

Controlled Hydrogen Fleet and Infrastructure Analysis



**2011 DOE Annual Merit
Review and Peer
Evaluation Meeting**

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Fuel Cell Electric Vehicle Learning Demo

Project Objectives, Relevance, and Targets

- Objectives

- Validate H₂ 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 H₂ Research and Development
- Publish Results for Key Stakeholder Use and Investment Decisions

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	\$2-4/gge**

*Project extended 2 years through 2011; **For 2020; Previously \$2-3/gge for 2015

Details of each of these 3 results in technical backup slides



Burbank, CA station. Photo: NREL

Project Overview

Timeline

- Project start: FY03
- Project end: early FY12
- ~90% of Task III complete (see timeline slide)

Budget

- NREL funding prior to FY10 : \$4867K
- NREL FY10 funding: \$650K
- NREL FY11 funding: \$650K

Partners

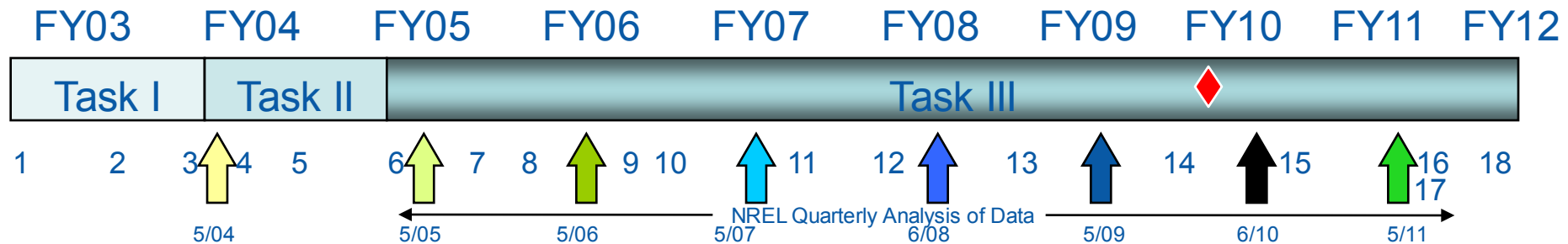
- See partner slide

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) [90% Complete]

♦ 2 teams concluded their projects

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

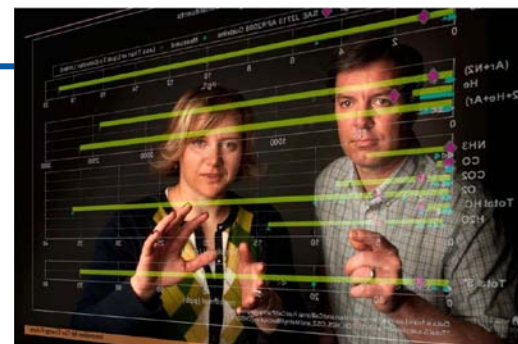
16 Conclusion of data submission to NREL on pre-commercial FCEVs (Sept. 2011)

17 DOE Milestone: Validate 40 adv. technology FCEVs with up to 600 hours operation

18 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)



Project Approach (cont.)

Supporting Both DOE/Public as Well as Fuel Cell Developers

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



Internal analysis completed quarterly

HSDC



NREL's Hydrogen Secure Data Center



Results

DDPs

CDPs

Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data¹

Composite Data Products (CDPs)

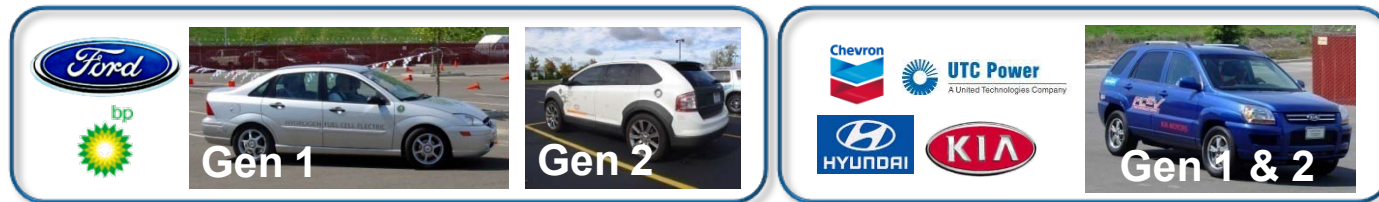
- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data²

1) Data exchange may happen more frequently based on data, analysis, & collaboration

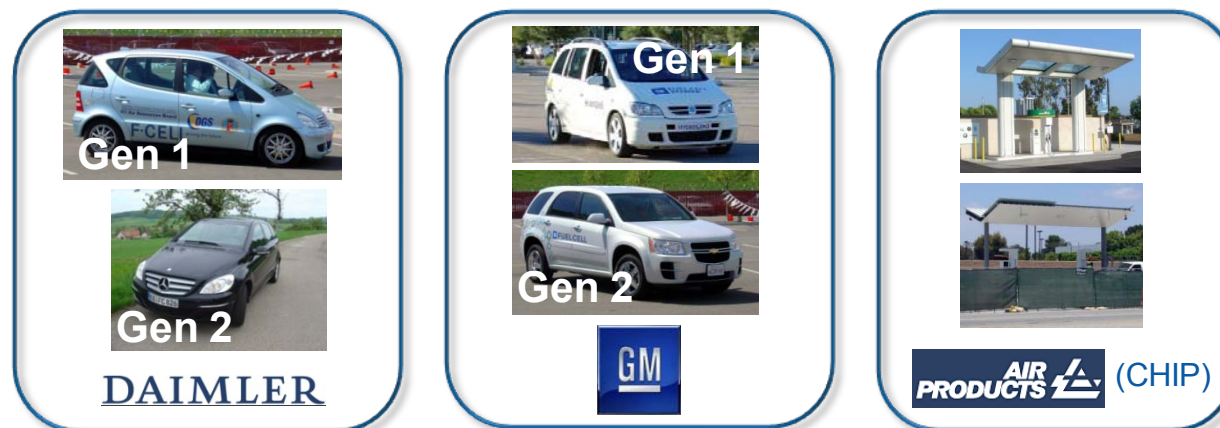
2) Results published via NREL Tech Val website, conferences, and reports (http://www.nrel.gov/hydrogen/proj_learning_demo.html)

Industry Partners: Two Teams Concluded Their Projects in 2009, Three are Continuing through 2011

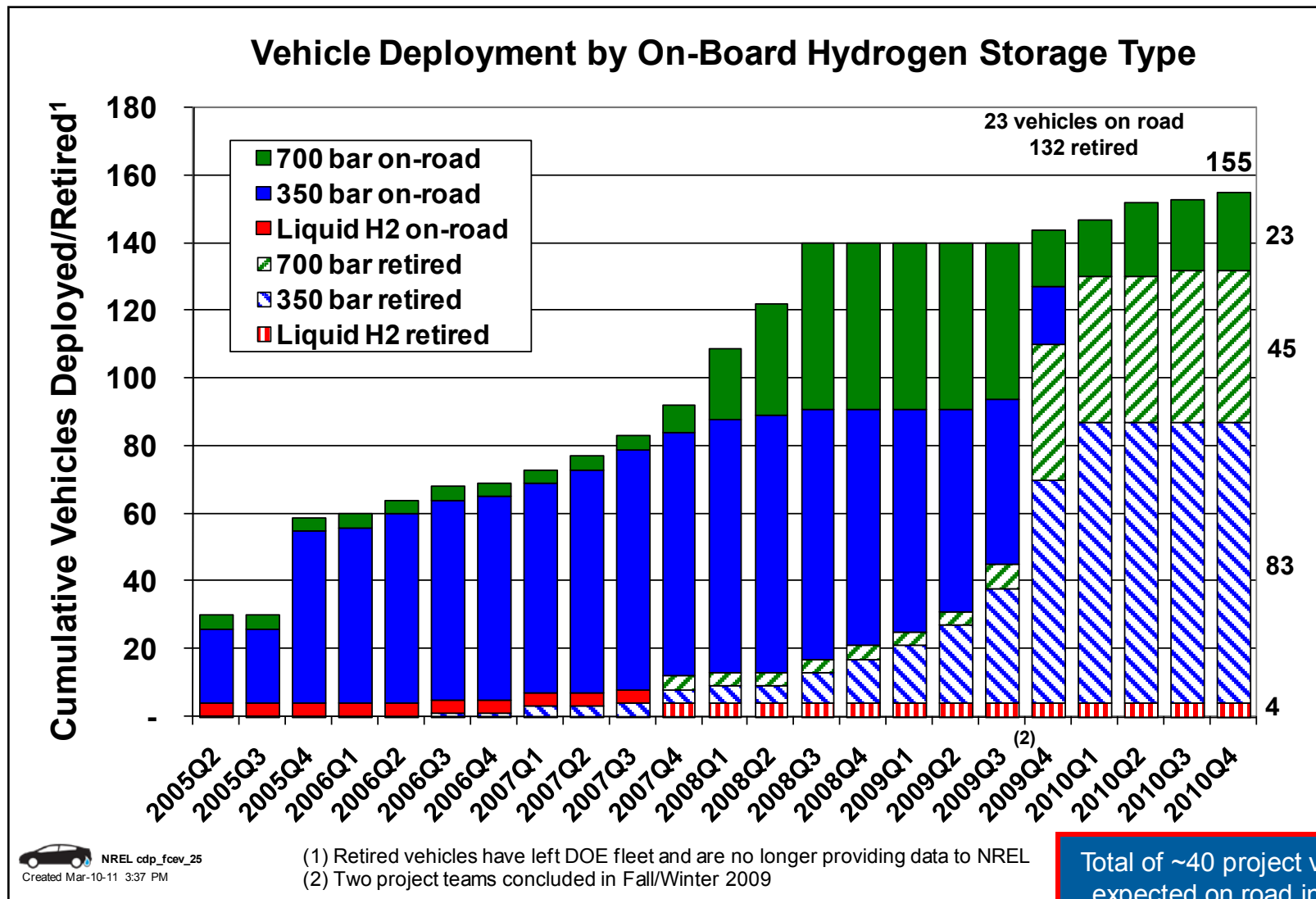
Ford/BP and Chevron/Hyundai-Kia Concluded in 2009



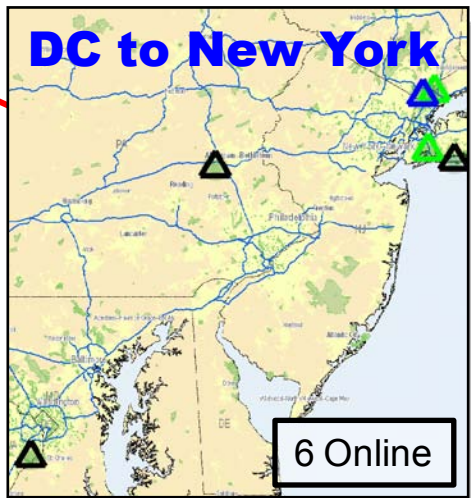
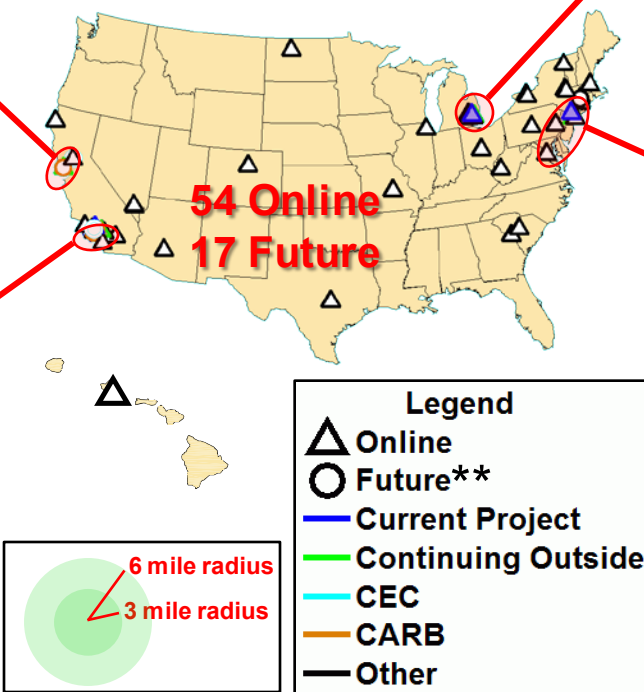
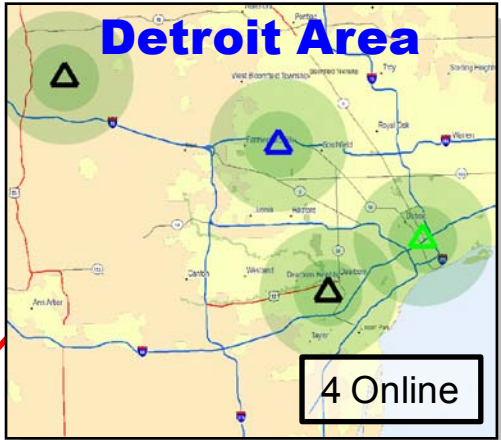
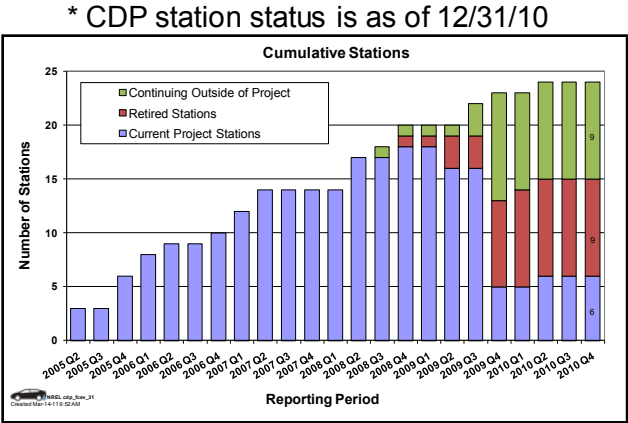
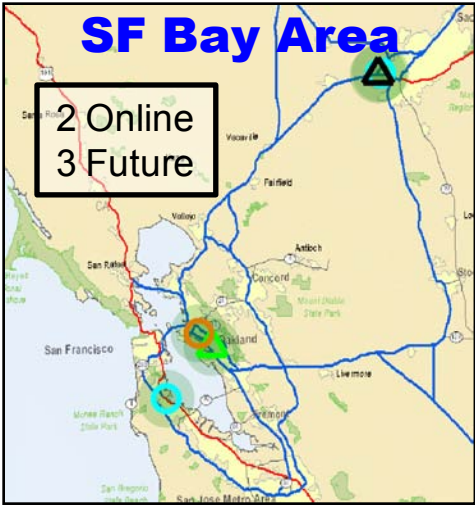
Daimler, GM, and Air Products Continue to Demonstrate Vehicles/Stations within Project through 2011



Vehicle Status: All Project Vehicles on Road Use 700 bar Storage



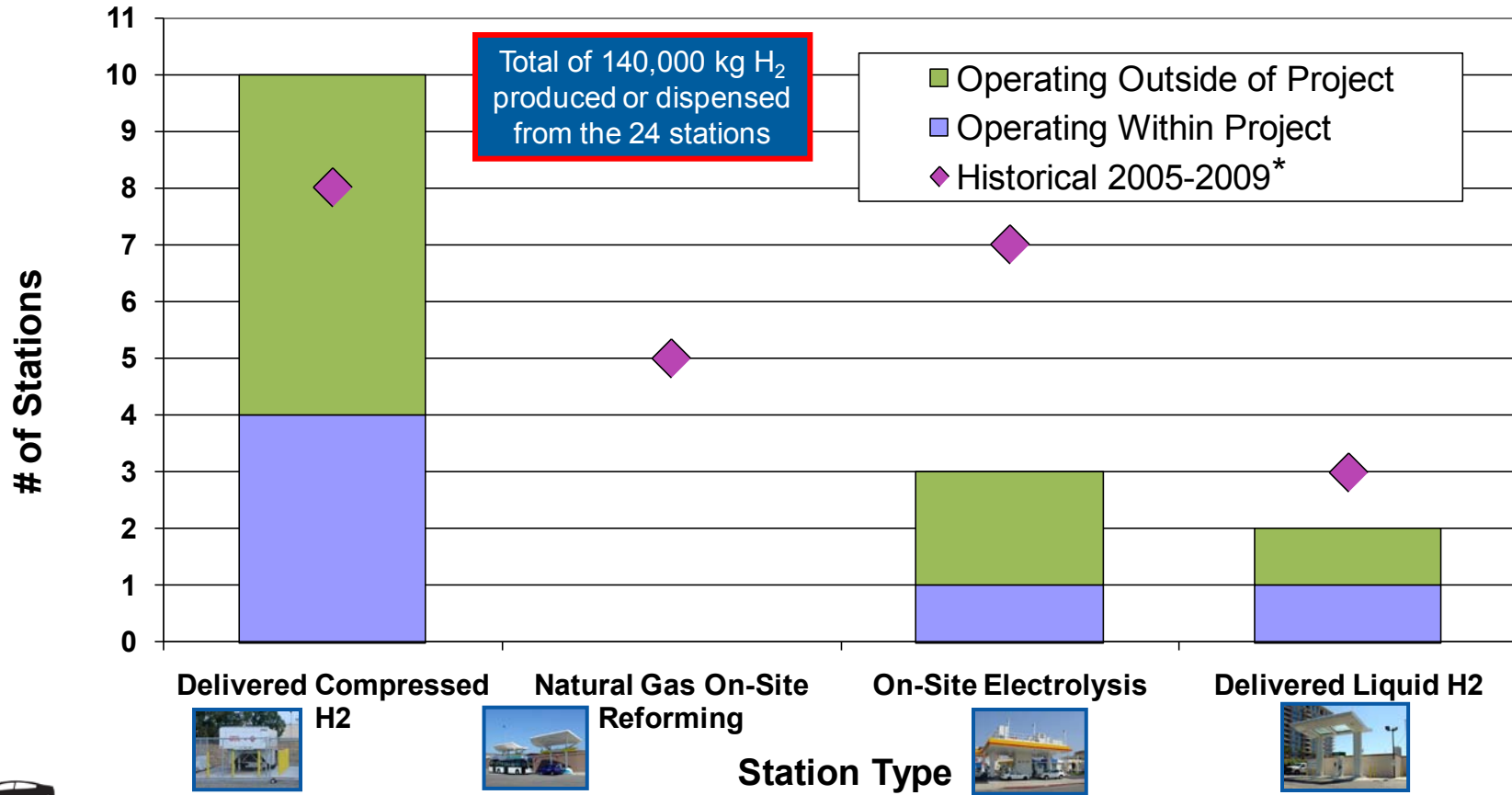
Status: Out of 24 Project Stations, 15 Are Still Operational* (3/5 outside of DOE project)



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

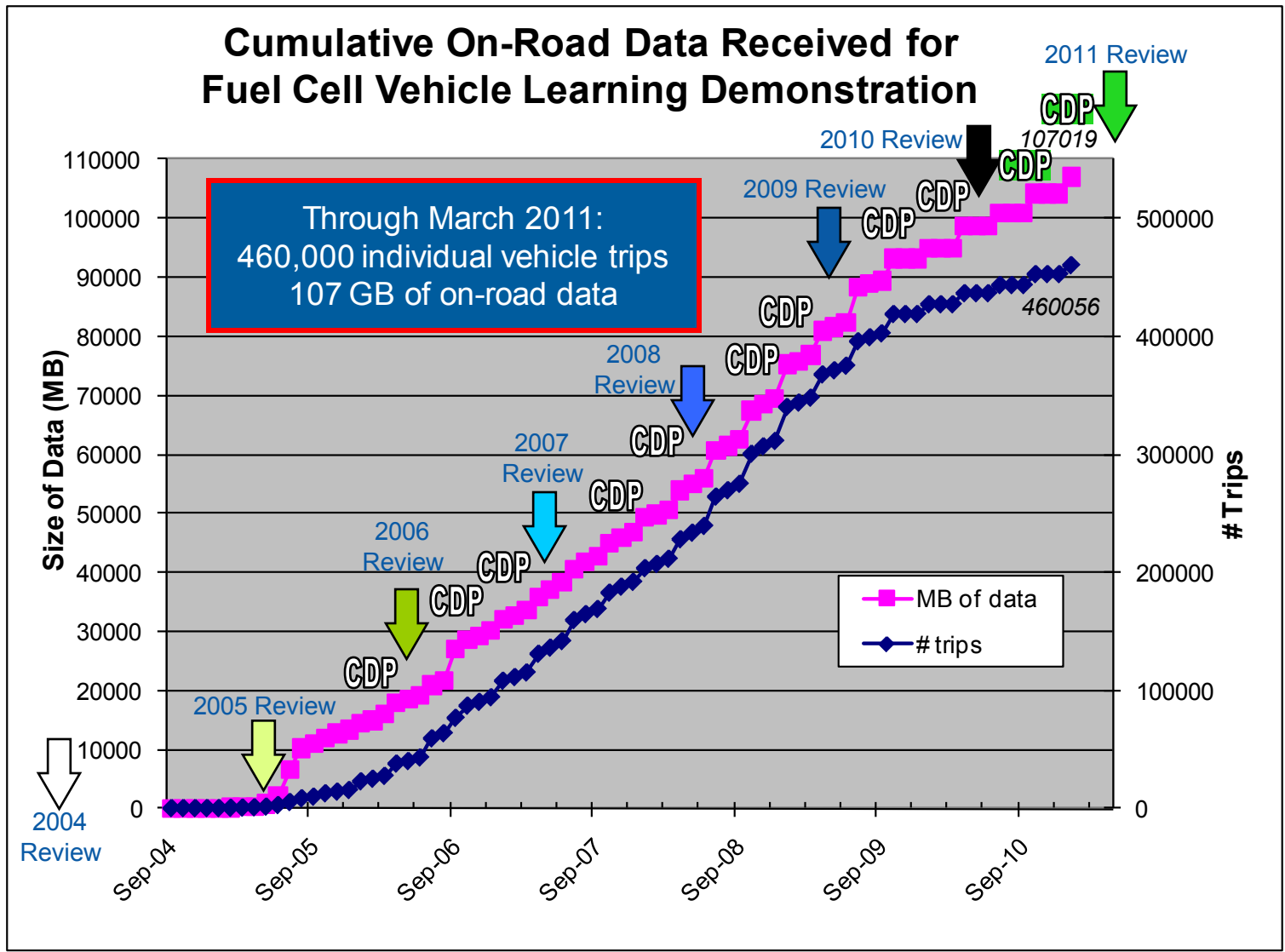
Station Status: The Project Stations Still in Operation Use Delivered H₂ (80%) or Electrolysis (20%)

Learning Demonstration Hydrogen Stations By Type



*Some project teams concluded Fall/Winter 2009. Markers show the cumulative stations operated during the 2005-2009 period

Accomplishment: 23 Quarters (~6 years) of Data Analyzed to Date, Two New Sets of Composite Data Products Published

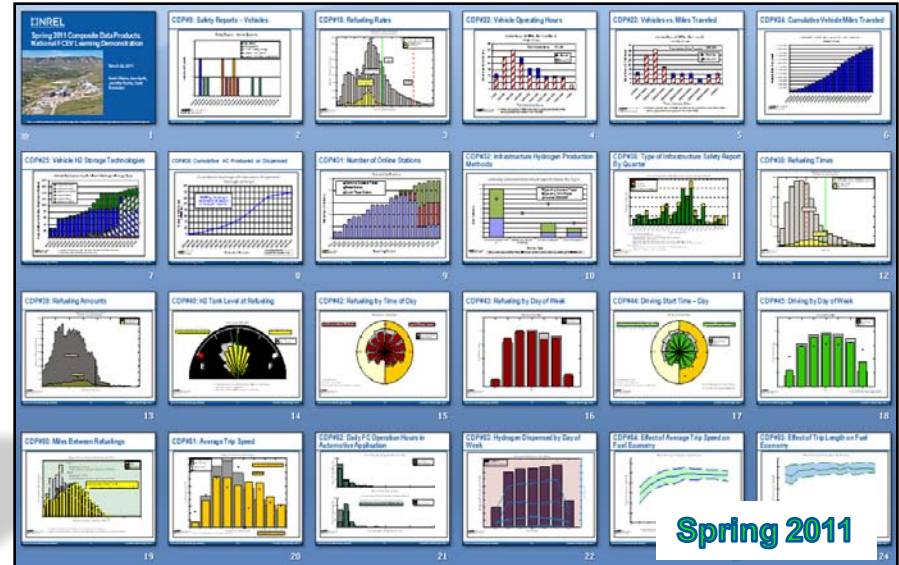


Accomplishment: Continued Publication of Two Sets of CDPs, Despite Fewer Teams



80 Spring 2010 Results

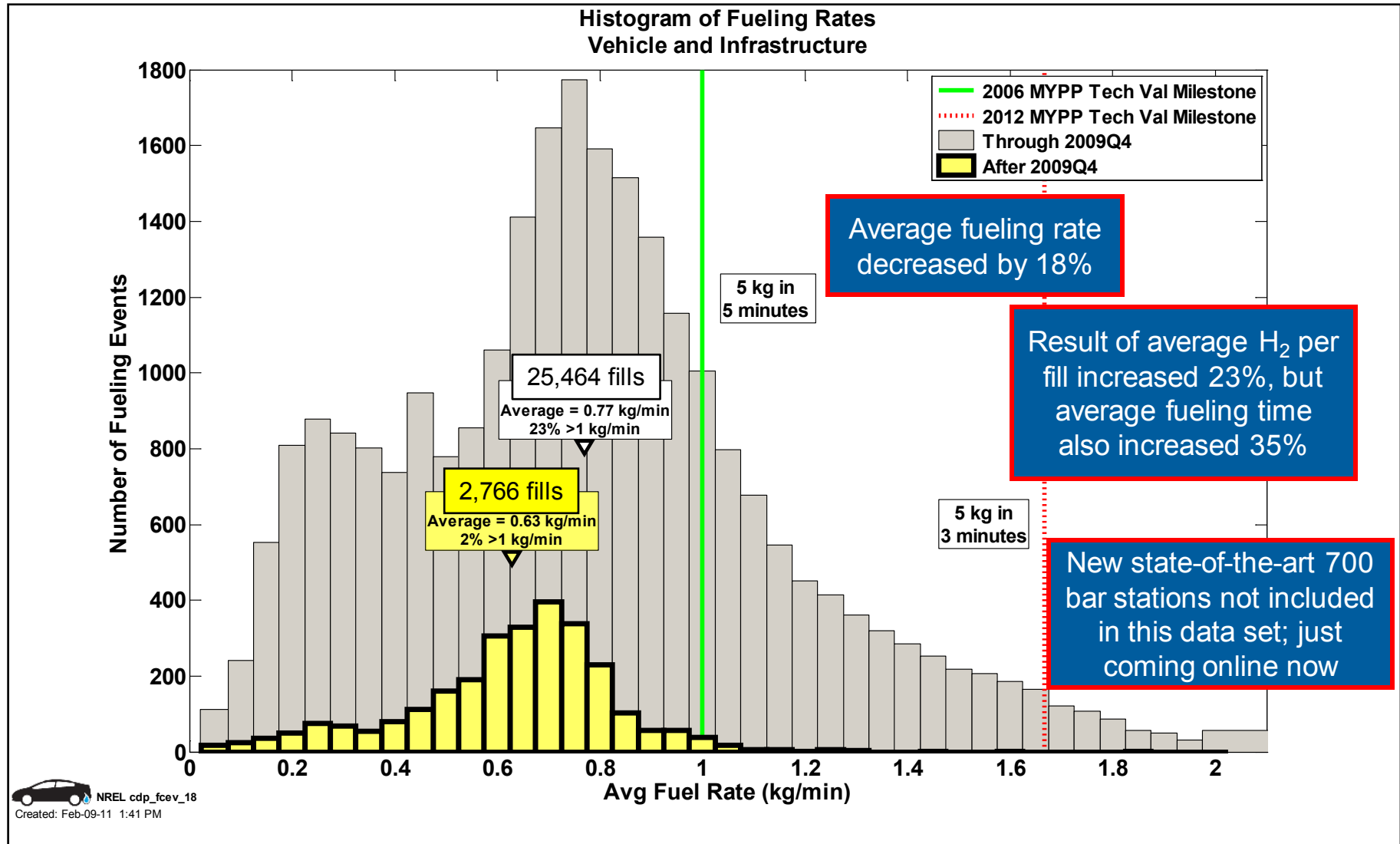
- Most comprehensive set we ever published
 - Includes durability, range, fuel economy
 - Covers data from all 4 Learning Demo teams + CHIP project over 5-year period
 - Majority of these will now stay static, serving as a historical record of Gen 1 & Gen 2 comparisons.
- (subset of results presented at 2010 AMR)



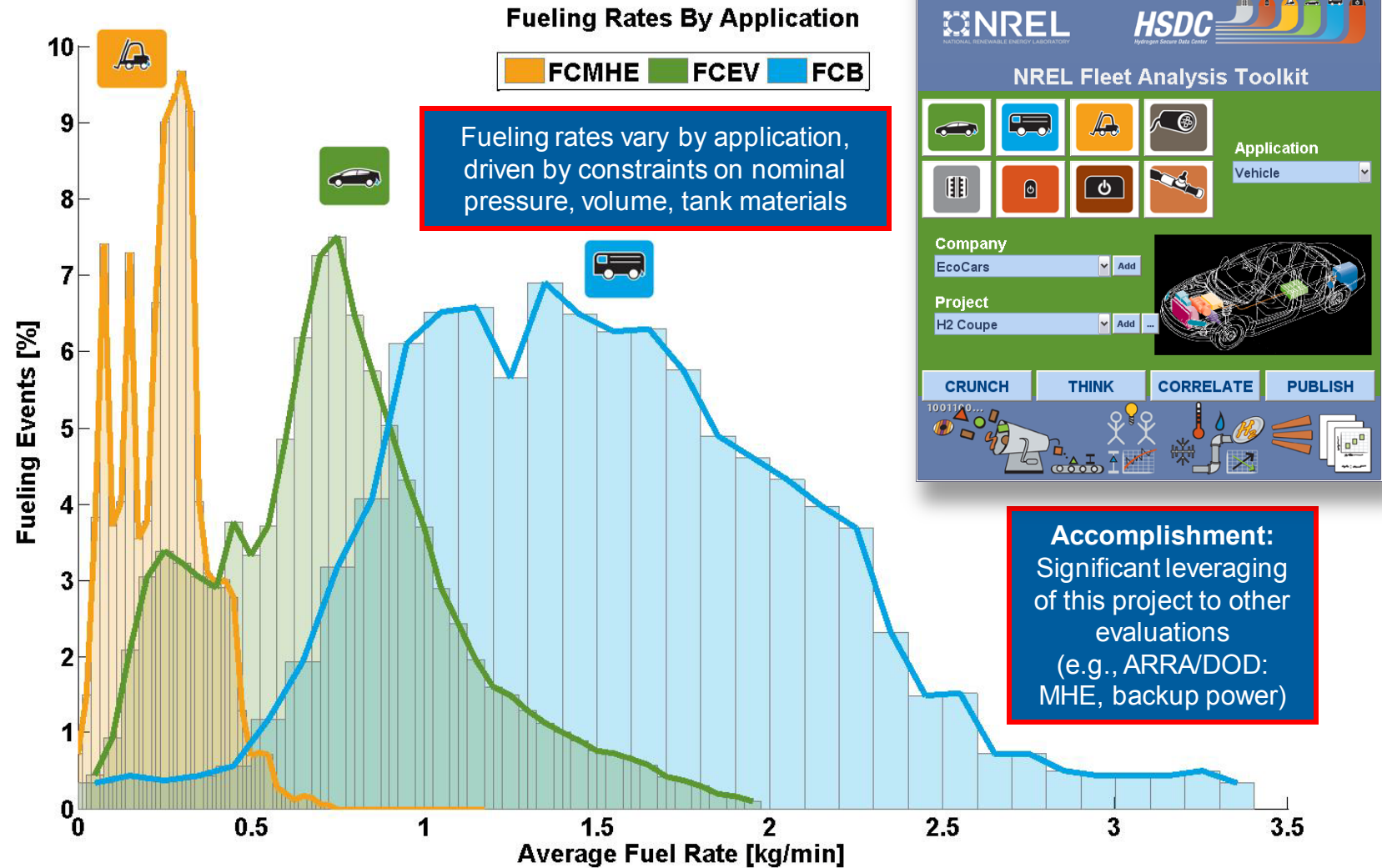
23 Spring 2011 Results

- 5 new CDPs, and updated 18 previously published CDPs with data from last 12 months
- Results on most recent durability, range, fuel economy, not yet possible to publish until more data accumulated (end of 2011)
- Covers data from 2 Learning Demo OEMs + CHIP project
- Emphasized changes observed in last 12 months through use of gray (old) and colors (new)

Accomplishment: Monitored Fueling Rate Trends as Stations Move to 700 bar as Standard

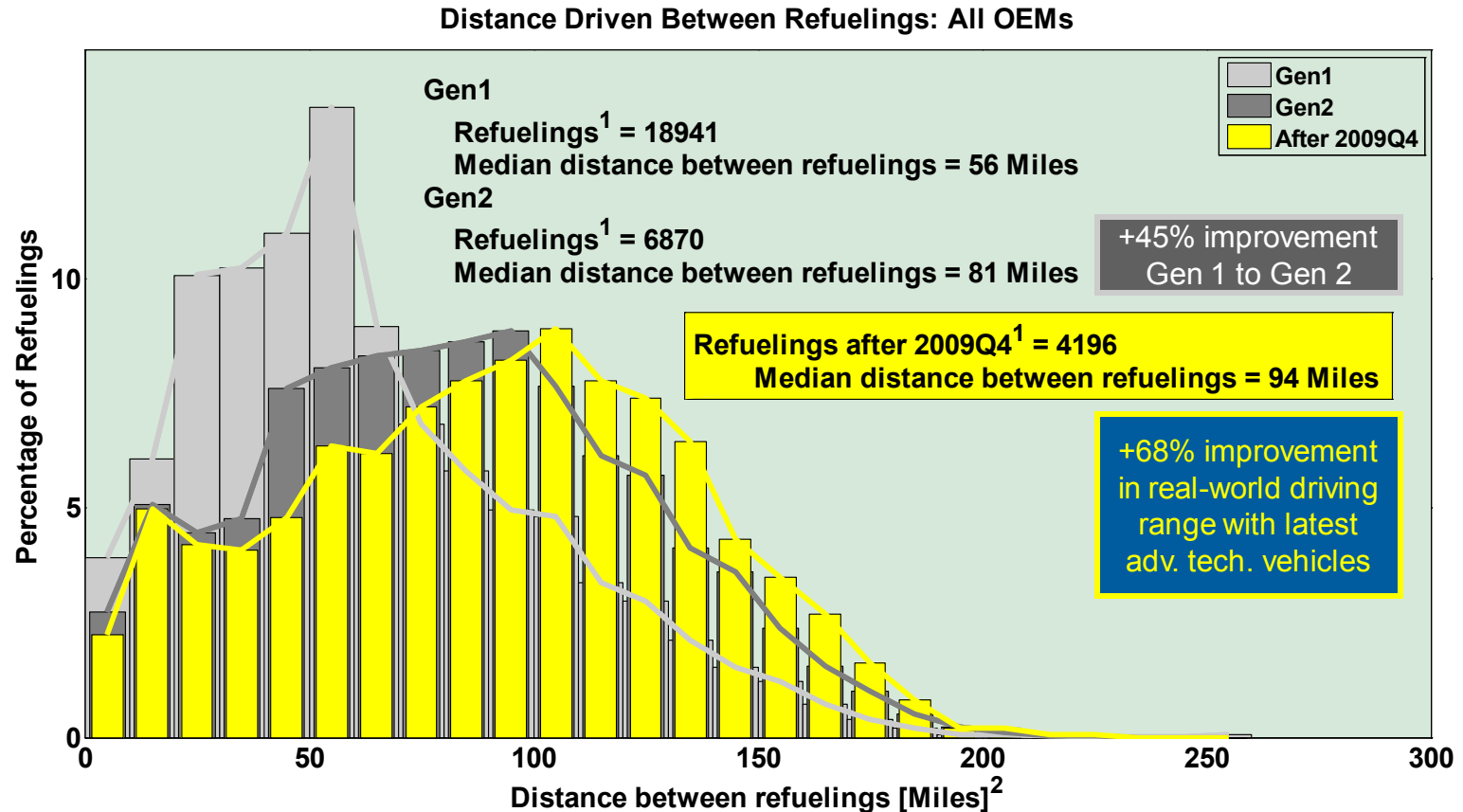


Accomplishment: Leveraging Effort to Other FC Applications; Cross-Application CDPs Initiated



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Accomplishment: Quantified Continued 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

Accomplishment: Based on Limited Number of Fuelings in Last 12 Months, Higher Level of Tank at Refueling Observed

Tank Levels: DOE Fleet

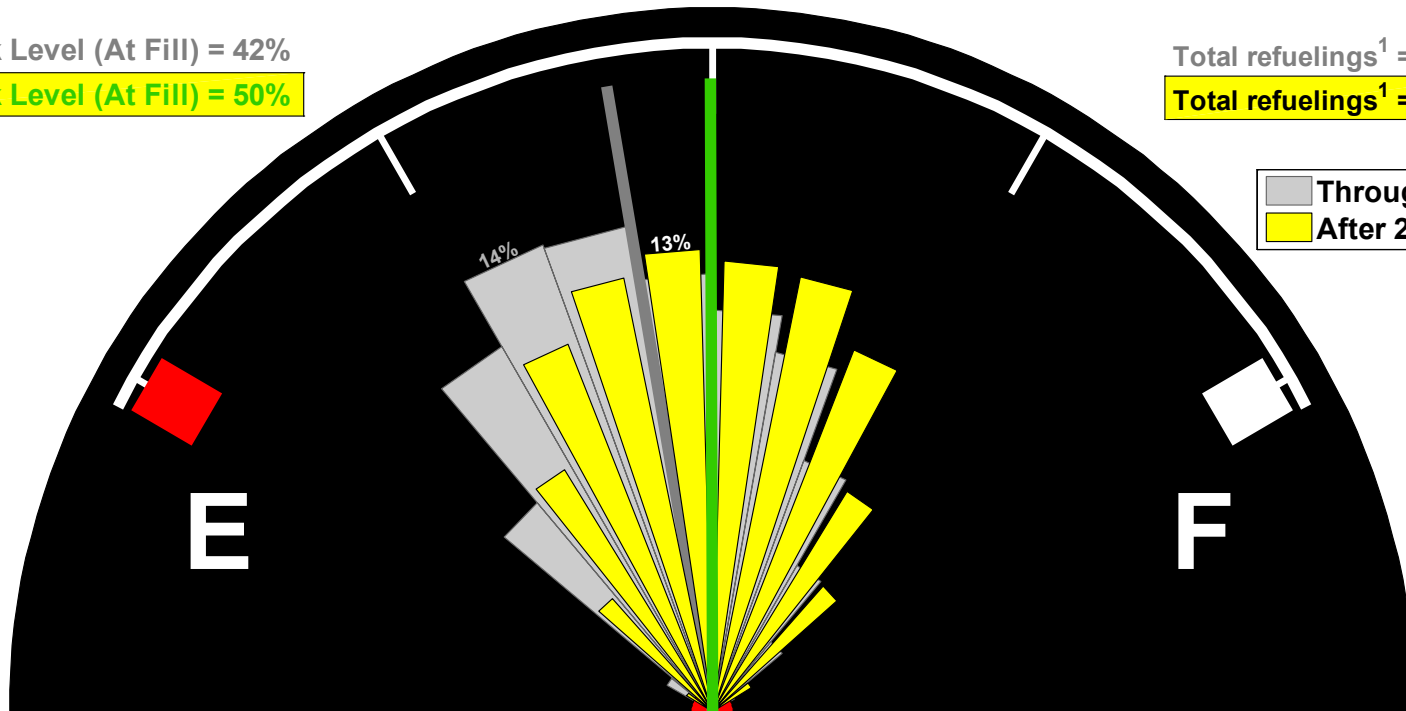
Median Tank Level (At Fill) = 42%

Median Tank Level (At Fill) = 50%

Total refuelings¹ = 27113

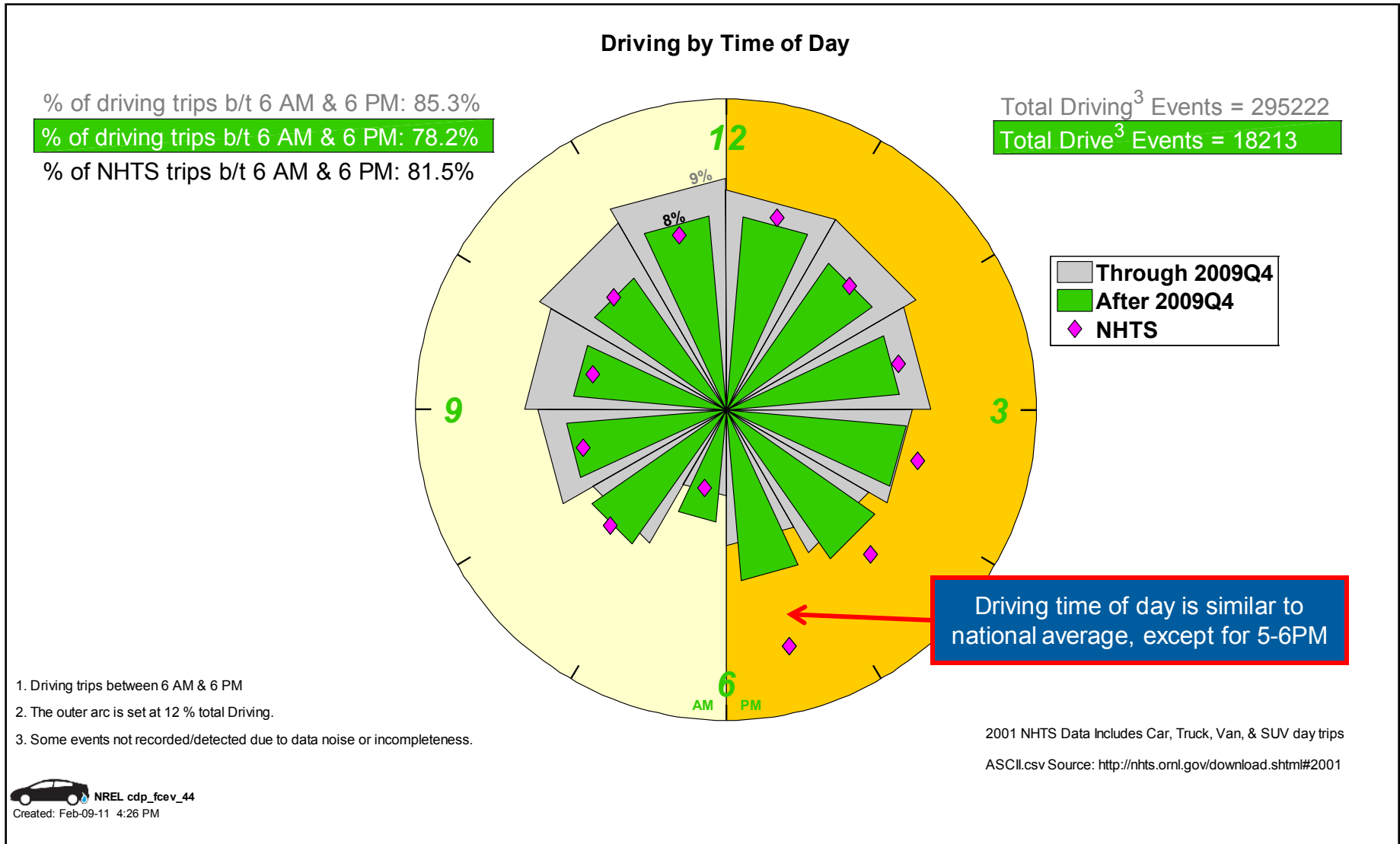
Total refuelings¹ = 4205

Through 2009Q4
After 2009Q4

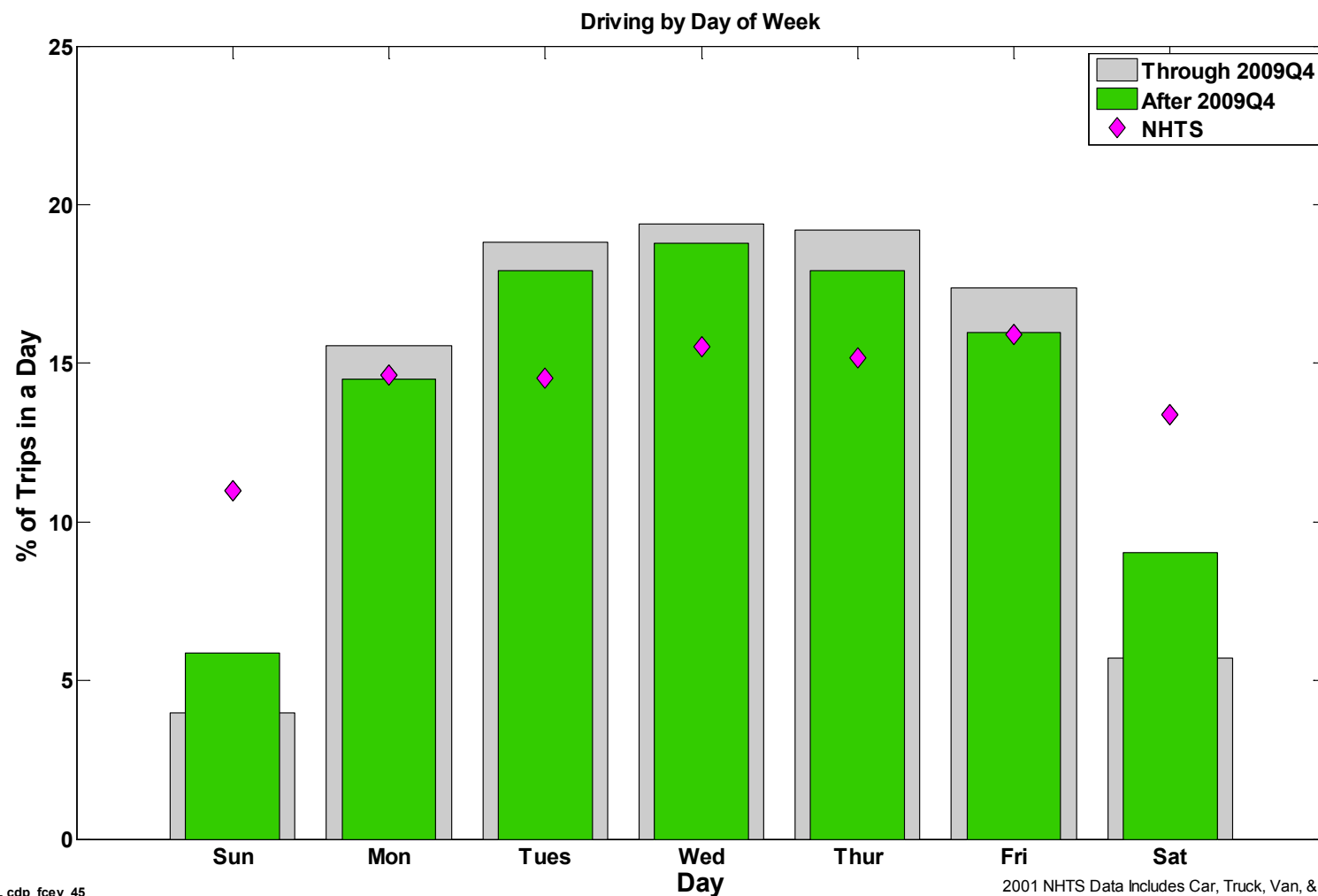


1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. The outer arc is set at 20% total refuelings.
3. If tank level at fill was not available, a complete fill up was assumed.

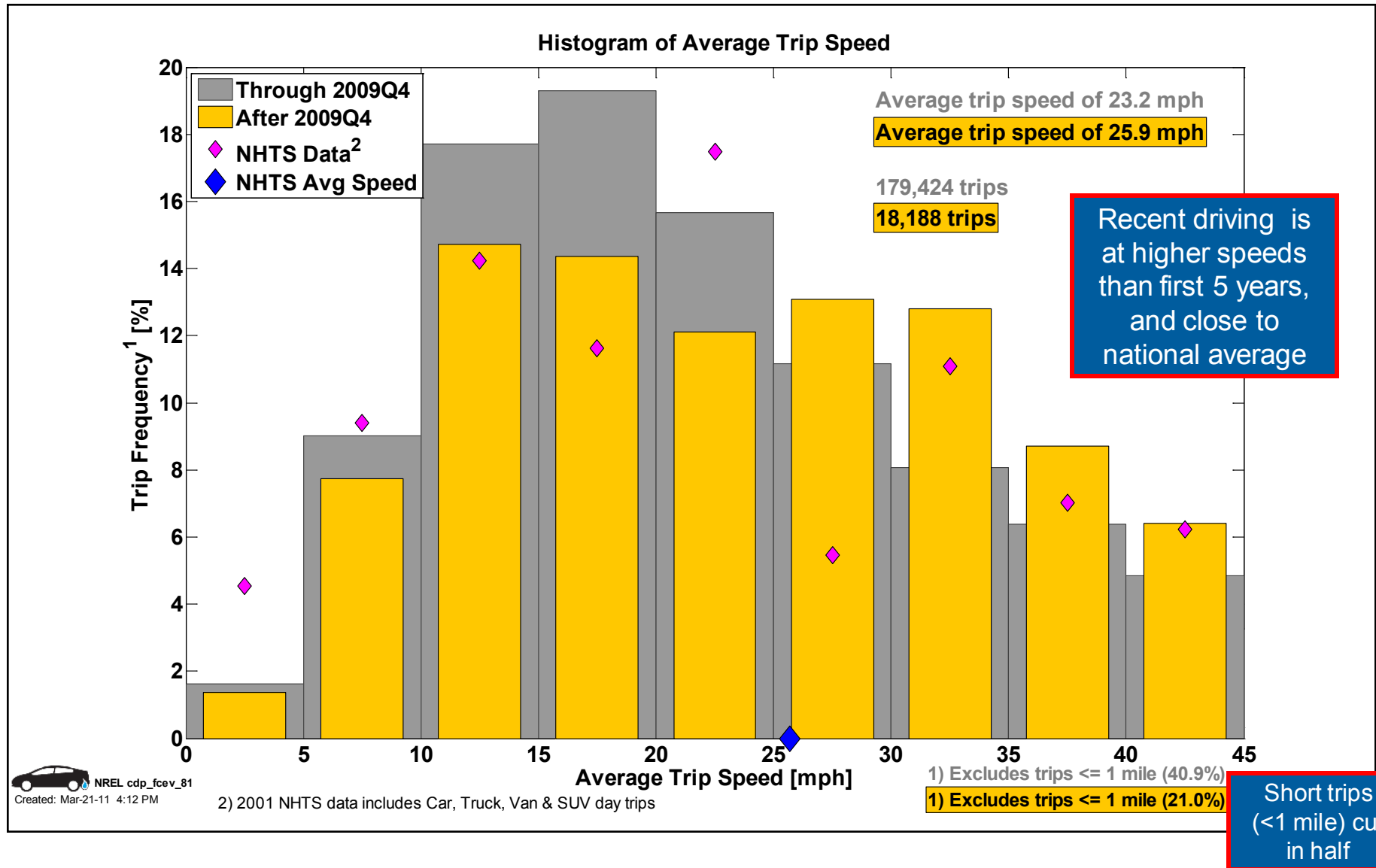
Accomplishment: Driving Behavior (Timing) in Last 12 Months Much More Similar to National Average



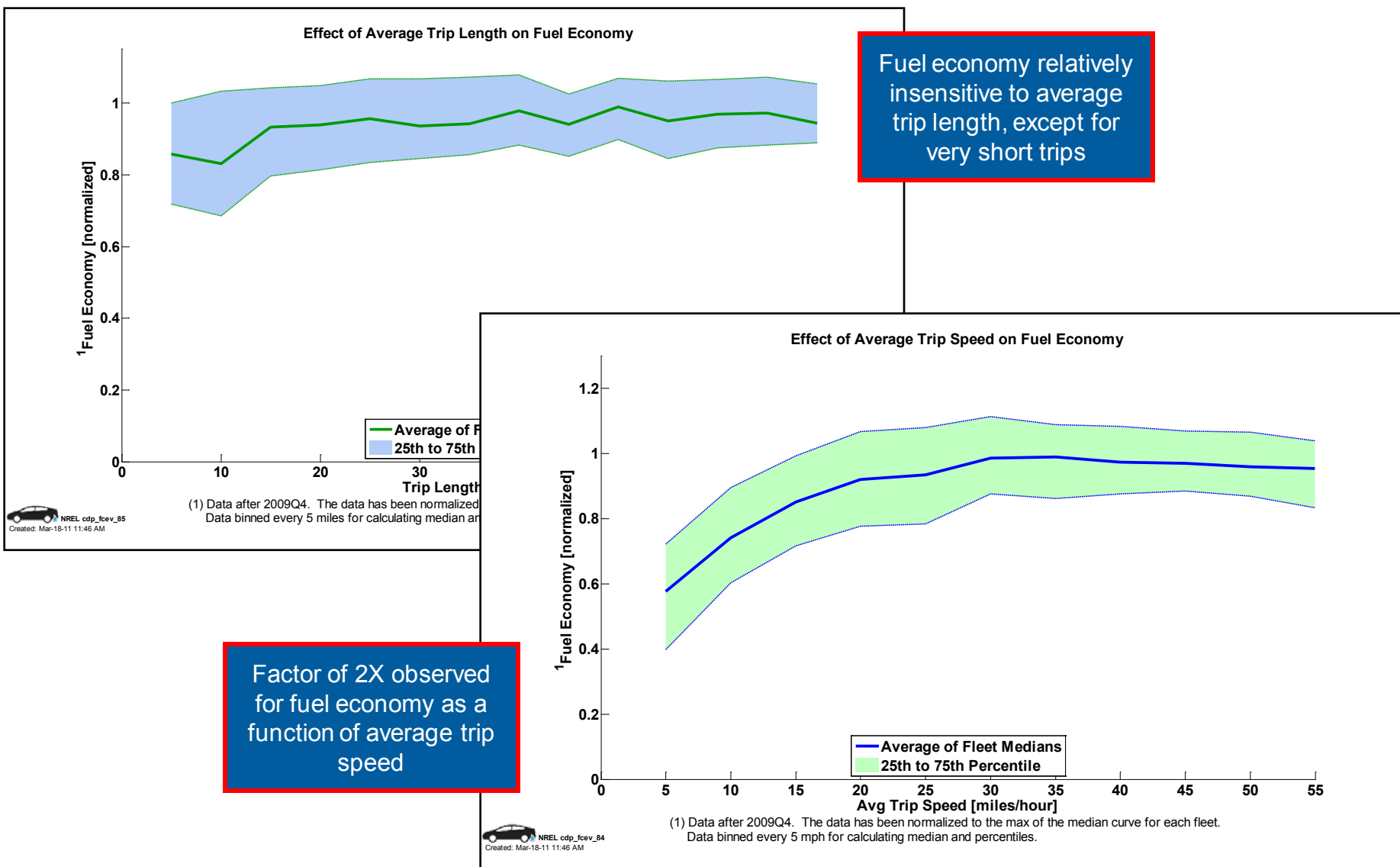
Accomplishment: More Weekend Driving Observed in Last 12 Months – Still Less than National Average



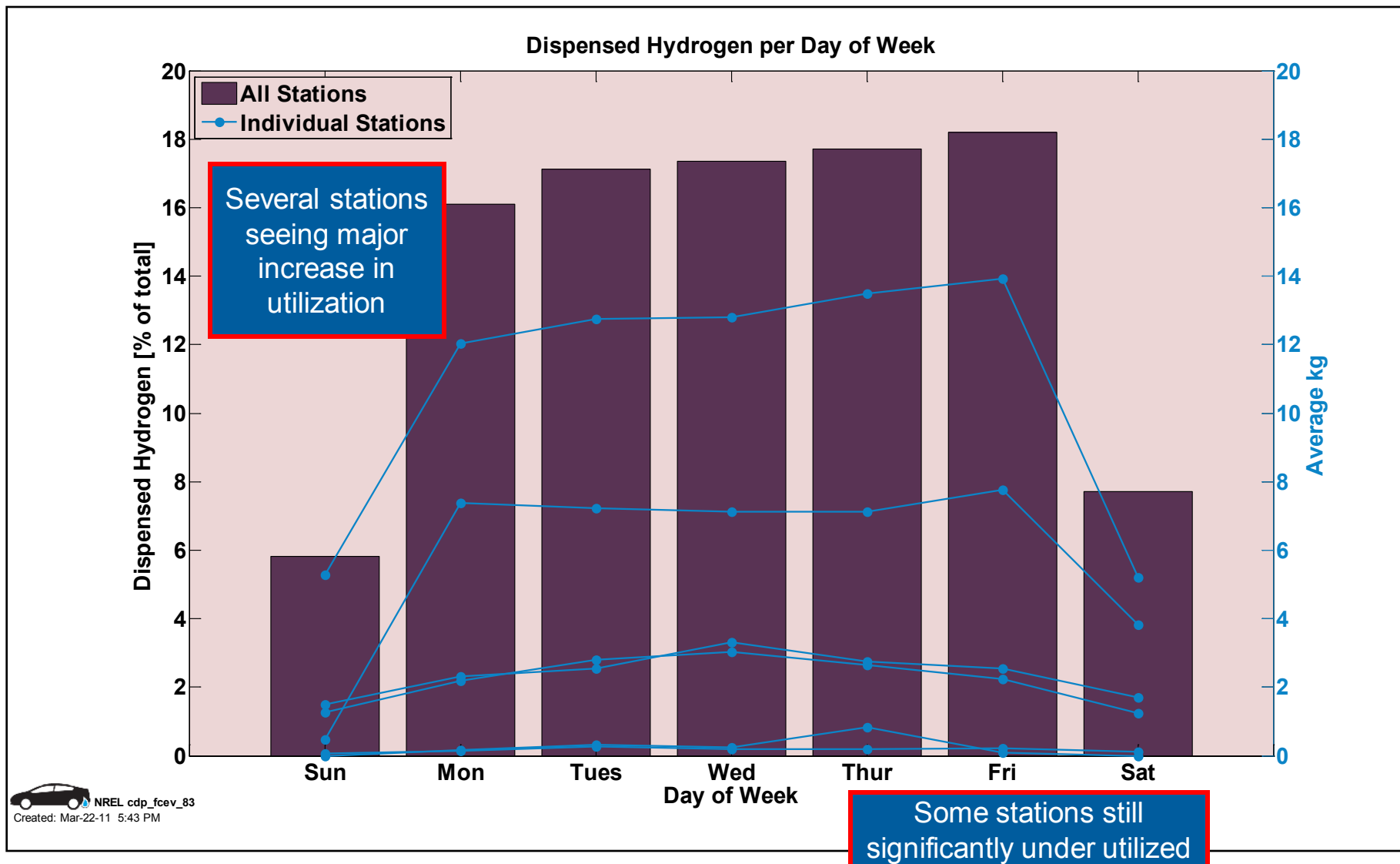
Accomplishment: Compared Recent Driving Speeds to First 5 Years and National Avg.



Accomplishment: Factors Affecting Fuel Economy Were Quantified, Showing Large Spread in Data



Accomplishment: Created New Infrastructure CDP to Give Insight Into Specific Fueling Usage Patterns



Highlights of Interactions and Collaborations in the Last Year

Auto/Energy Industry Partners

- Detailed discussion of NREL results and methodology
- Discussion of voltage degradation calculations; discussions of how to do new/previous CDPs with fewer teams
- Project partners review all results prior to publication



DAIMLER



FreedomCAR and Fuel Technical Teams

- H₂ Storage (4/11) Tech Team Briefing



FCHEA Technical Working Groups

- Transportation Working Group
- Joint H₂ Quality Task Force



California Organizations

- CaFCP and CHBC: NREL actively participating as member
- CARB and CEC: New stations to provide future data to NREL



Early FC Market Evaluations: DOD (DLA) and ARRA

- Leveraging experience to evaluate FC forklifts and backup power



Future Work

Remainder of FY11:

- Create new and updated composite data products (CDPs) based on data through June 2011 (potentially Sept 2011)
- Begin receiving performance data from new/restarted stations
 - Burbank reformer, Torrance pipeline, Fountain Valley tri-generation
- Support DOE milestone (Sept. 2011) to document operation of advance technology vehicles for up to 600 hours
- Support OEMs, energy companies, and state organizations in coordinating early infrastructure plans

FY12:

- Publish Fall 2011 composite data products as the last anticipated results from the project
- Submit final summary report for the project
- Present final results at conferences and meetings
- Continue to leverage analysis capability to other validations
- Identify and exploit new opportunities to document FC & H₂ progress publicly

Technical Summary

- Project has completed ~6 years of validation
- Vehicle operation: 131,000 hours, >3 million miles, 460,000 trips
- H₂ station operation: 140,000 kg produced or dispensed, 28,000 fuelings
- Safety: No vehicle safety reports since last AMR; no infrastructure incidents & major reduction in safety reports
- DOE Key Technical Targets Met:
 - FC Durability >2,000 hours and Range >250 miles
- New CA fueling stations planned for inclusion in future NREL infrastructure analysis as they come online and provide data

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 capability
- Technical Accomplishments and Progress
 - 85 total CDP analysis results available; publication at conferences every 6 months
 - Project has achieved its key technical targets (refer to technical backup slides and 87 page Progress Report)
- Collaborations
 - Worked closely with industry partners to validate methodology and ensure relevance of results
- Future Work
 - Document final project results (report and presentation)
 - Seek new opportunities to objectively evaluate status of H₂ & FC technology

Questions and Discussion; Contact Info. and Web Resources

**Project Contact: Keith Wipke, National Renewable Energy Lab
303.275.4451 keith.wipke@nrel.gov**





NREL's Renewable H₂ Station, storing over 250 kg H₂ and dispensing at 350 bar

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

TECHNICAL BACKUP SLIDES

Project Achieved Both Technical Goals; Outside Analysis Used for Cost Evaluation (2010 AMR)

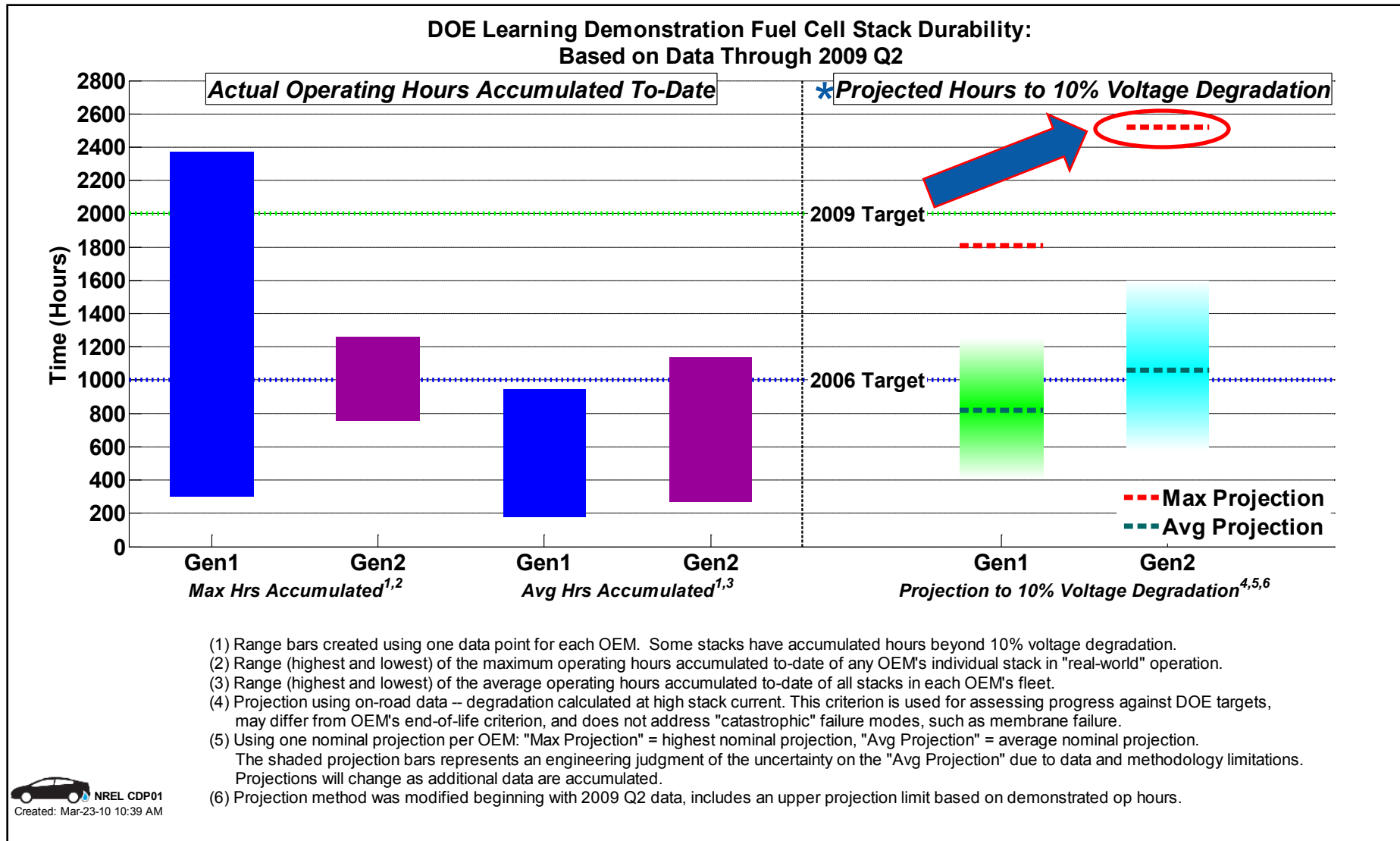
Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target
Fuel Cell Stack Durability			2000 hours
Max Team Projected Hours to 10% Voltage Degradation	1807 hours	<u>2521</u> hours 	
Average Fuel Cell Durability Projection	821 hours	1062 hours	
Max Hours of Operation by a Single FC Stack to Date	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
Average H₂ 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)



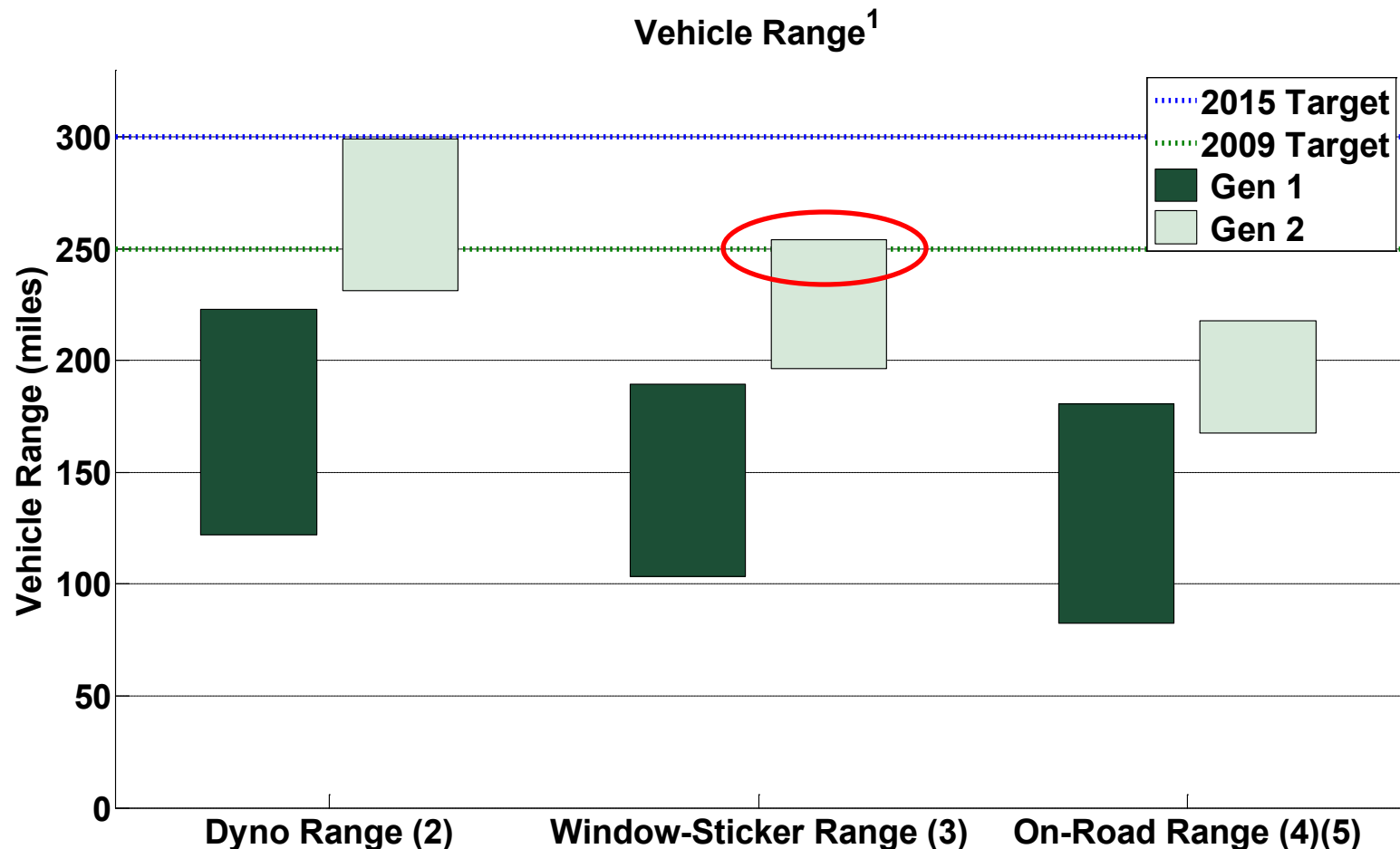
1) FC Durability Target of 2000 Hours Met By Gen 2 Projections (2010 AMR)



★ 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 AMR)



(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.

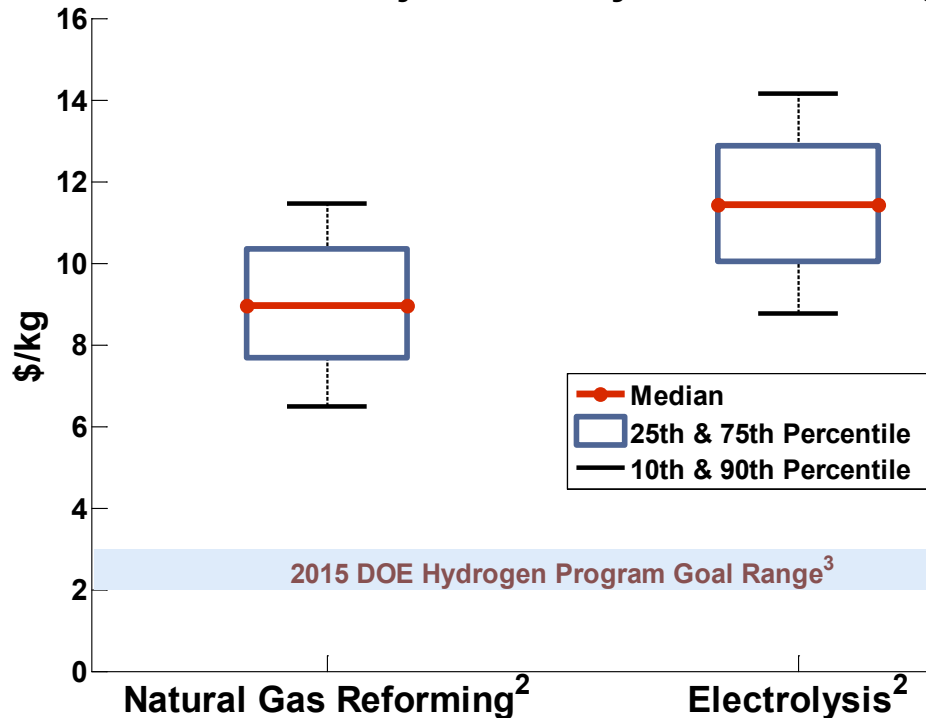
(3) Fuel economy from EPA Adjusted combined City/Hwy ($0.78 \times \text{Hwy}$, $0.9 \times \text{City}$).

(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.

3) Projected Early Market H₂ Production Cost from Learning Demo Energy Partners' Inputs (2010 AMR)

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.

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)