueling and exclude data within 4 hours of a previous fill
-The plot to the left excludes ambient temperatures less than -5 deg C

This result allowed participants in J2601 to use validated/realistic initial conditions to their computer models for tank temperature rise

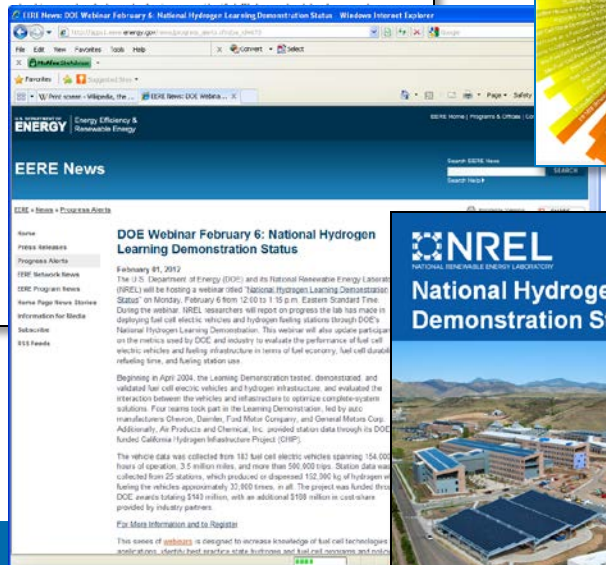
Final Project Results Communicated to Broad Audience via Multiple Paths

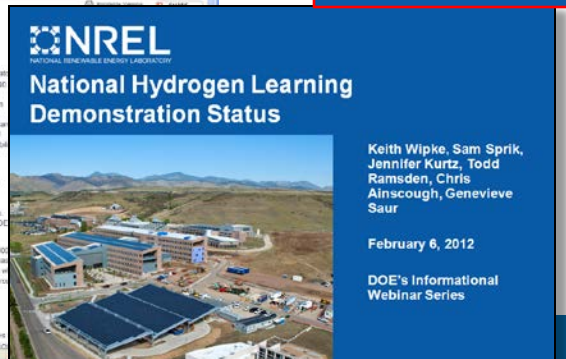
- **Final report published in April and posted on NREL's web site**
- **EVS-26 paper**
- **Held public webinar**
  - 260 participants (400 registered)
  - Active Q&A
- **Created more interactive way to access CDP results from web site (now live)**





Link to sunburst





Summary of Key Technical Results

Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target	After 2009Q4
Fuel Cell Stack Durability			**2,000 hours**	
Max Team Projected Hours to 10% Voltage Degradation	**1,807 hours**	**2,521 hours**		--
Average Fuel Cell Durability Projection	821 hours	1,062 hours		1,748 hours
Max Hours of Operation by a Single FC Stack to Date	2,375 hours	1,261 hours		1,582 hours
Driving Range			**250 miles**	
Adjusted Dyno (Window Sticker) Range	**103-190 miles**	**196-254 miles**		--
Median On-Road Distance Between Fuelings	56 miles	81 miles		98 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	After 2009Q4
H_2 Cost at Station (early market)	On-site natural gas reformation **$7.70 – $10.30/kg**	On-site Electrolysis **$10.00 – $12.90/kg**	**$3/gge**	--
Average H_2 Fueling Rate	0.77 kg/min		1.0 kg/min	0.65 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)

Outside review panel

Future Work

- **Support DOE in launching new *vehicle* evaluation project**
  - "Light-Duty Fuel Cell Electric Vehicle Validation Data" (FOA 625)
- **Support DOE in launching new *infrastructure* evaluation project**
  - Transition H_2 station analysis activity to "Next Generation H2 Station Analysis" project led by Sam Sprik, initiated in January
  - Support DOE in launching new infrastructure validation project: "Validation of Hydrogen Refueling Station Performance" (FOA 626, topic 1)
- **Continue to leverage analysis capability to other validations**
- **Identify and exploit new opportunities to document FC & H2 progress publicly**

Summary

183 Vehicles: 154,000 hours, 3.6M miles, 500K trips
25 Stations: 152,000 kg produced/dispensed, 33K fuelings

- **Relevance**
  - Provided DOE and taxpayers **strong return on investment** made in this 7-year project, the **largest** single FCEV & infrastructure demonstration in the world to date
  - Many system-level DOE program targets validated by this project
- **Approach**
  - Collaborative relationship to analysis with **industry partners**
  - Established core **HSDC and analysis capability** and tools
  - This project is the 1st time such **comprehensive data** was collected by an independent 3rd-party and consolidated for public dissemination
- **Technical Accomplishments and Progress**
  - **99 total CDP analysis results** available; published at conferences every 6 months
  - Project **achieved the two key technical targets** on driving range (>250 miles) and FC durability (>2,000 hours) [refer to technical backup slides and Final Report]

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

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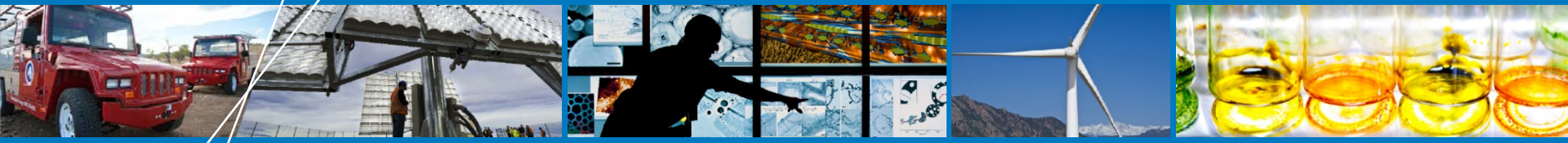
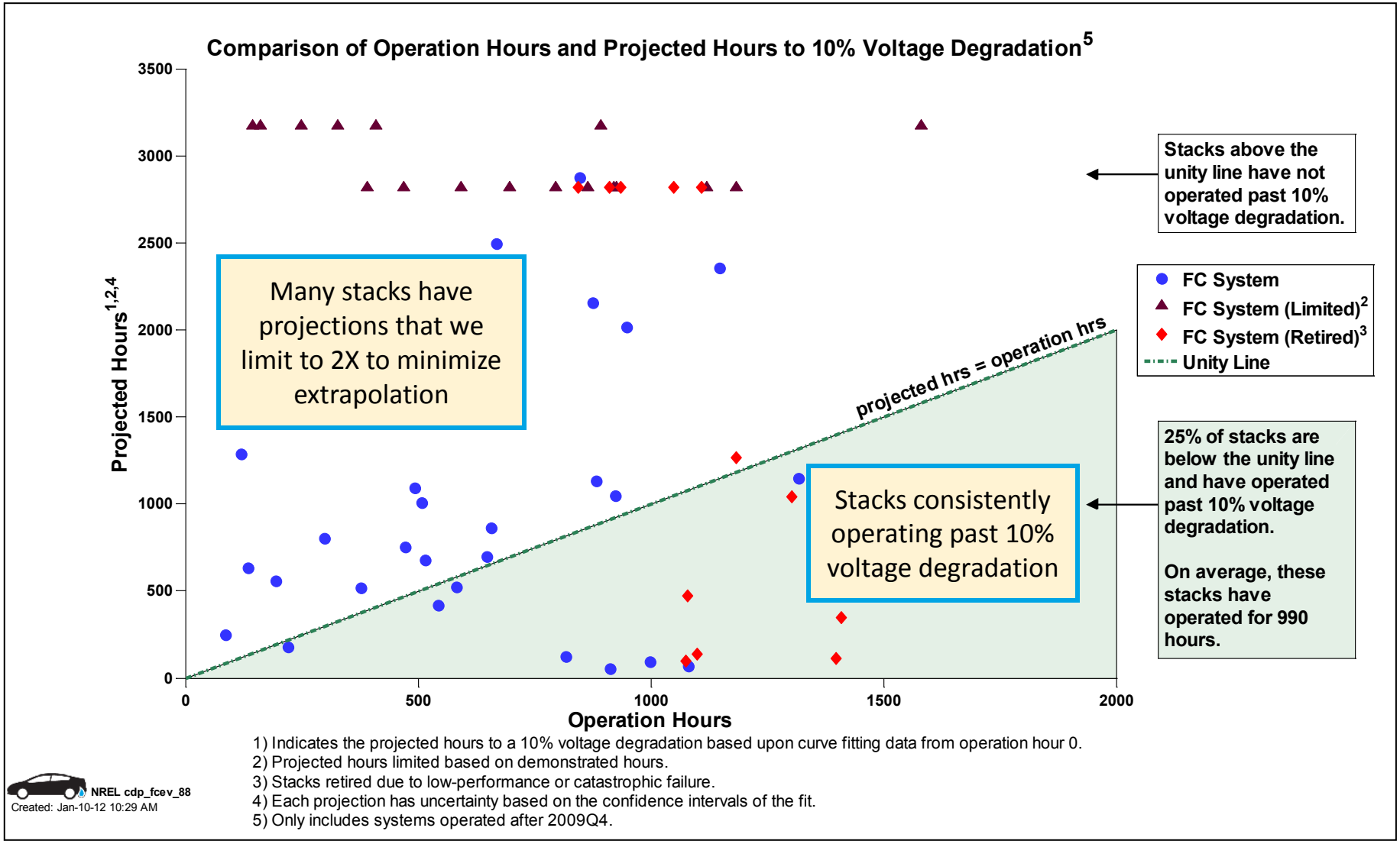
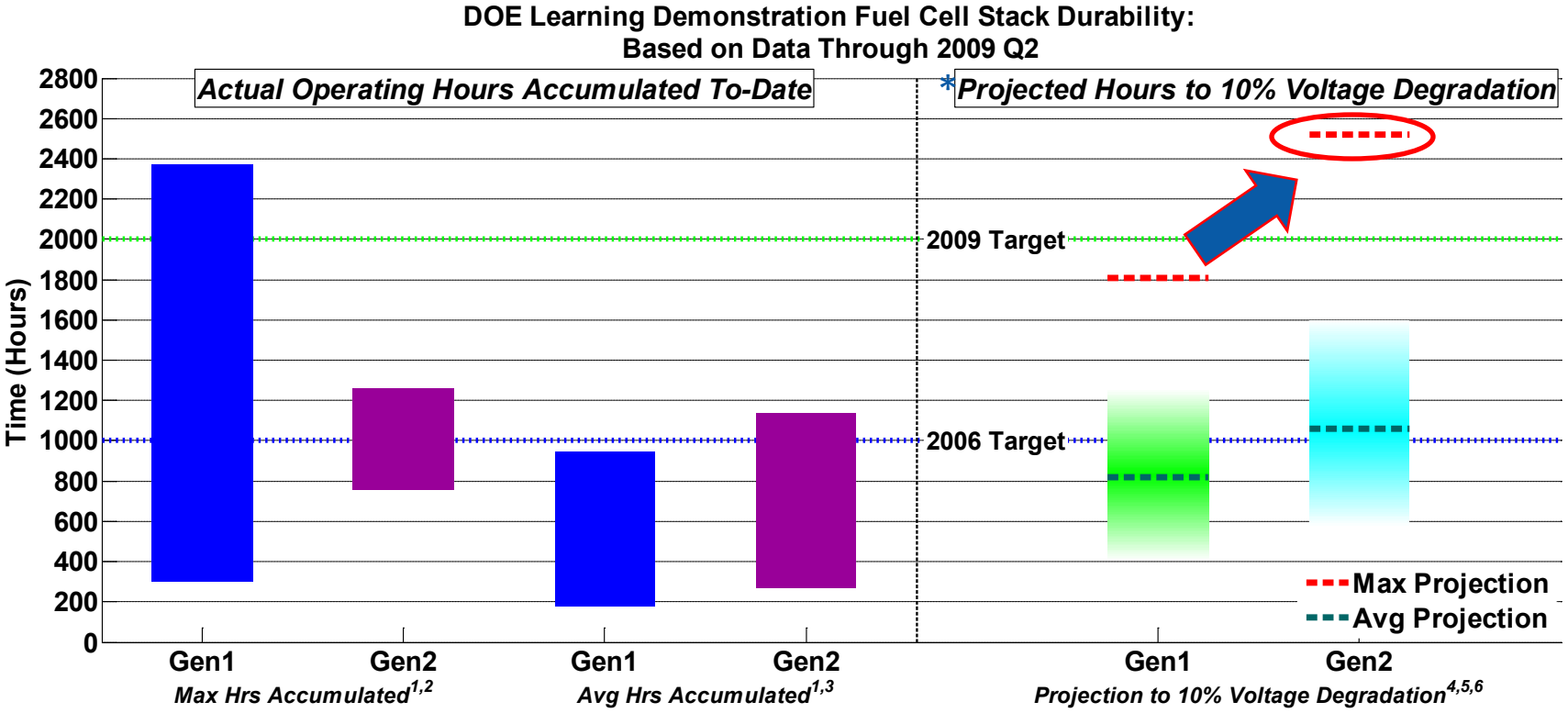


Technical Backup Slides

Accomplishment: Scatter Plot of Fuel Cell Operation Hours and Projected Hours to 10% Voltage Degradation



1) FC Durability Target of 2000 Hours Met By Gen 2 Projections (2010)



(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.

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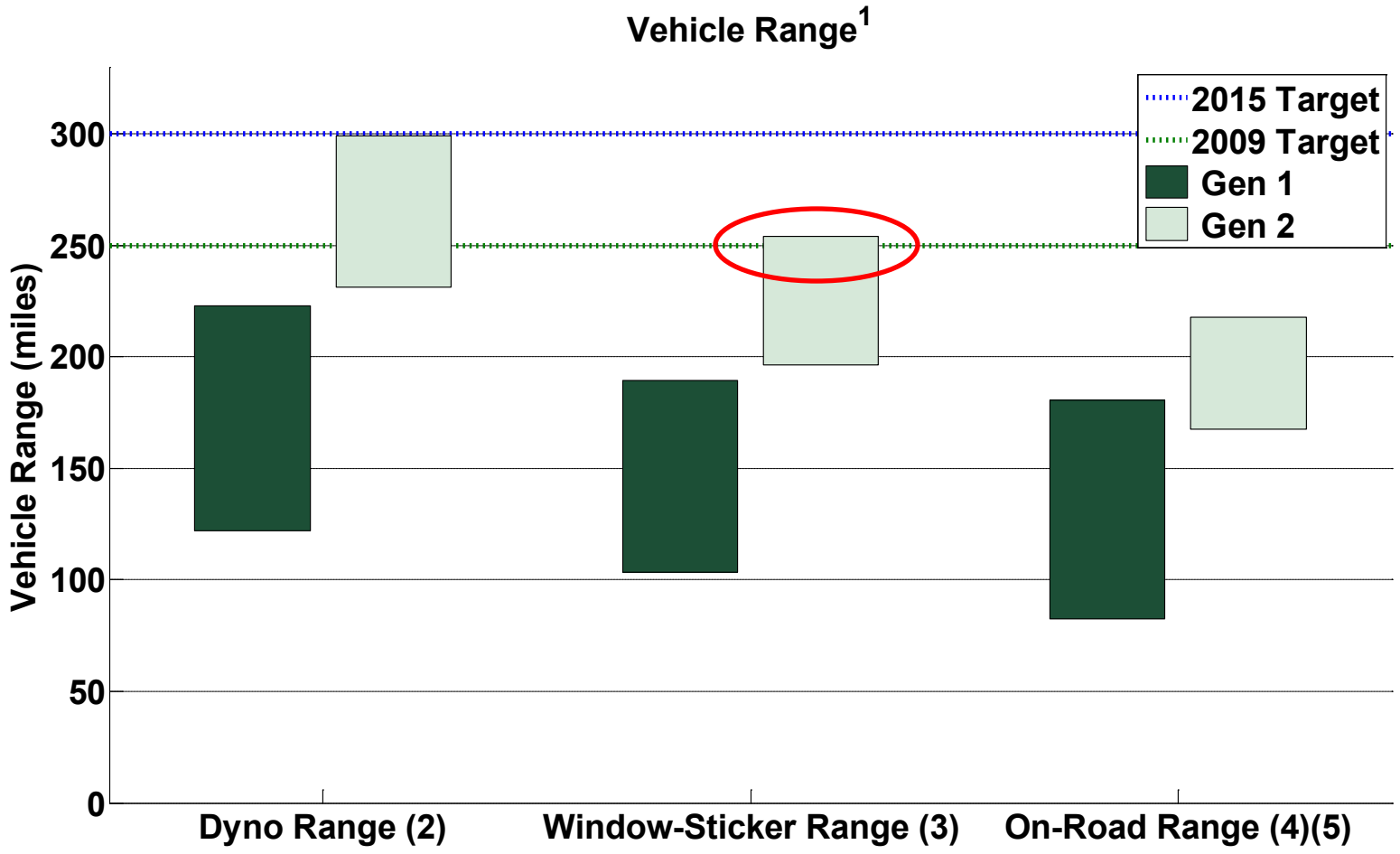
* Durability is defined by DOE as projected hours to 10% voltage degradation

Spring 2010

2) Vehicle Range Achieved 2009 Target of 250 Miles with Gen 2 Adjusted Fuel Economy (2010)



(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(5) Fuel economy calculated from on-road fuel cell stack current or mass flow readings.

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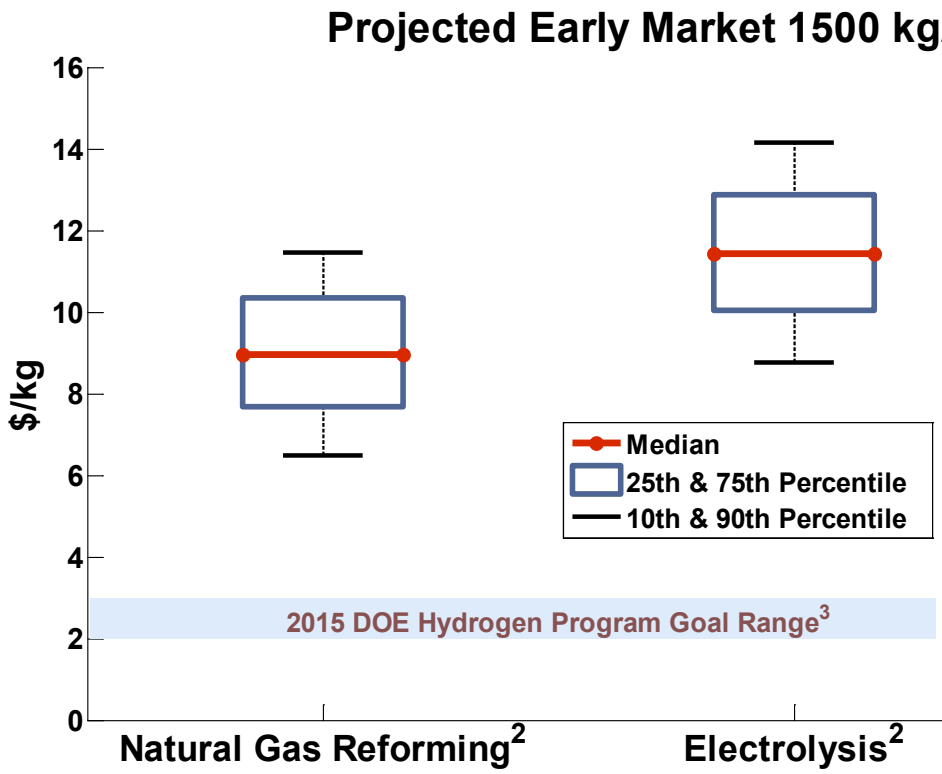
Spring 2010

3) Projected Early Market H_2 Production Cost from Learning Demo Energy Partners' Inputs (2010)



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 were 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.

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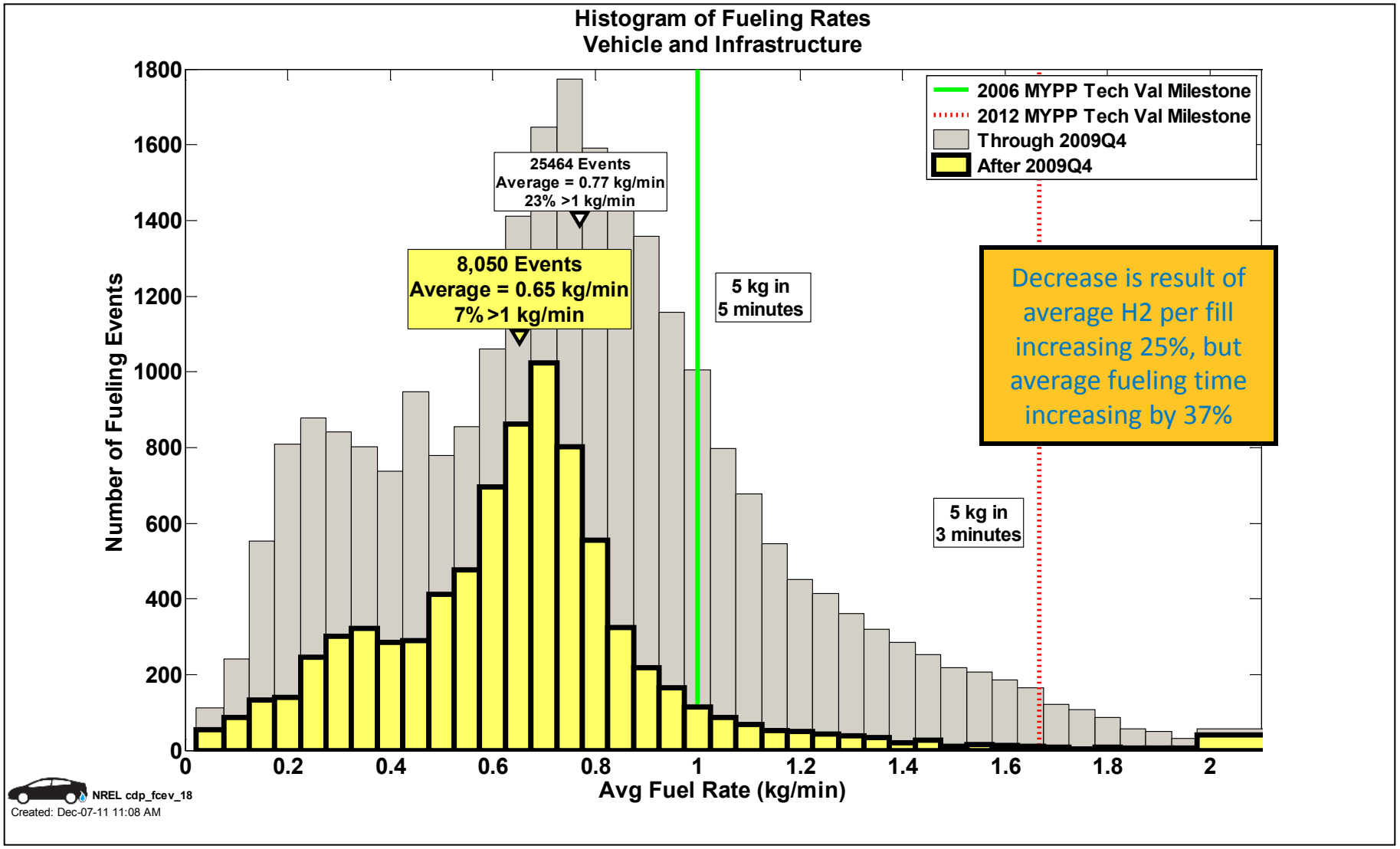
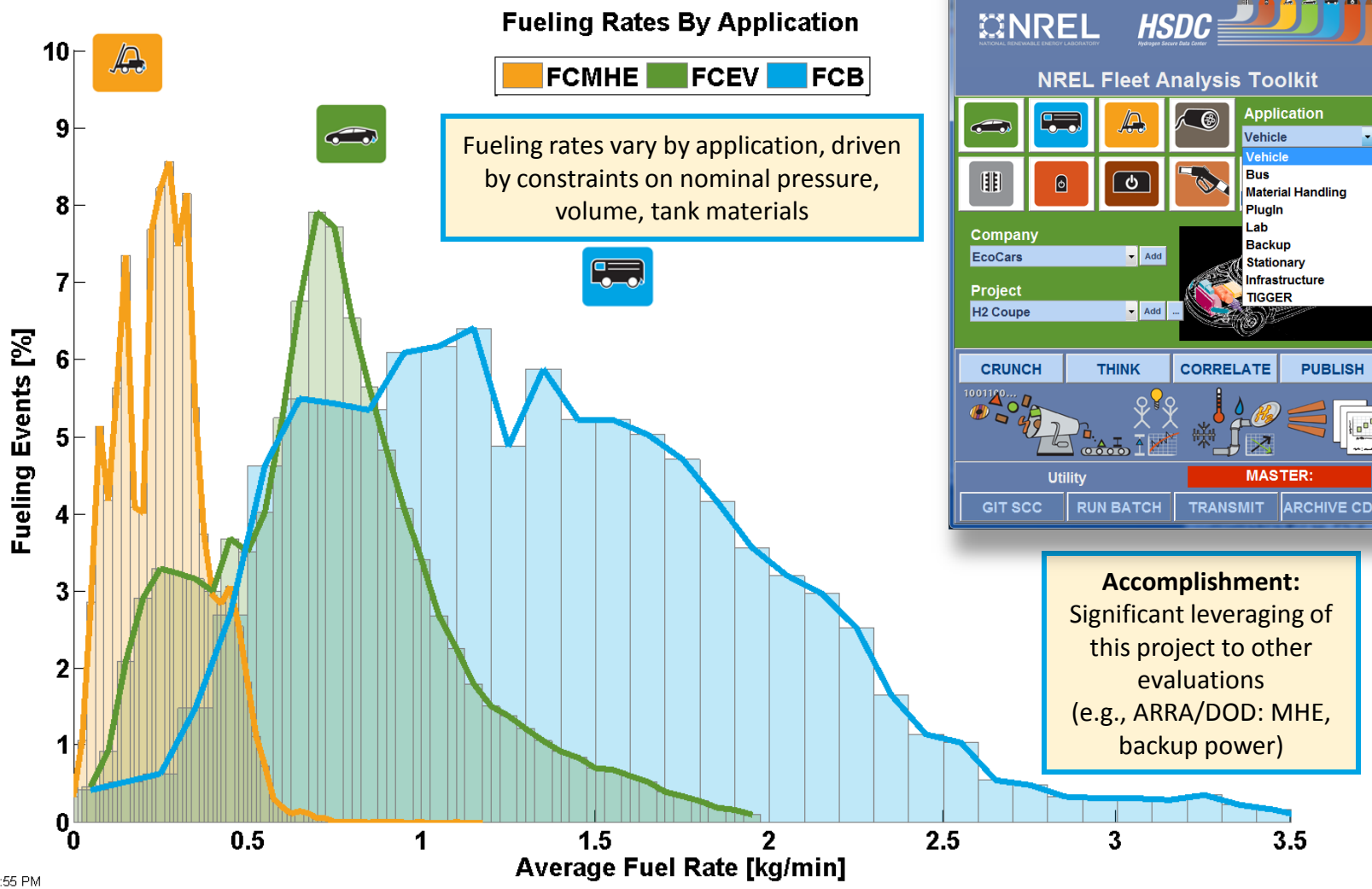
Outside of this project, DOE independent panels concluded at 500 replicate stations/year:
Distributed natural gas reformation at 1500 kg/day: **$2.75-$3.50/kg** (2006)
Distributed electrolysis at 1500kg/day: **$4.90-$5.70** (2009)

Average Fueling Rate Decreased 16% Due to Some High Throughput Stations Leaving Project



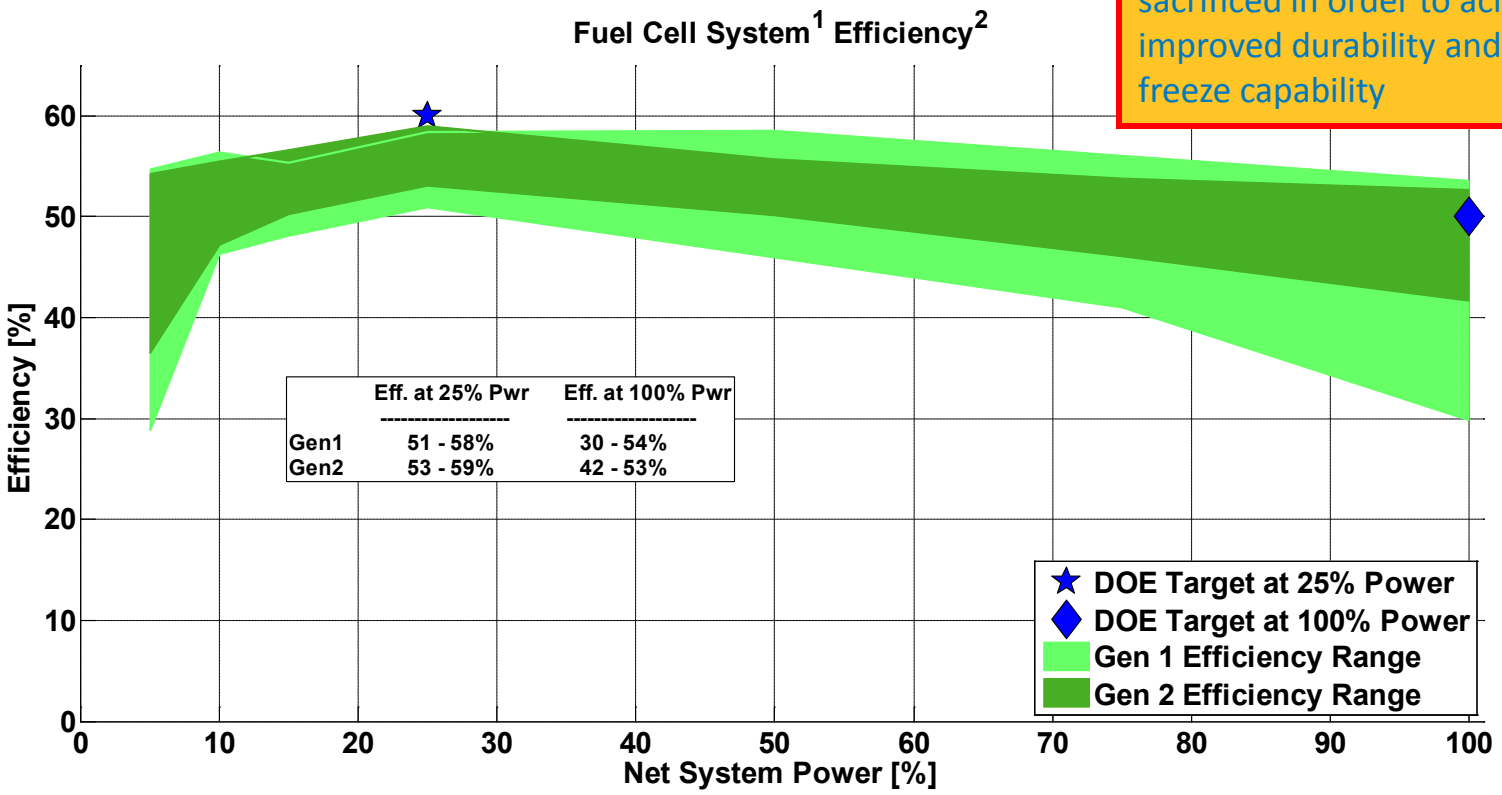
FUELING: Leveraged Effort to Other Fuel Cell Applications; Cross-Application CDPs Expanding



Accomplishment:
Significant leveraging of this project to other evaluations (e.g., ARRA/DOD: MHE, backup power)

EFFICIENCY: 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



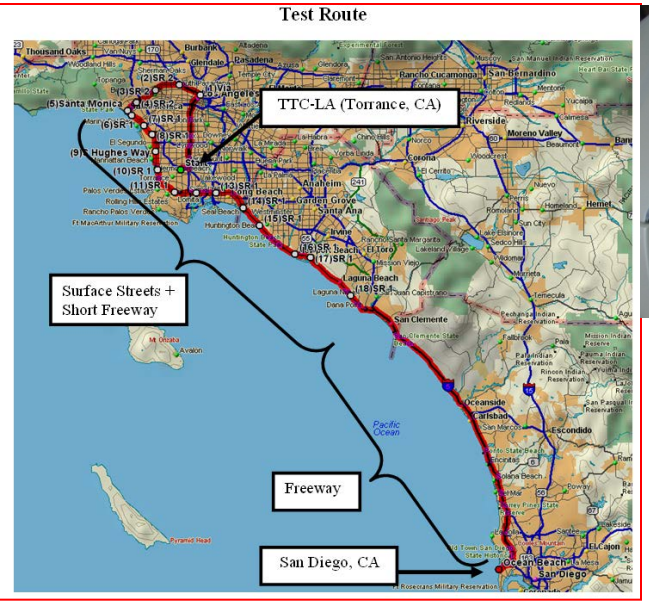
[1] Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.

[2] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).

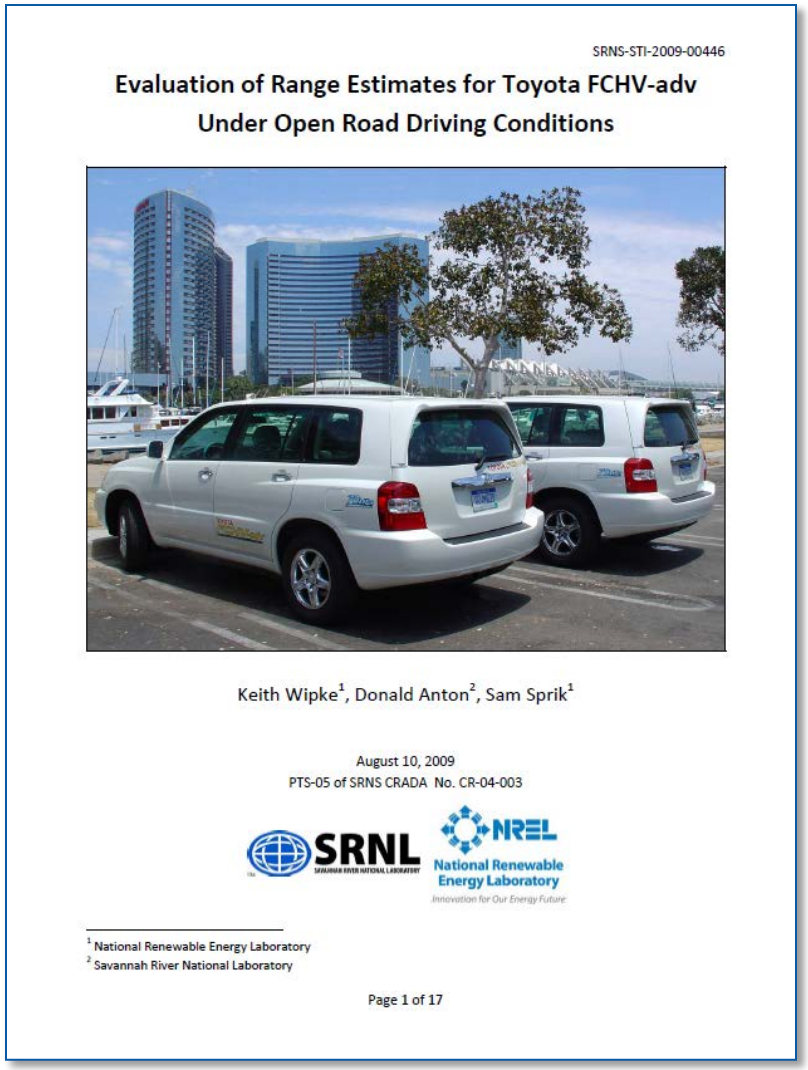
[3] Individual test data linearly interpolated at 5,10,15,25,50,75,and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

NREL CDP08
Created: Sep-02-09 11:27 AM

RANGE: NREL/SRNL Experiment Verified Toyota FCHV-adv Capable of up to 430-Mile Driving Range 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	


SRNS-STI-2009-00446

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

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

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

SRNL SAVANNAH RIVER NATIONAL LABORATORY
NREL National Renewable Energy Laboratory Innovation for Our Energy Future

[1] National Renewable Energy Laboratory
[2] Savannah River National Laboratory

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

Report: http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf