NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Project ID#
TV001

Controlled Hydrogen Fleet and Infrastructure Analysis

2011 DOE Annual Merit Review and Peer Evaluation Meeting

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

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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
- Relevance
  - 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	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**

Outside review panel

**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 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

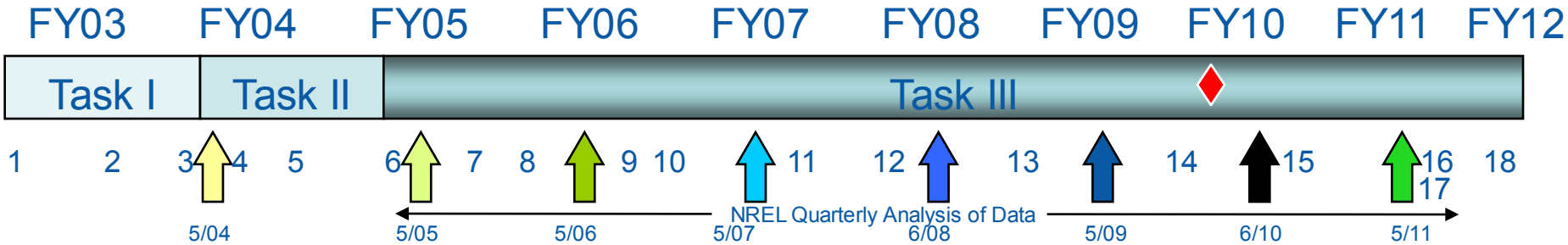
D. **Maintenance and Training Facilities** – lack of facilities and trained personnel

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]

2 teams concluded their projects

Task III – Data Analysis and Feedback to R&D activities (partial list) [90% Complete]

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 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)

Project Approach (cont.)

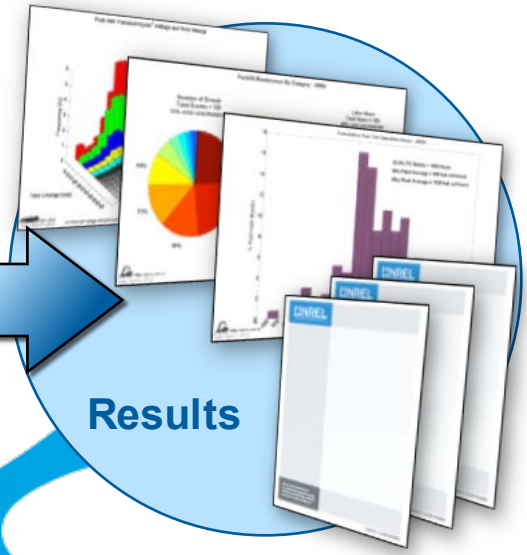
Supporting Both DOE/Public as Well as Fuel Cell Developers

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 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)

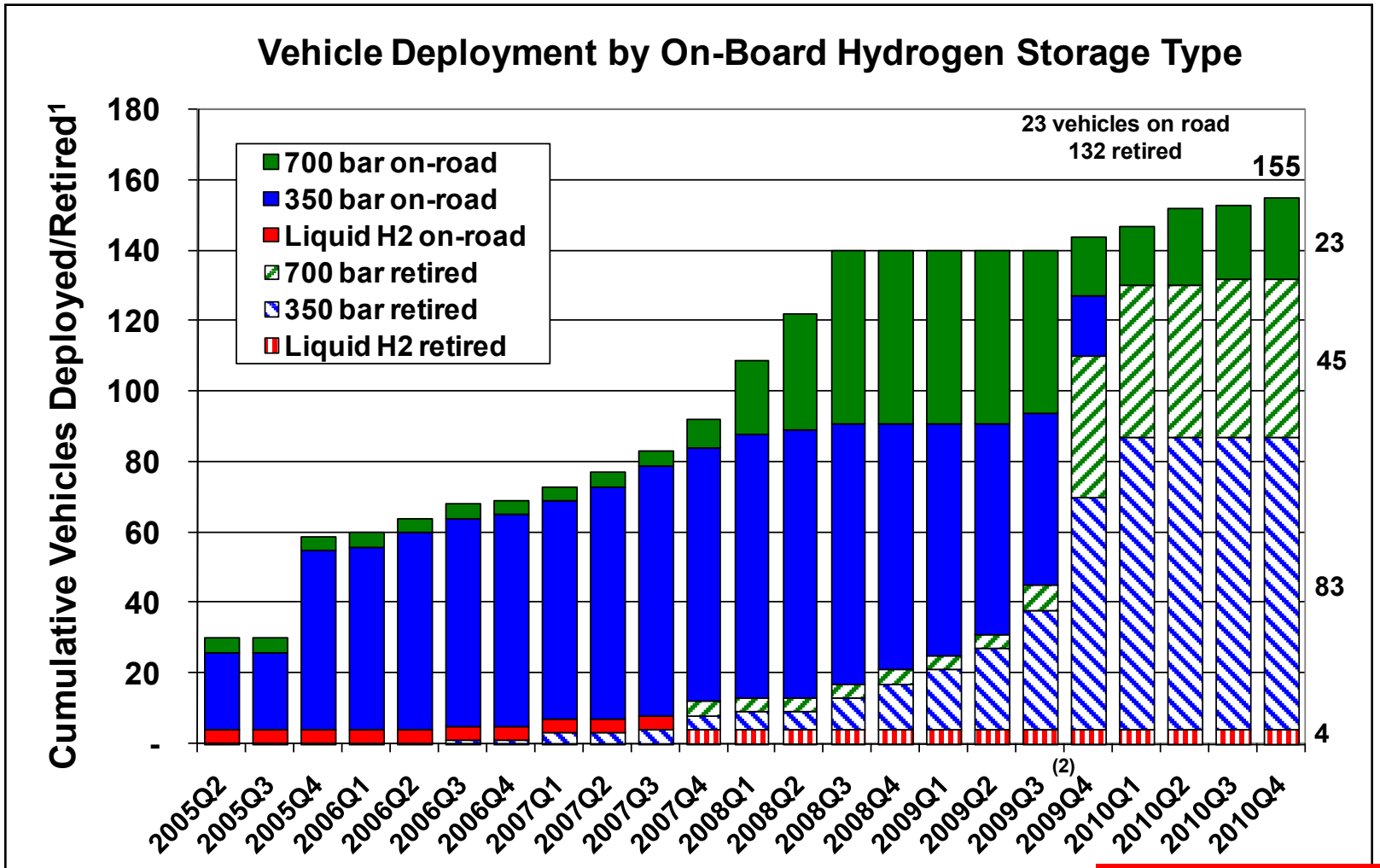
Industry Partners: Two Teams Concluded Their Projects in 2009, Three are Continuing through 2011

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

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

(CHIP)

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

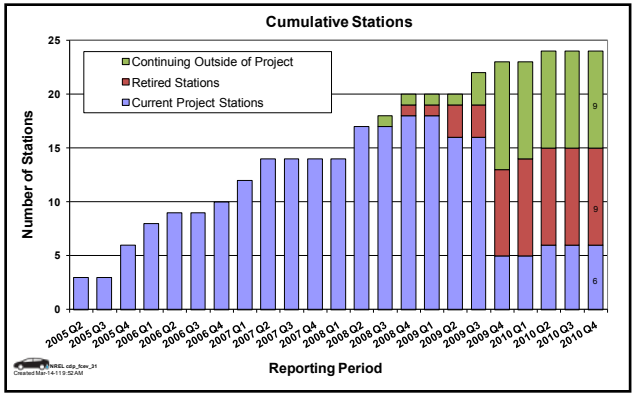


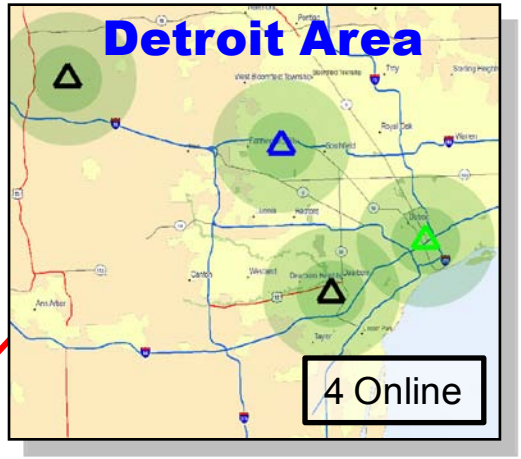
(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009

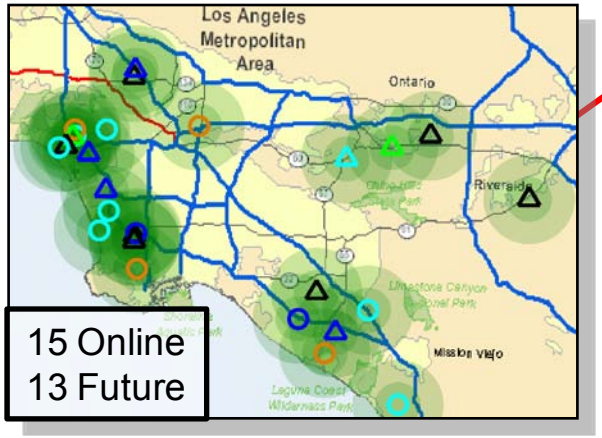
Total of ~40 project vehicles expected on road in 2011, for total of ~170 deployed

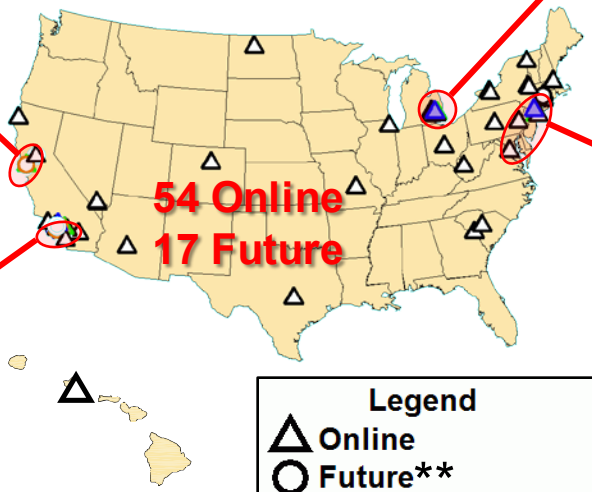
Status: Out of 24 Project Stations, 15 Are Still Operational* (3/5 outside of DOE project)

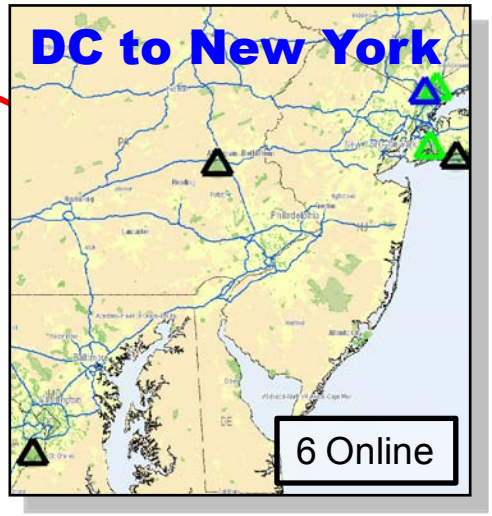
* CDP station status is as of 12/31/10

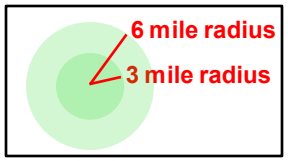












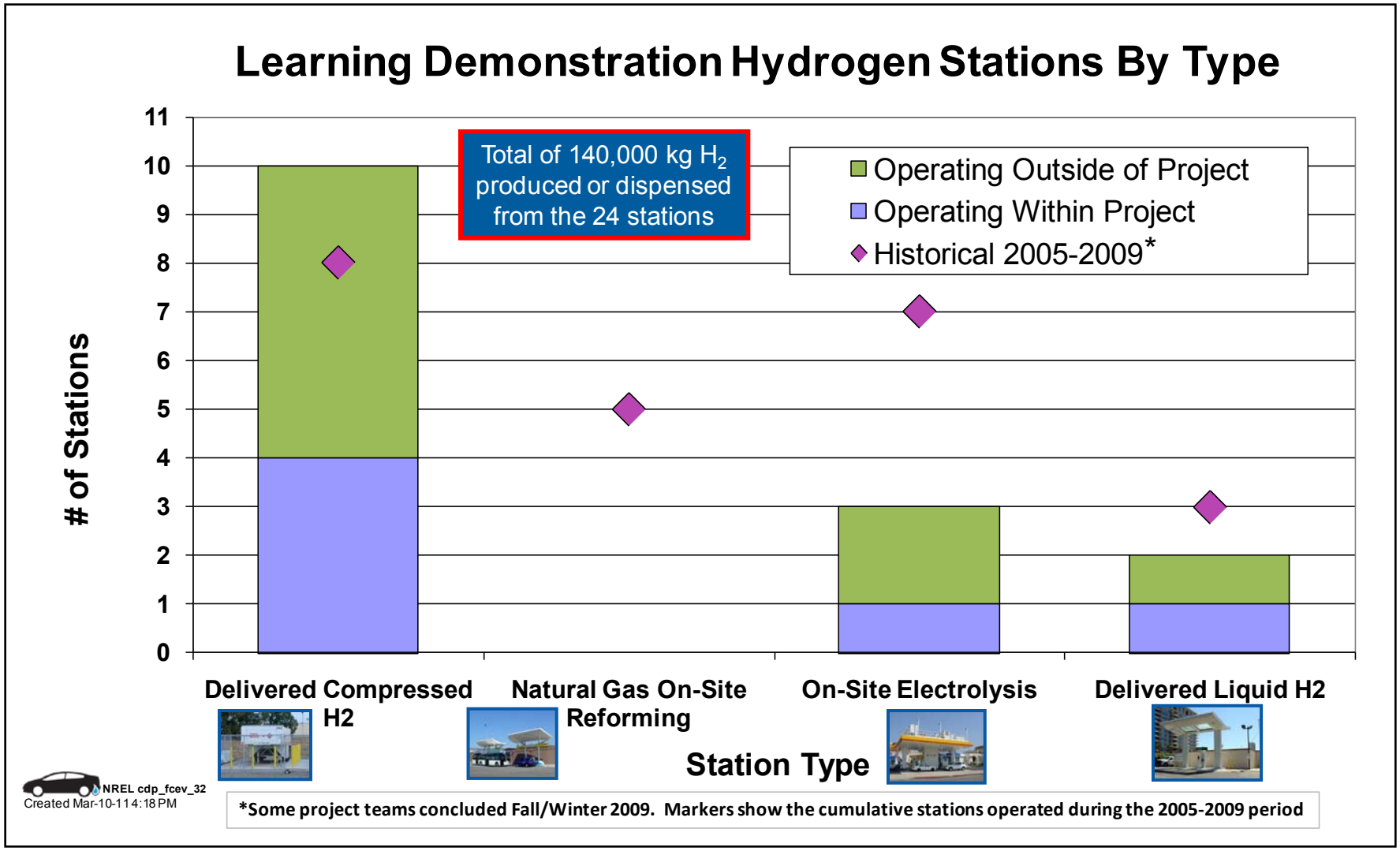
Legend

- Online
- Future**
- Current Project
- Continuing Outside
- CEC
- CARB
- Other

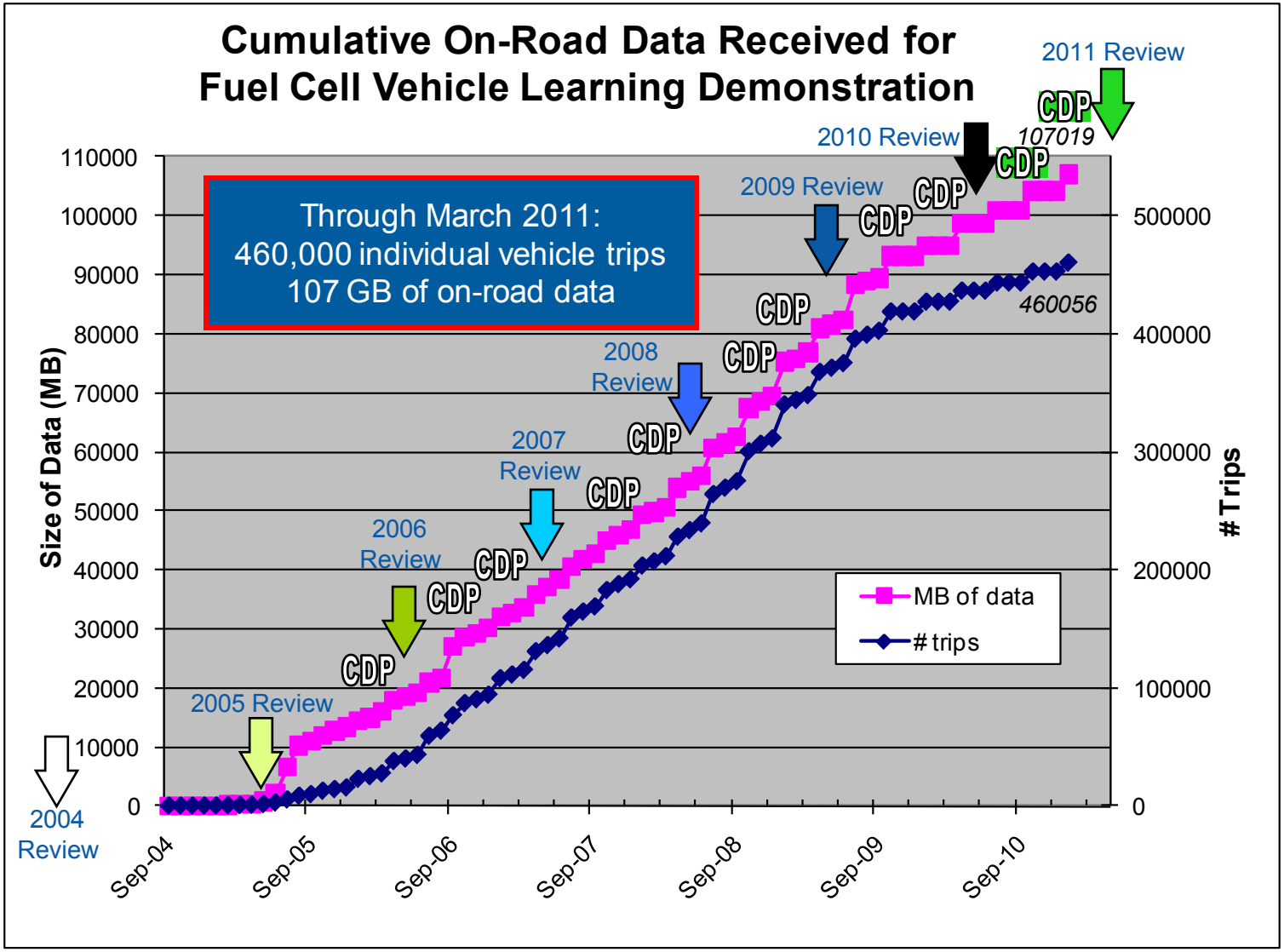
** Funded by state of CA or others, outside of this project

Mar-31-2011

Station Status: The Project Stations Still in Operation Use Delivered H_2 (80%) or Electrolysis (20%)

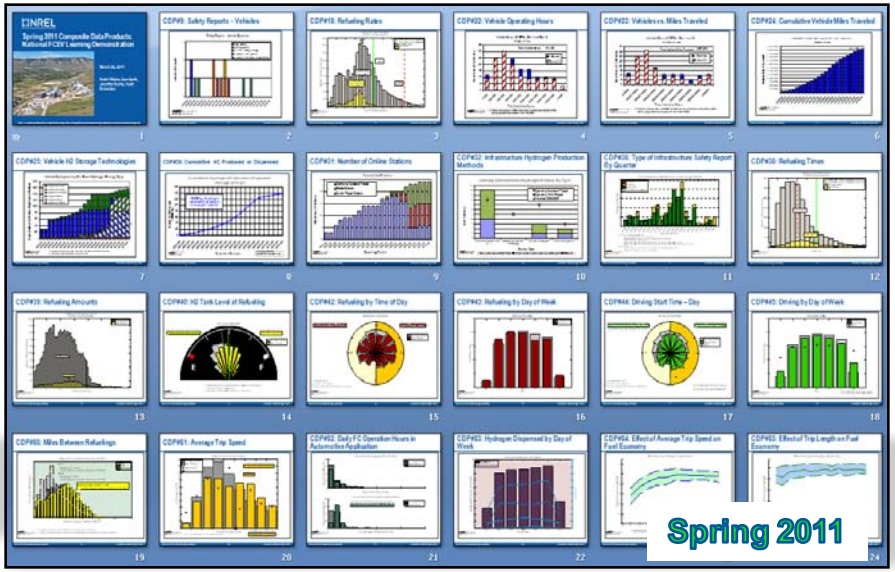


Accomplishment: 23 Quarters (~6 years) of Data Analyzed to Date, Two New Sets of Composite Data Products Published



CDP = Composite Data Products Published

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



80 Spring 2010 Results

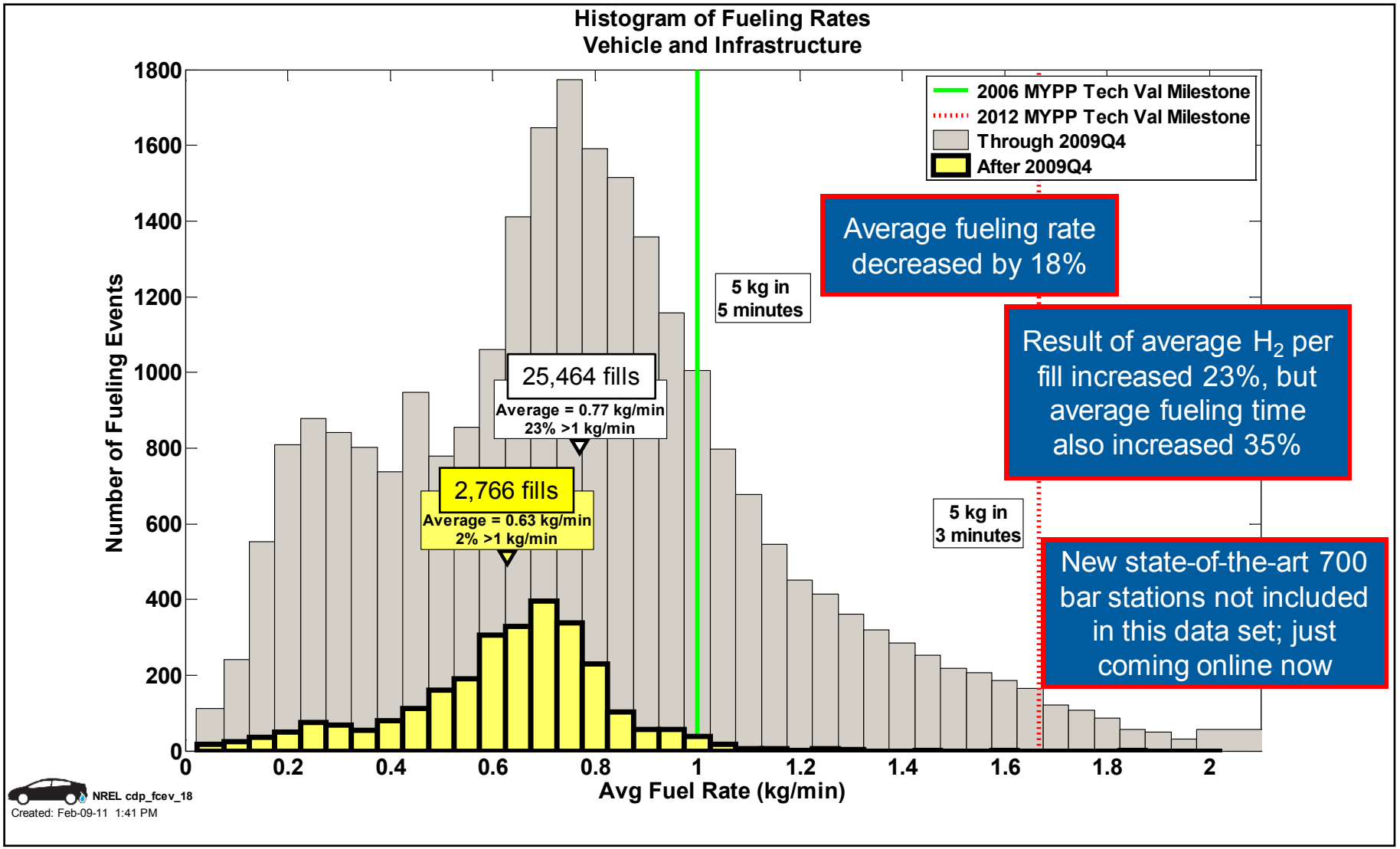
- Most comprehensive set we ever published
- Includes durability, range, fuel economy
- Covers data from all 4 Learning Demo teams + CHIP project over 5-year period
- Majority of these will now stay static, serving as a historical record of Gen 1 & Gen 2 comparisons.

(subset of results presented at 2010 AMR)

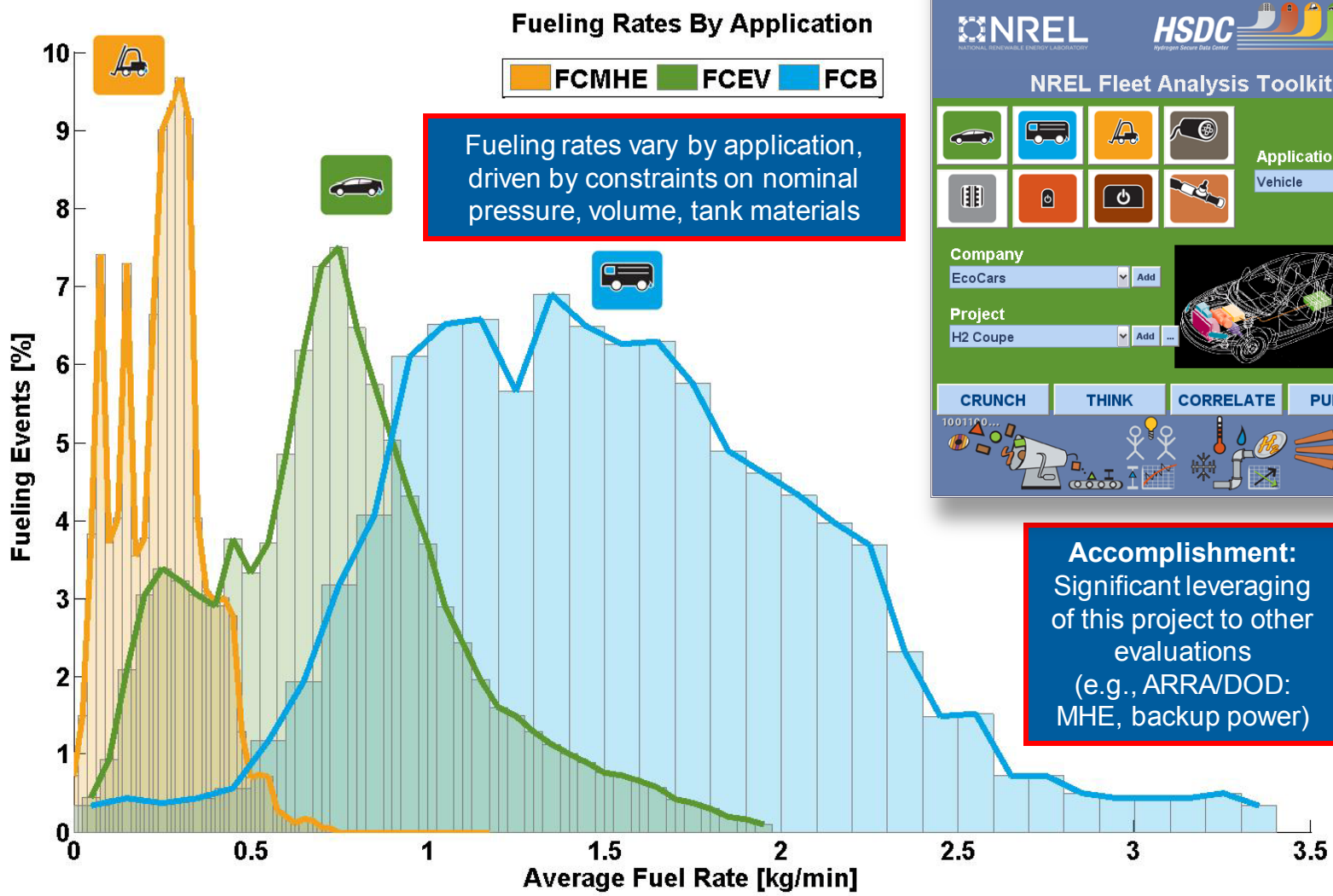
23 Spring 2011 Results

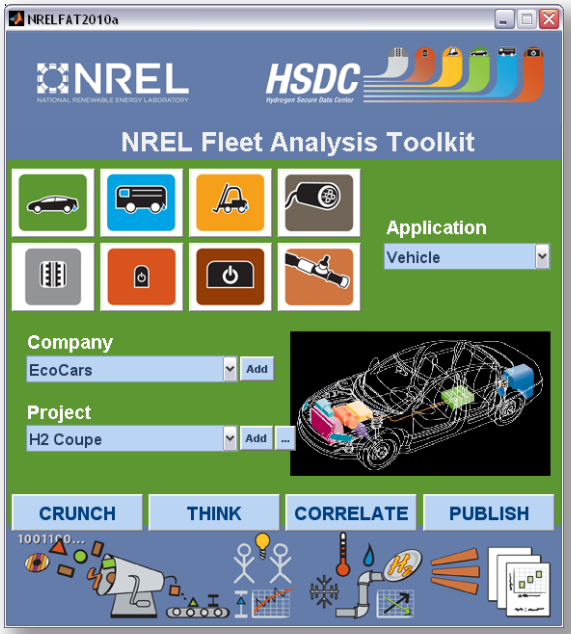
- 5 new CDPs, and updated 18 previously published CDPs with data from last 12 months
- Results on most recent durability, range, fuel economy, not yet possible to publish until more data accumulated (end of 2011)
- Covers data from 2 Learning Demo OEMs + CHIP project
- Emphasized changes observed in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

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



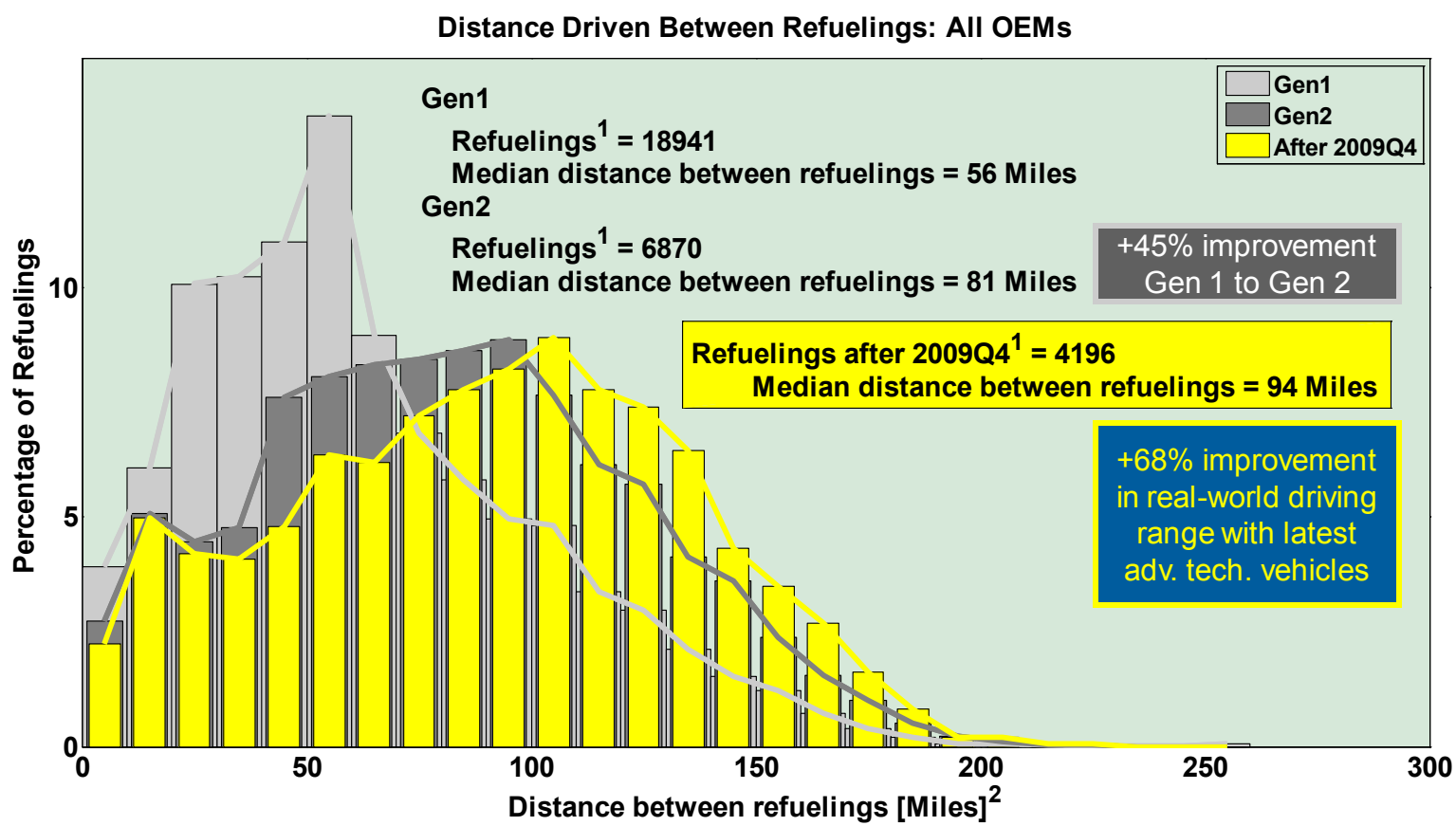
Accomplishment: Leveraging Effort to Other FC Applications; Cross-Application CDPs Initiated





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

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.

NREL cdp_fcev_80
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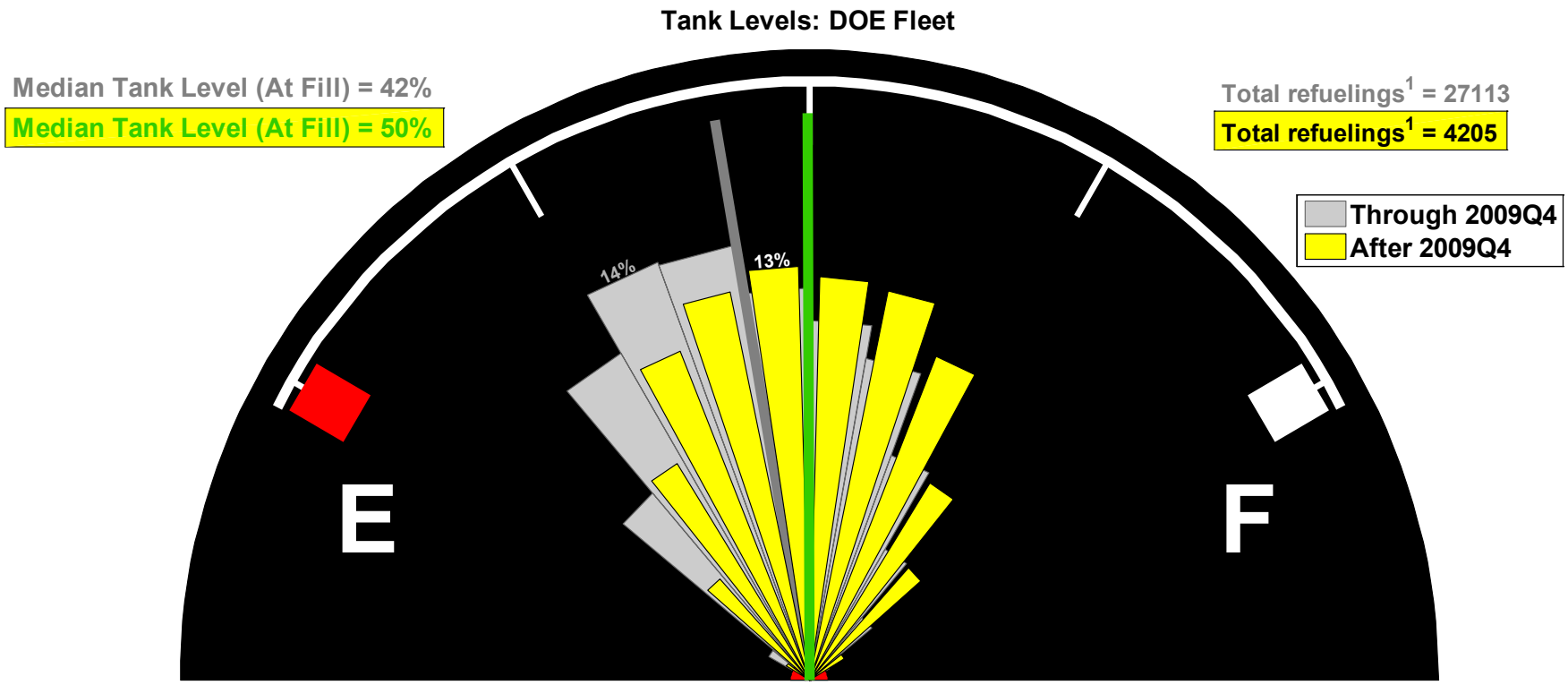
Note: Actual range possible >200 miles

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



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.

NREL cdp_fcev_40
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Fall 2010

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

Driving by Time of Day

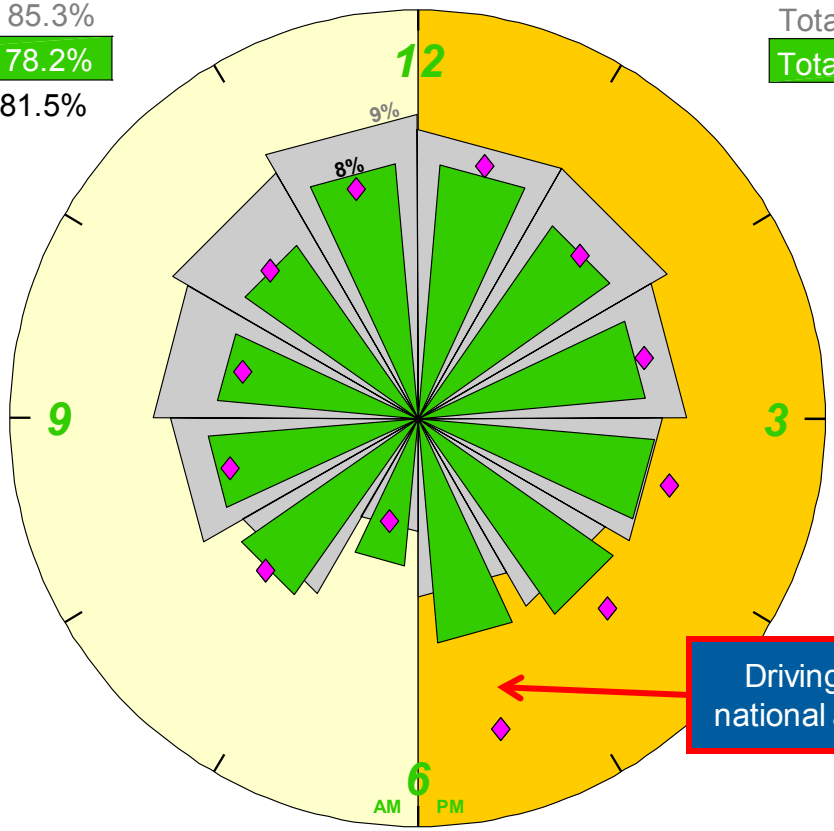
% of driving trips b/t 6 AM & 6 PM: 85.3%

% of driving trips b/t 6 AM & 6 PM: 78.2%

% of NHTS trips b/t 6 AM & 6 PM: 81.5%

Total Driving[3] Events = 295222

Total Drive[3] Events = 18213



Through 2009Q4

After 2009Q4

NHTS

Driving time of day is similar to national average, except for 5-6PM

1. Driving trips between 6 AM & 6 PM
2. The outer arc is set at 12 % total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips

ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

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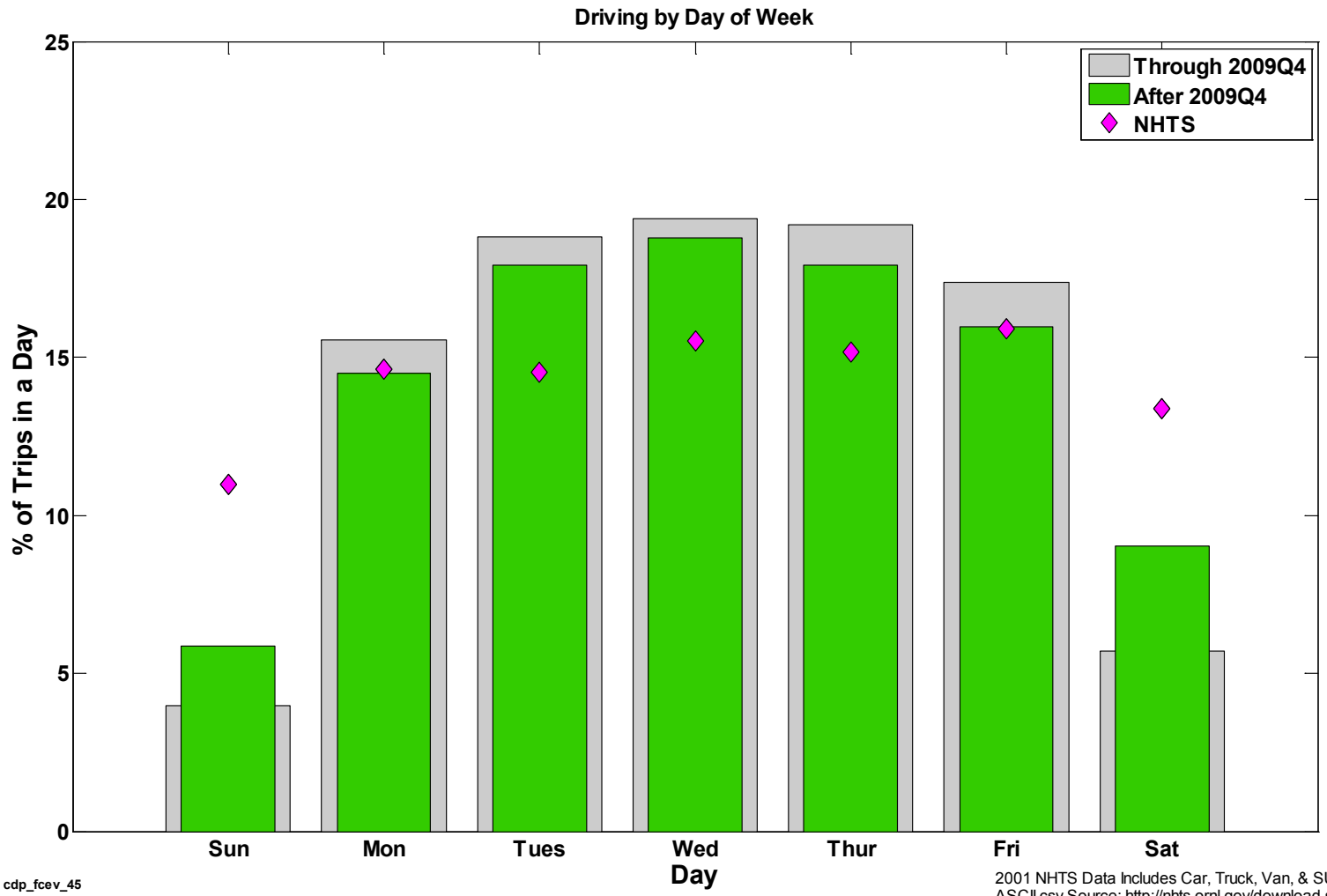
Fall 2010

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



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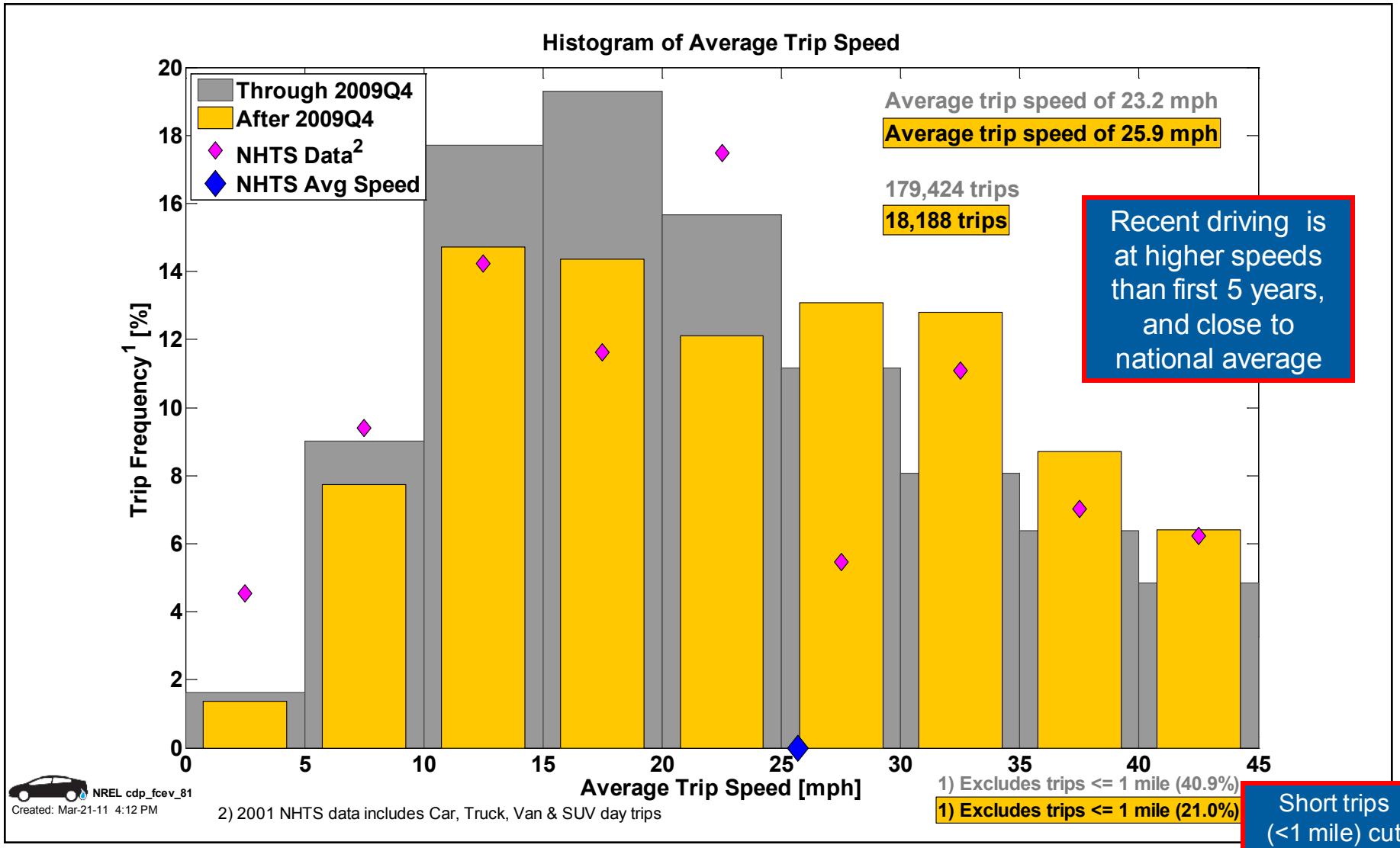
2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

Fall 2010

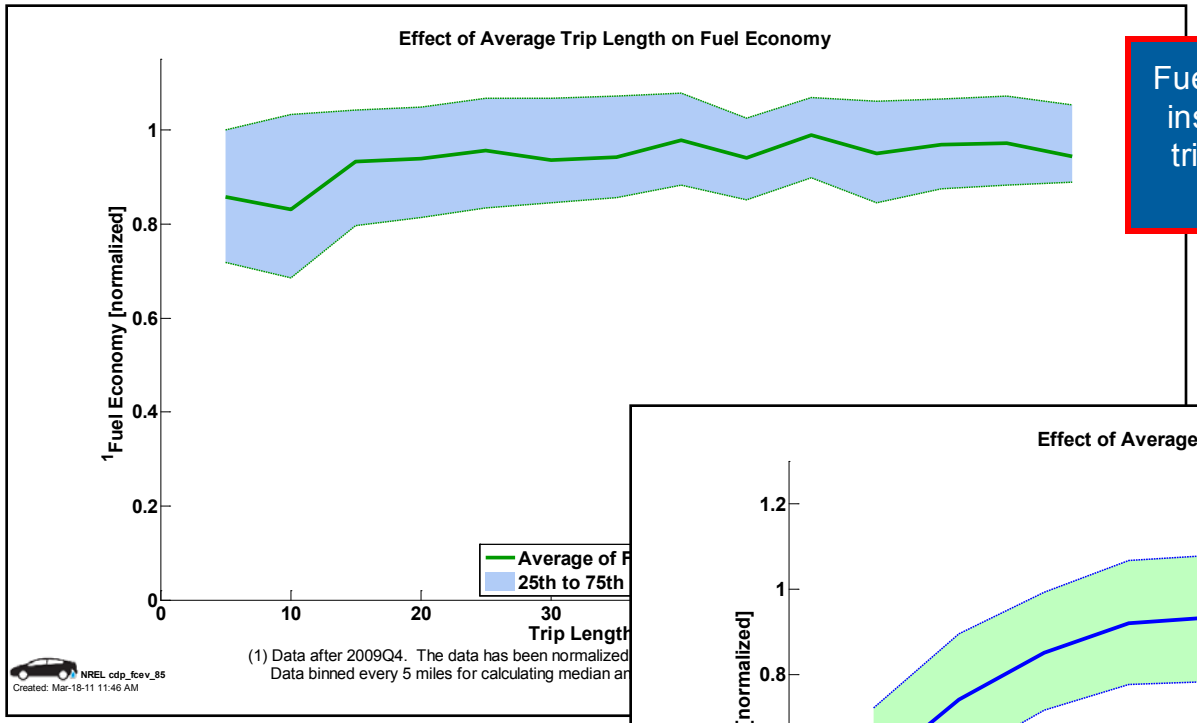
Accomplishment: Compared Recent Driving Speeds to First 5 Years and National Avg.



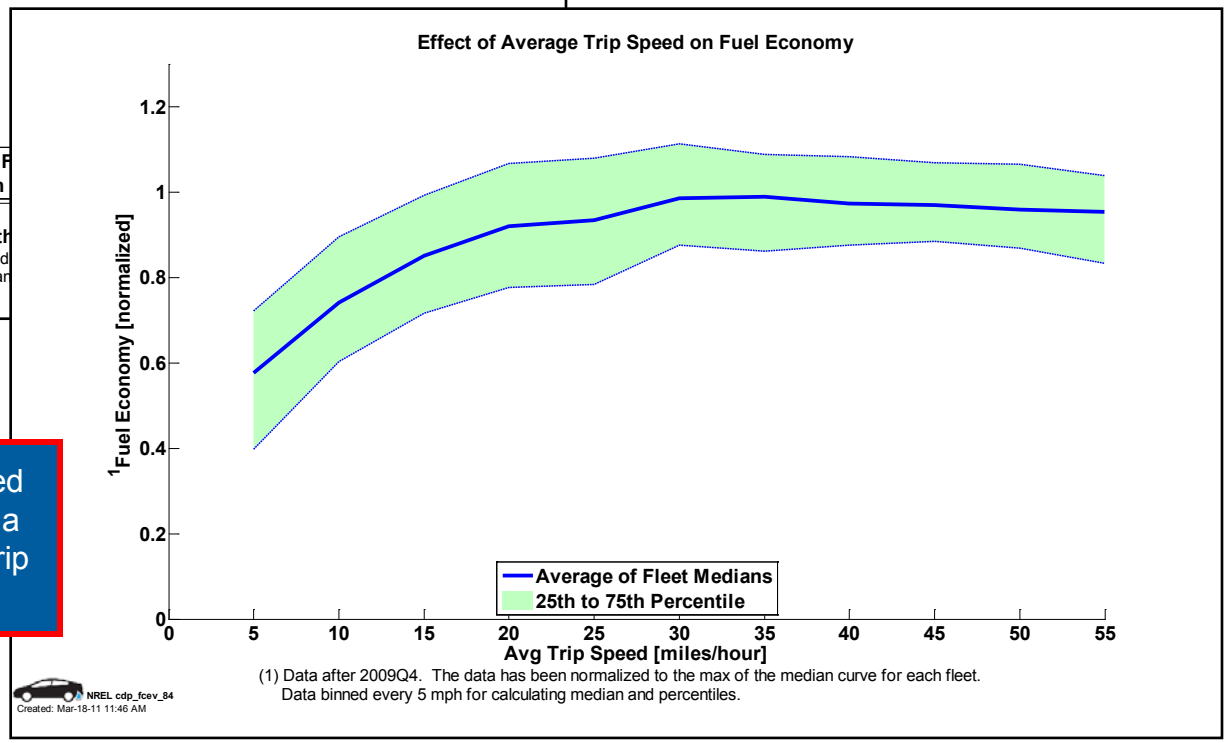
Recent driving is at higher speeds than first 5 years, and close to national average

Short trips (<1 mile) cut in half

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

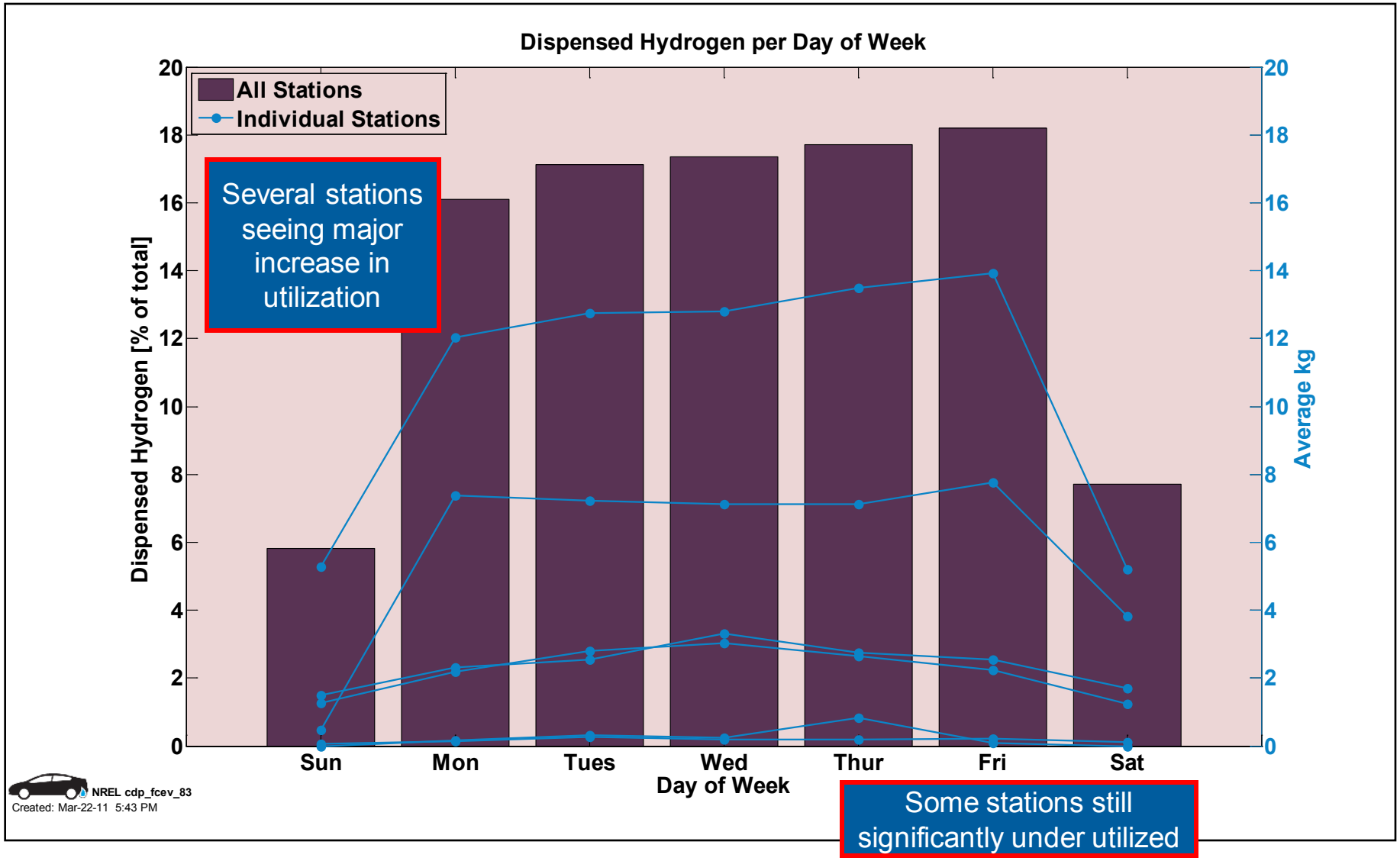


Fuel economy relatively insensitive to average trip length, except for very short trips



Factor of 2X observed for fuel economy as a function of average trip speed

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

FreedomCAR and Fuel Technical Teams

- H_2 Storage (4/11) Tech Team Briefing

FCHEA Technical Working Groups

- Transportation Working Group
- Joint H_2 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 & H_2 progress publicly

Technical Summary

- Project has completed ~6 years of validation
- Vehicle operation: 131,000 hours, >3 million miles, 460,000 trips
- H_2 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 H_2 & 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 H_2 Station, storing over 250 kg H_2 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)

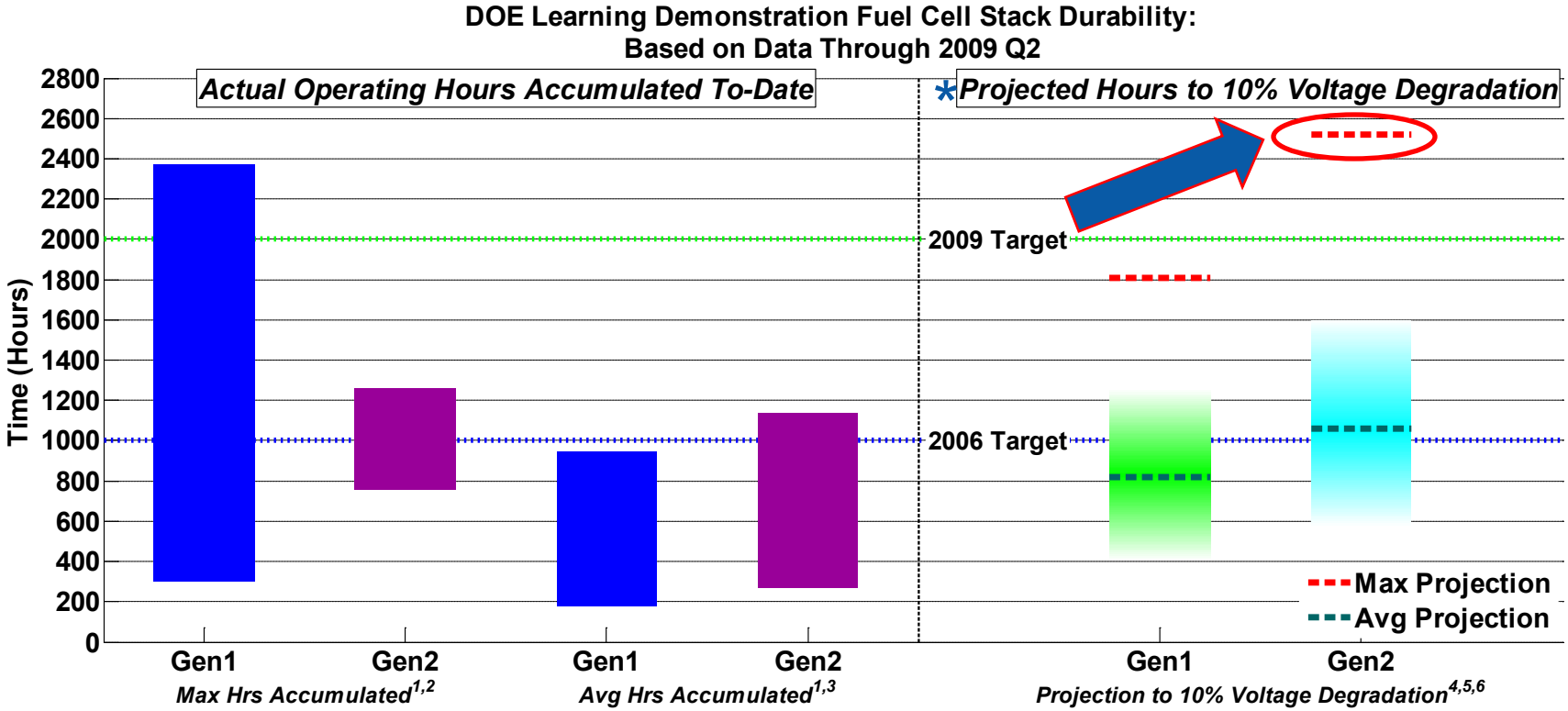
Vehicle Performance Metrics	Gen 1 Vehicle	Gen 2 Vehicle	2009 Target
Fuel Cell Stack Durability			**2000 hours**
Max Team Projected Hours to 10% Voltage Degradation	**1807 hours**	**2521 hours**	
Average Fuel Cell Durability Projection	821 hours	1062 hours	
Max Hours of Operation by a Single FC Stack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

Outside review panel

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



(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.

NREL CDP01
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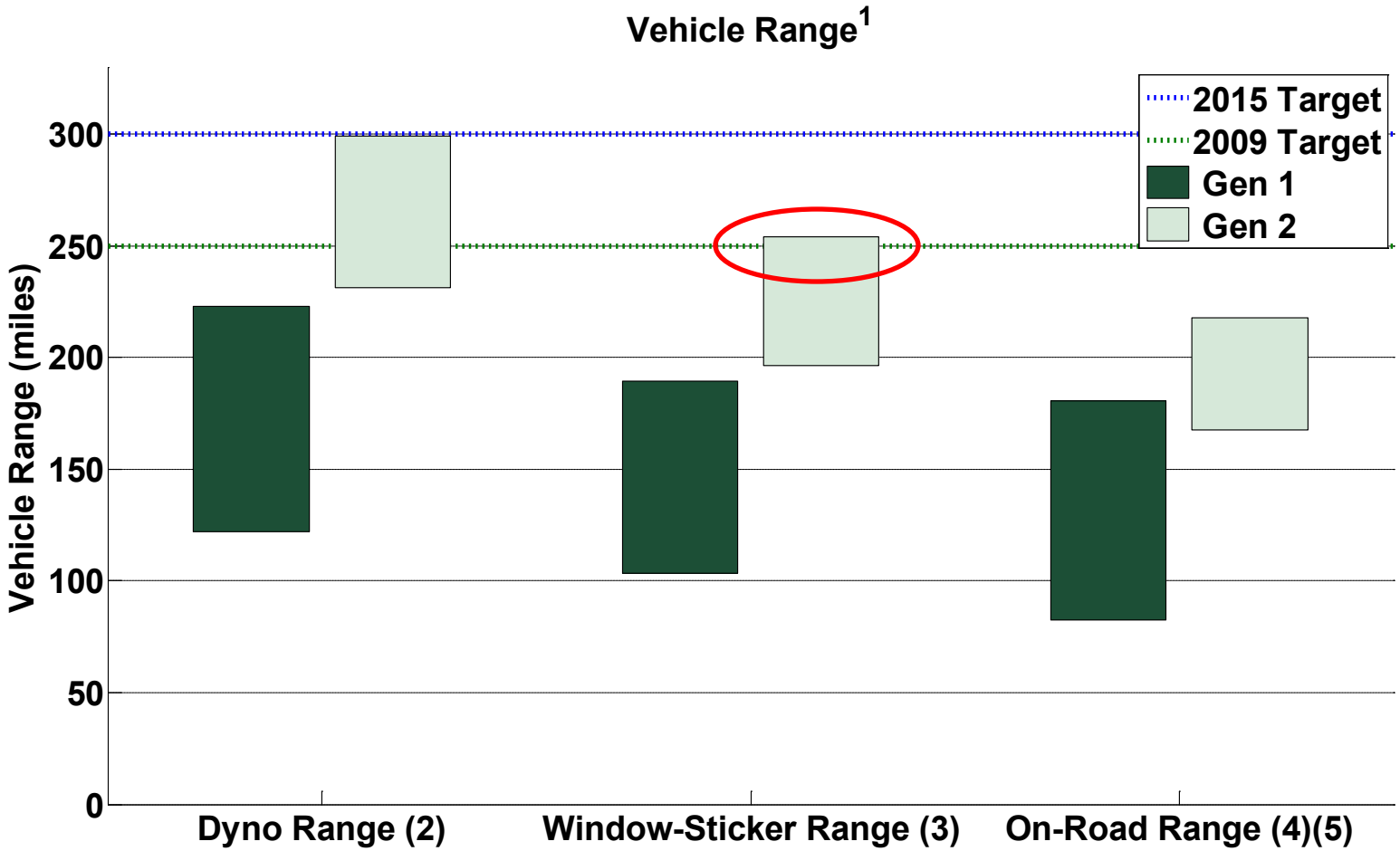
* Durability is defined by DOE as projected hours to 10% voltage degradation

Spring 2010

2) Vehicle Range Achieved 2009 Target of 250 Miles with Gen 2 Adjusted Fuel Economy (2010 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 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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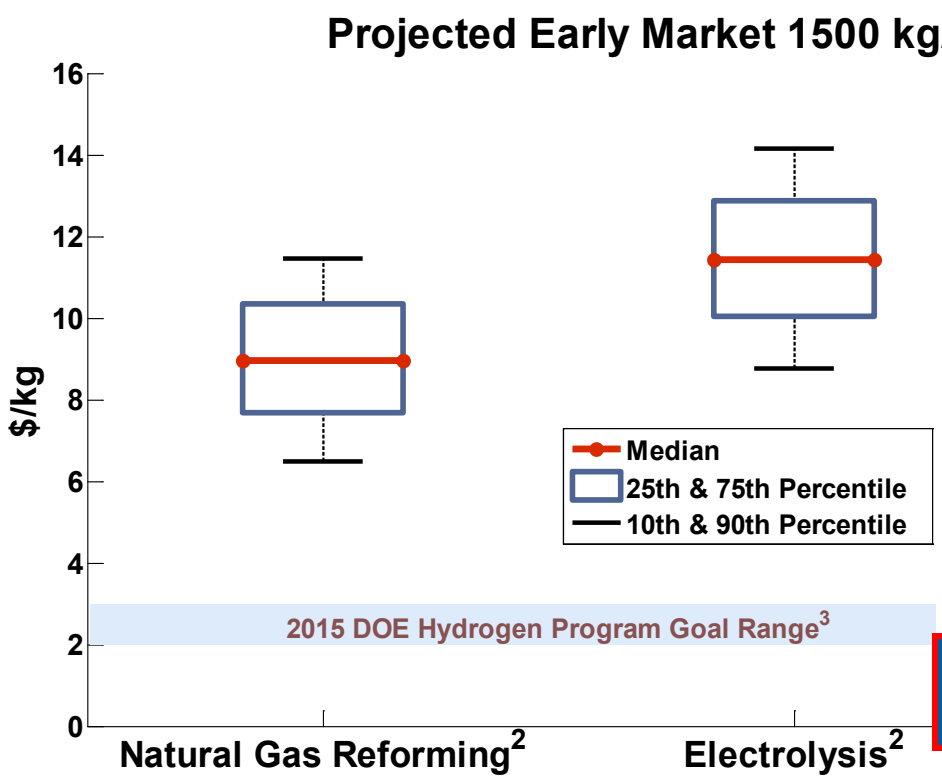
3) Projected Early Market H_2 Production Cost from Learning Demo Energy Partners' Inputs (2010 AMR)



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)

REVIEWER-ONLY SLIDES

Responses to Previous Year (FY10) Reviewers' Comments

Three Related comments about promotion of results more broadly:

Q: "Need better marketing and promotion of the program and results to the media, both public and government"

Q: "There should be an expanded presentation of results from primarily fuel cell events to broader auto events, government conferences, etc."

Q: "Need to promote findings and activities more. If the public and/or government knew of the scope of this project and results and data found, it would greatly help industry fight critics and skeptics who write off FCVs. A website is not enough because most people would not know to look there."

Response:

A: Our role in this project is to objectively evaluate the performance and progress of FCEVs and H2 stations and make the information publicly available. We do this at least 3 times a year at FCHEA, FC Seminar, and AMR, but also periodically at EVS, JHFC, and CARB meetings. *We would be interested to hear specific ideas or venues that we could use to further broadcast the results.*

Q: "A final project report dissemination plan should be developed. The plan should include a presentation at the IPHE and IEA."

A: If invited and supported by DOE we would be pleased to present at IPHE and IEA.

Q: "Battery analysis could be improved. The life-cycle cost analysis should be looked at and analyzed."

A: Our battery analysis intentionally limited, as evaluation of battery performance is not one of the objectives of this project. We are now collaborating with NREL's transportation center on analyzing battery degradation analogous to our FC evaluation.

Publications and Presentations

(Since FY10 AMR, Key Text in Bold)

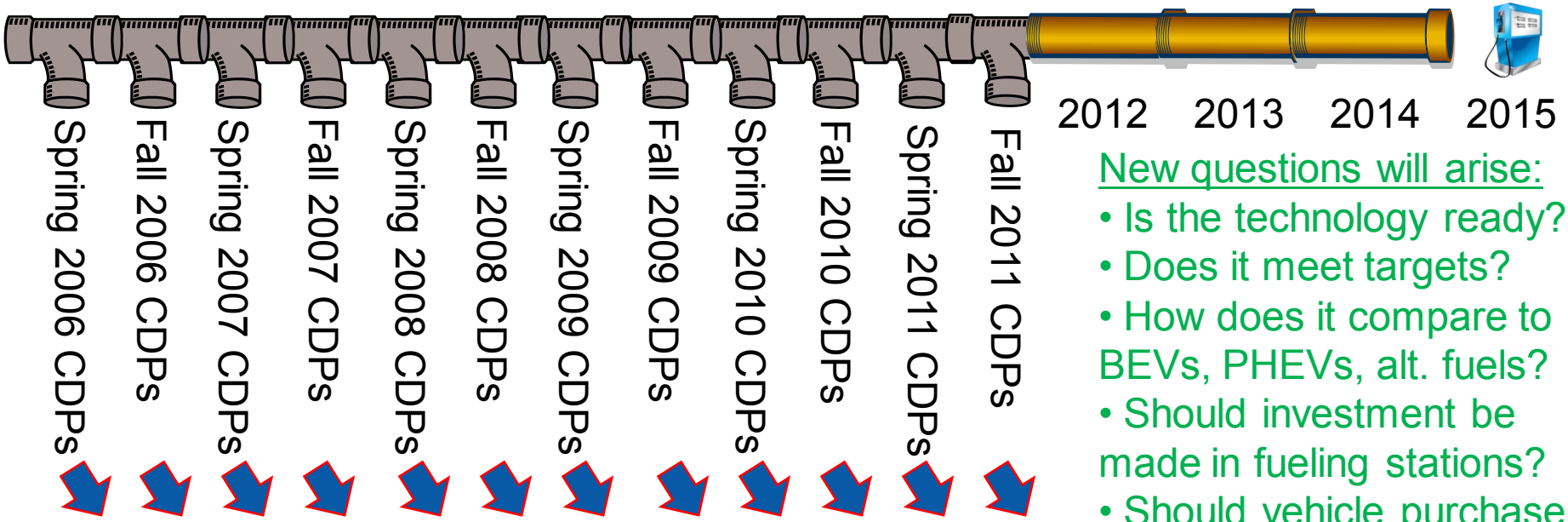
1. Wipke, K., presentation of Learning Demonstration results to **FreedomCAR and Fuels Hydrogen Storage Tech Team**, April 2011. (presentation)
2. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Status of U.S. FCEV and Infrastructure Learning Demonstration Project," Japan Hydrogen Fuel Cell (**JHFC**) Demonstration Project, March 2011 (presentation)
3. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "**Spring 2011 Composite Data Products** for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, published March 2011. (presentation)
4. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., Ainscough, C., Saur, G., "Next Steps for the FCEV Learning Demonstration Project," **Fuel Cell & Hydrogen Energy Conference (FCHEA)**, Washington, DC, February, 2011. (presentation)
5. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., "Entering a New Stage of Learning from the U.S. Fuel Cell Electric Vehicle Demonstration Project," prepared for the 25th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium (**EVS-25**), Shenzhen, China, November 2010. (paper and presentation).
6. Kurtz, J., Wipke, K., Eudy, L., Sprik, S., Ramsden, T., "Fuel Cell Technology Demonstrations and Data Analysis," draft submitted to editors of **CRC book entitled Hydrogen Energy and Vehicle Systems**, November, 2010. (book chapter)
7. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., **2010 Annual Progress Report** for NREL's "Controlled Hydrogen Fleet and Infrastructure Analysis Project," Section VIII.1, November 2010. (paper)
8. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "U.S. Fuel Cell Electric Vehicle Demonstration Project 2010 Status Update," presented at the **2010 Fuel Cell Seminar and Exposition**, San Antonio, TX, October 2010. (presentation)
9. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "**Fall 2010 Composite Data Products** for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, published September 2010. (presentation)
10. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., "**Learning Demonstration Interim Progress Report – July 2010**," NREL/TP-560-49129, September 2010. (paper)
11. Wipke, K., Sprik, S., Kurtz, J., Ramsden, T., and Garbak, J., "DOE's National Fuel Cell Vehicle Learning Demonstration Project – NREL's Data Analysis Results," **Electric and Hybrid Vehicles, Power Sources, Models, Sustainability, Infrastructure and the Market, Chapter 12**, ISBN 978-0-444-53565-8, NREL/CH-560-47111, Elsevier B.V., August 2010. (paper)

Critical Assumptions and Issues

- **Issue:** After the Learning Demonstration Concludes, there Will Be a Gap in Public Knowledge on Actual FCEV and H_2 Station Performance and Status
  - *[See next slide for graphical representation]*
  - Many critical questions will remain unanswered before vehicles enter the market in ~2015
  - Information flow on technology progress and benefits must be continuous to build market confidence
  - Decision makers (private & public) may withhold investment without a credible objective source to provide actual technology progress and benefits
- **Proposed solution:**
  - We will work with our industry partners to find a way to continue to provide objective information to decision makers in the future

Issue (cont.) -- Learning Demo Feeds Pipeline of Objective Info for Decision Makers; Potential Data Gap Approaching

Learning Demo Ends in 2011



New questions will arise:

- Is the technology ready?
- Does it meet targets?
- How does it compare to BEVs, PHEVs, alt. fuels?
- Should investment be made in fueling stations?
- Should vehicle purchase incentives be provided?

OBJECTIVE CREDIBLE EVALUATIONS LEAD TO INFORMED DECISIONS

POTENTIAL DELAYS OF INVESTMENT BY DECISION-MAKERS DUE TO UNCERTAINTY