

Controlled Hydrogen Fleet and Infrastructure Analysis

Project ID#
tv_01_wipke



**2009 U.S. DOE
Hydrogen Program and
Vehicle Technologies
Program Annual Merit
Review and Peer
Evaluation Meeting**

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Ramsden**

**May 20, 2009
Washington, DC**

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

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

- Objectives

- Validate H₂ FC Vehicles and Infrastructure in Parallel
- Identify Current Status and Evolution of the Technology

- Relevance

- Objectively Assess Progress Toward Technology Readiness
- Provide Feedback to H₂ Research and Development

Key Targets

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



Solar Electrolysis Station, Sacramento, CA

Photo: NREL

Project Overview

Timeline

- Project start: FY03
- Project end: FY10
- ~80% of Task III complete (see timeline slide)

Budget

- Context: Overall DOE project is ~\$170M over 5 years
 - Equal investment by industry
- NREL funding prior to FY08 : \$3042K
- NREL FY08 funding: \$900K
- NREL FY09 funding: \$700K

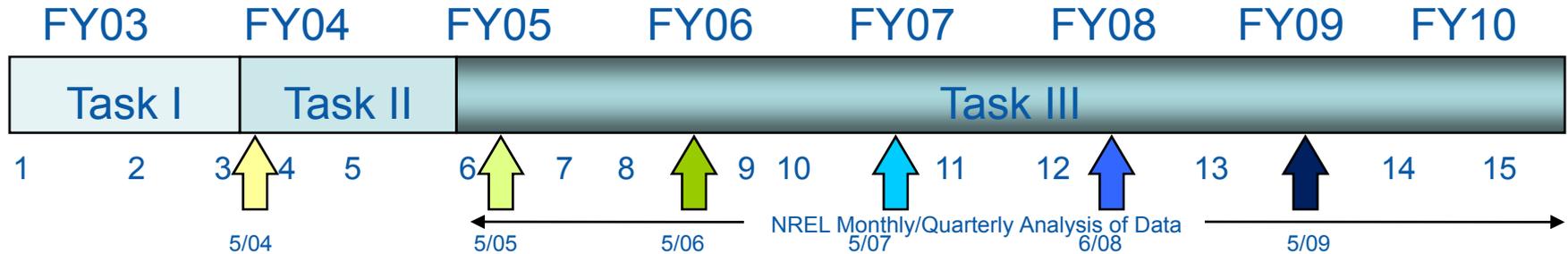
Partners

- See partner slide

Tech. Val. Barriers

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

Project Timeline and Major Milestones



Task I – Project Preparation [100% Complete]

- 1 Support development of RFP, statement of objectives (Appendix C)
- 2 Bidder's meeting in Detroit – launch of RFP
- 3 Create data analysis plan and presentation for discussion with industry

Task II – Project Launch [100% Complete]

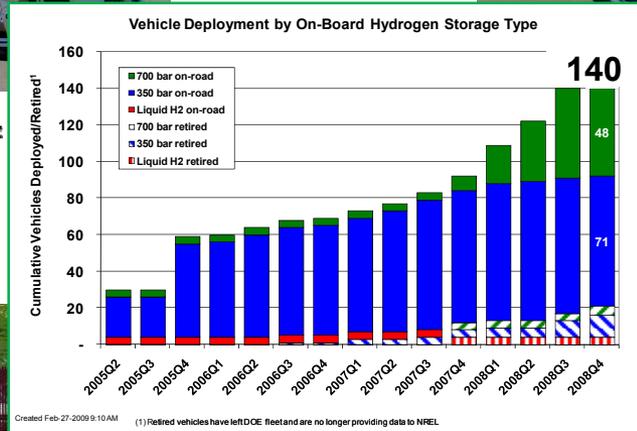
- 4 Announcement of successful bidders (4/04)
- 5 Kick-off meetings and cooperative agreement awards

Task III – Data Analysis and Feedback to R&D activities (partial list) [80% 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 Decision to proceed with Phase 2 of the Learning Demonstration

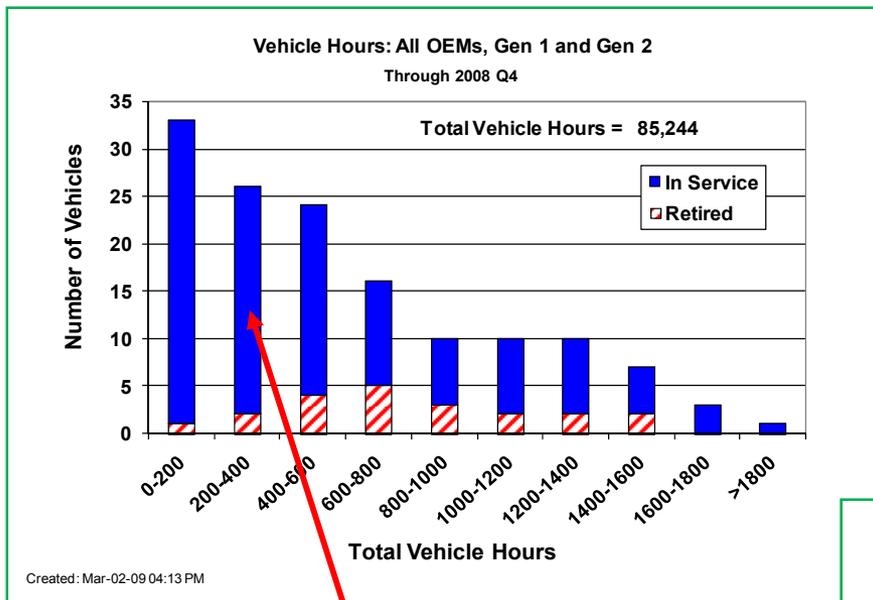
Industry Partners: 4 Automaker/Energy-Supplier Teams; Gen 2 Fleet Is Now Fully Deployed, Some Vehicles Retired



21 vehicles retired
119 still on road

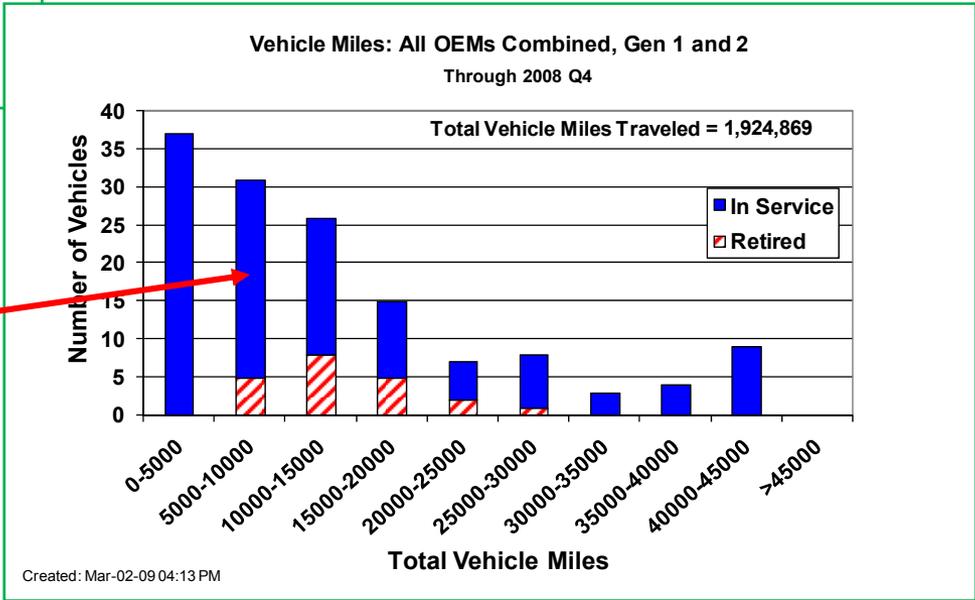


DOE Learning Demo Fleet Has Surpassed 85,000 Vehicle Hours and 1.9 Million Miles



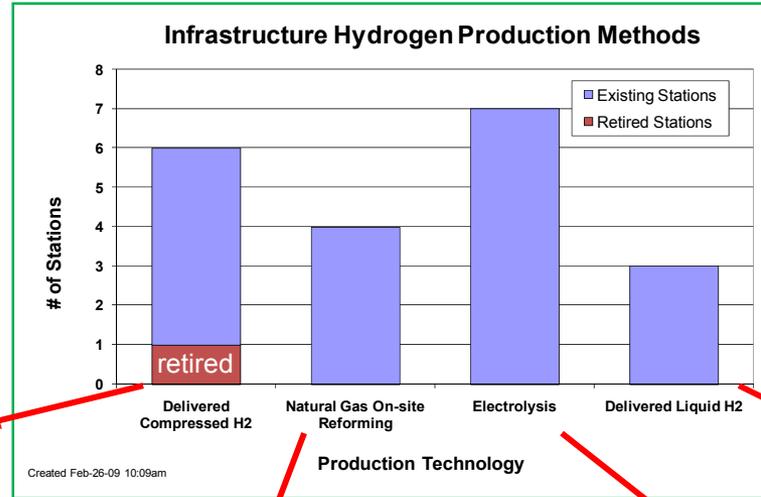
Some Gen 1 vehicles have now been retired (red bars)

Gen 2 vehicles make up most of 2nd bulge at low hours/miles

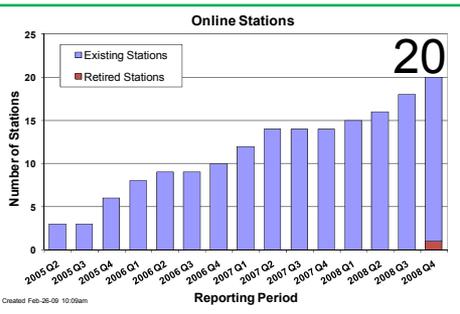


Majority of Project's Fixed Infrastructure to Refuel Vehicles Has Been Installed – Examples of 4 Types

**Mobile Refueler
Sacramento, CA**



**Delivered Liquid, 700 bar
Irvine, CA**



**Steam Methane Reforming
Oakland, CA**



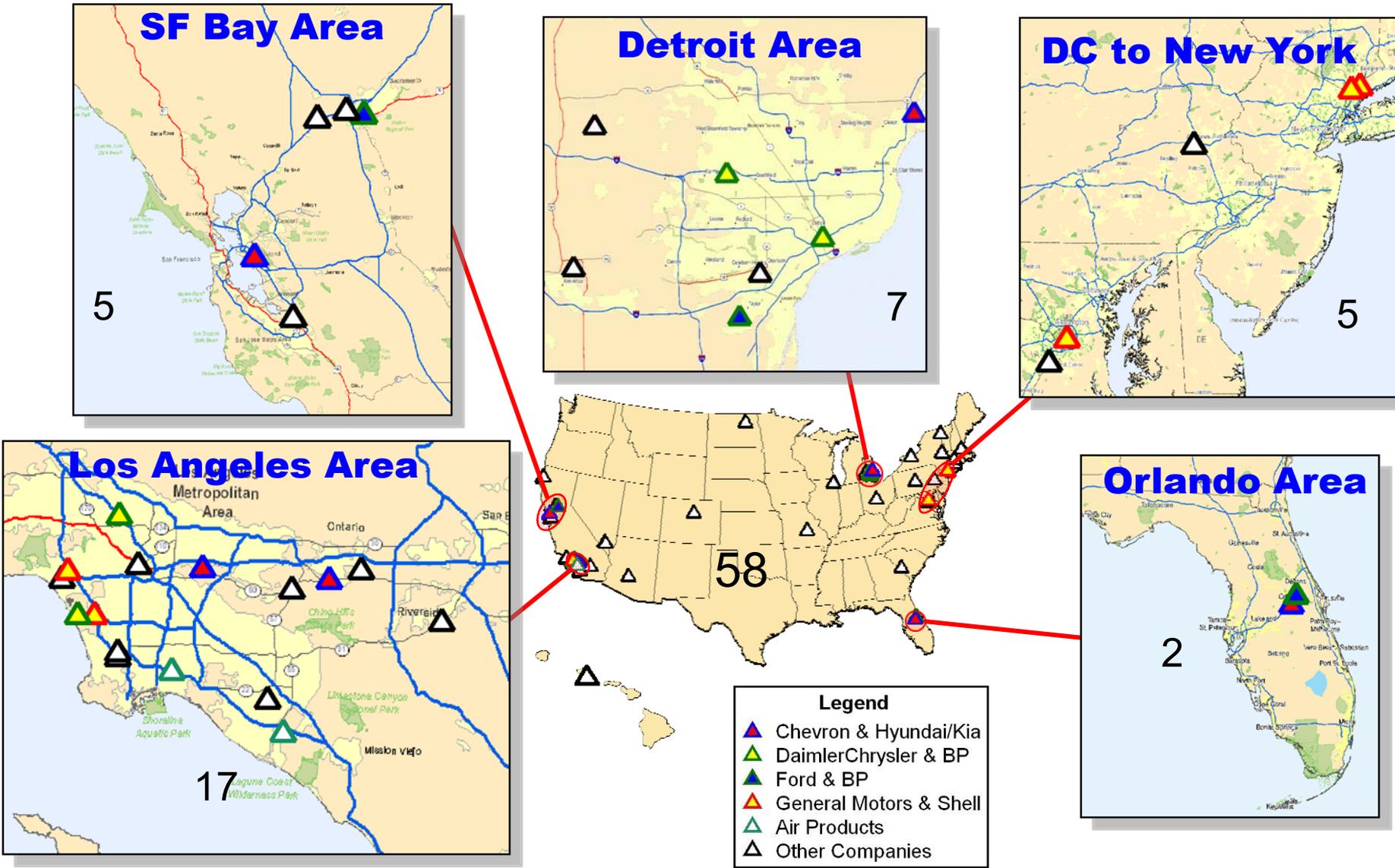
**Water Electrolysis
Santa Monica, CA**



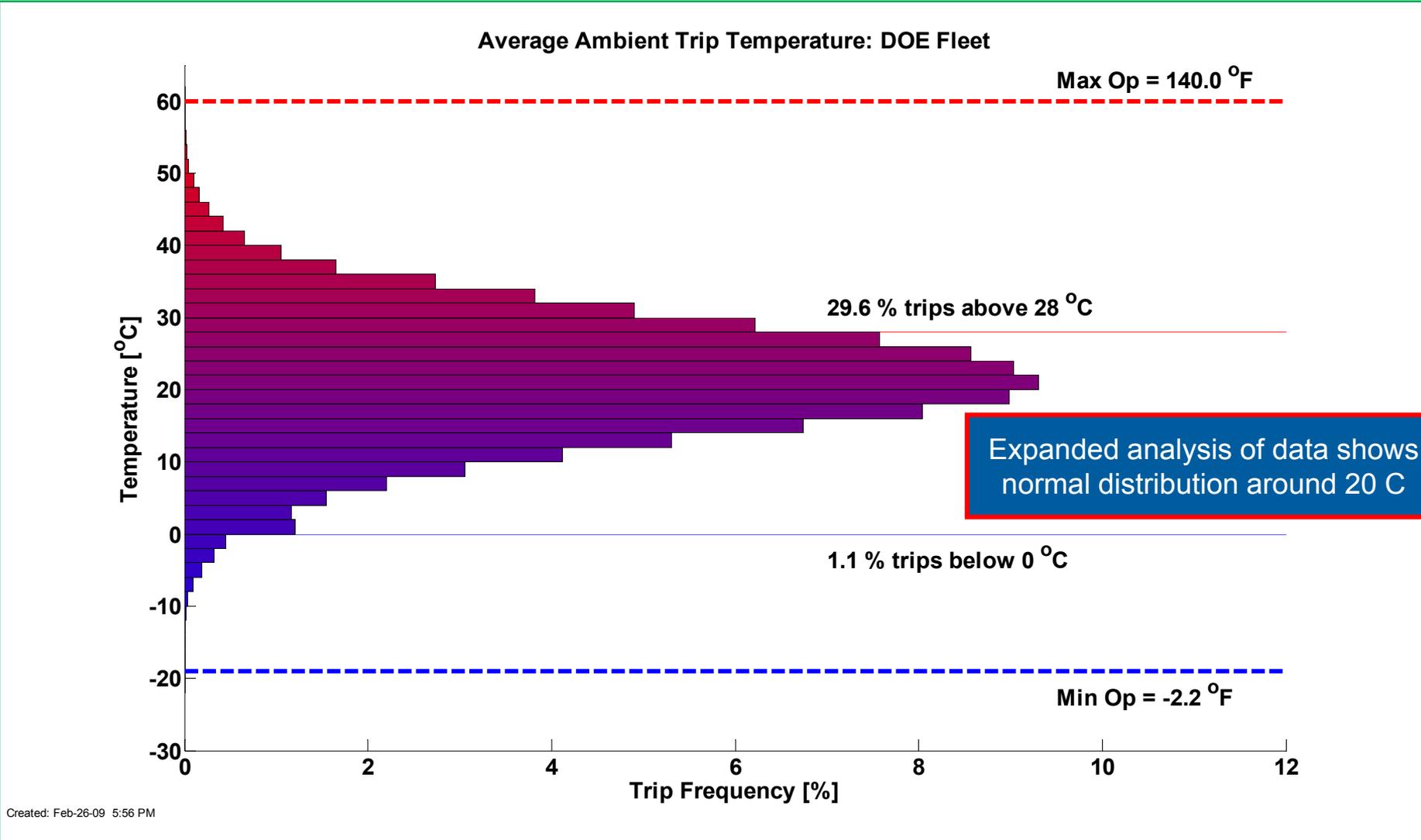
**Total of 90,000 kg H₂
produced or dispensed**

**Stations added since June 2008:
Burbank, Long Beach, Ardsley, LAX-east
20 stations now deployed through Dec.**

Refueling Stations Test Performance in Various Climates; Learning Demo Stations Comprise ~1/3 of all U.S. Stations



Distribution of Average Ambient Temperature During Vehicle Operation



Project Approach

- Provide facility and staff for securing and analyzing industry sensitive data
 - NREL Hydrogen Secure Data Center (HSDC)
- Perform analysis and simulation 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)



Approach: Providing Data Analysis and Results for Both the Public and the Industry Project Teams

Hydrogen Secure Data Center (HSDC)

Raw Data,
Reports



- Located at NREL: Strictly Controlled Access
- Detailed Analyses, Data Products, Internal Reports



Composite Data Products

- Aggregate data results for public
- No confidential information

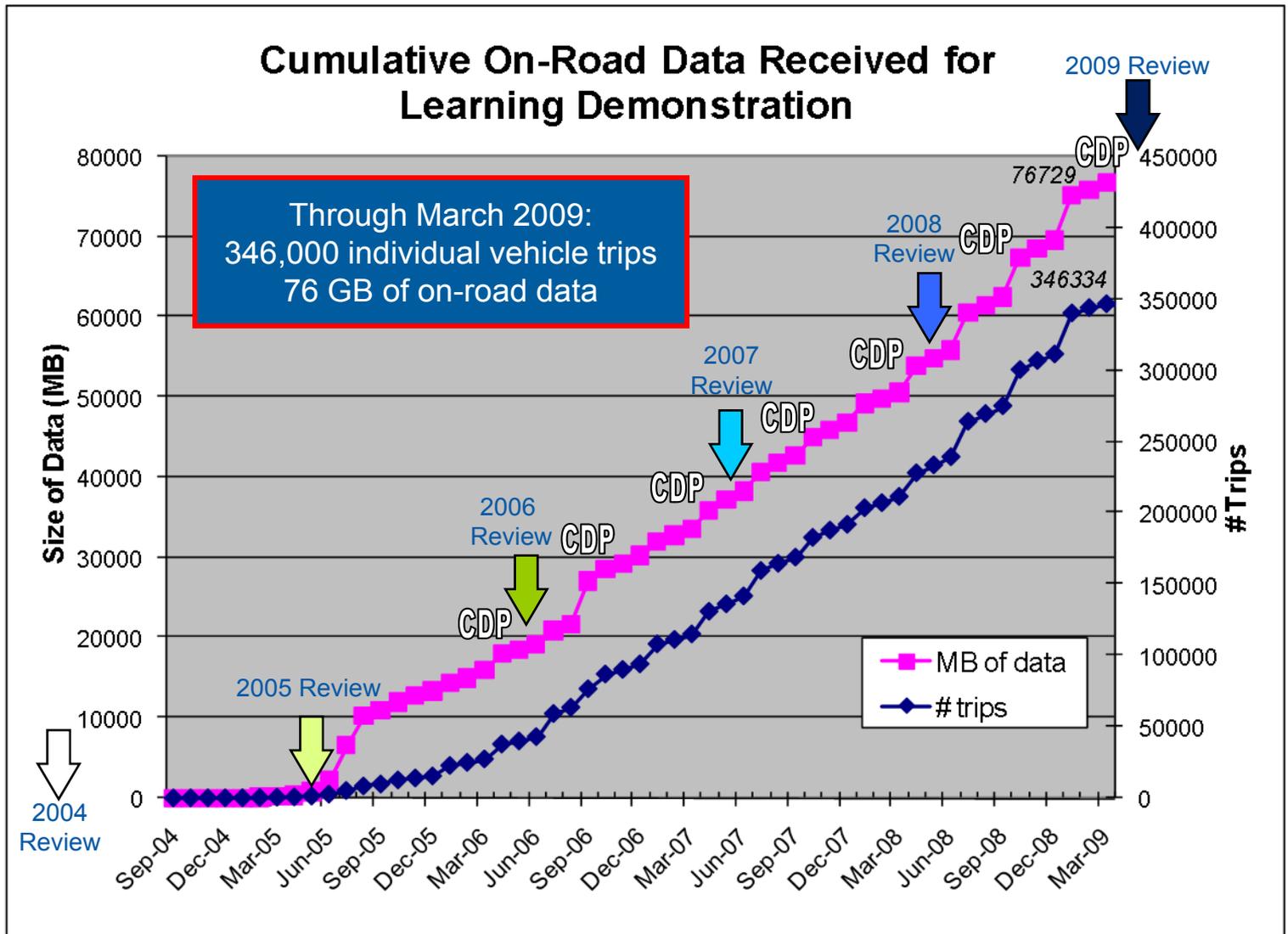
http://www.nrel.gov/hydrogen/cdp_topic.html

Detailed Data Products

- Only shared with company/team that originated the data

DDPs now provided at time of CDP review

Accomplishment: 15 Quarters of Data Analyzed to Date, Two New Sets of Composite Data Products Published

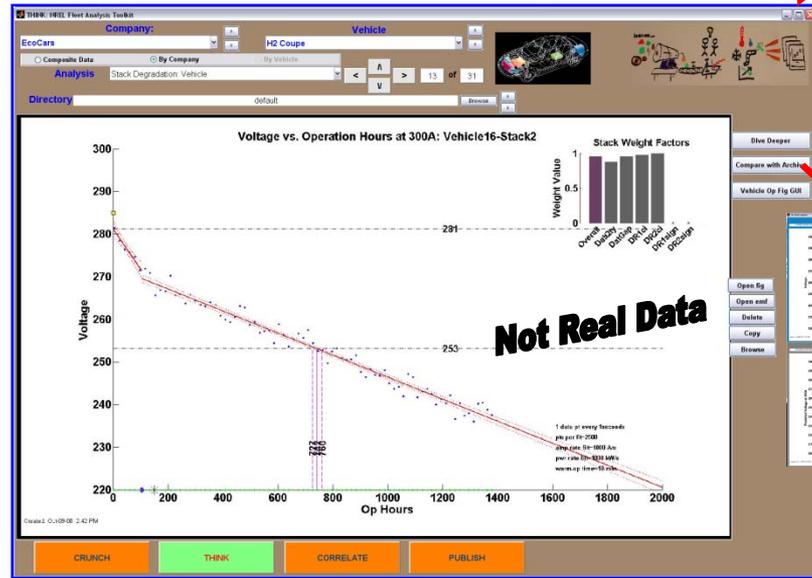


CDP = Composite Data Products Published

Accomplishment: Expanded NREL's Data Analysis Tool – Fleet Analysis Toolkit (FAT)

This screenshot shows the main configuration window of the NREL Fleet Analysis Toolkit. It includes sections for 'Processing to Perform' (New CD, Selected Below), 'Archive Previous Results', 'Raw Data Conversion', 'Fuel Economy' (with options for Create Raw, Trip Summary, Fill Summary, Stack Summary, Trip Length Effect, and Range), 'Range' (with options for Create Raw and Vehicle), 'Data Percent Complete', and 'Stack Degradation'. A 'GO' button is prominently displayed at the bottom right.

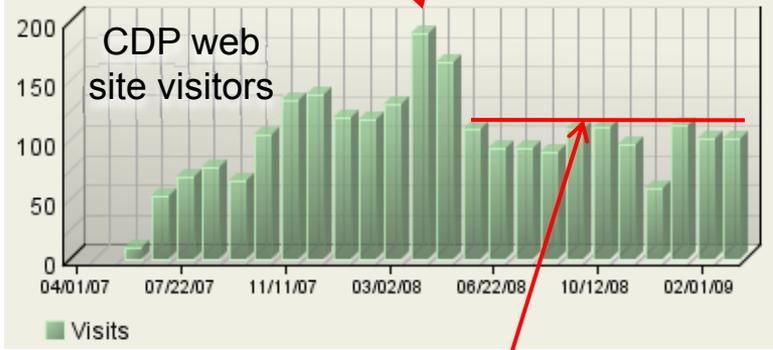
This is the splash screen for the NREL Fleet Analysis Toolkit V1.0. It features the toolkit's logo and a central image of a car. Below the image are four large buttons labeled 'CRUNCH', 'THINK', 'CORRELATE', and 'PUBLISH', which correspond to the main analysis stages.



This screenshot shows the 'CORRELATE' stage of the analysis. It includes a 'New Data Set Properties' section for 'EcoCars' and 'H2 Coupe', a 'Data Figures' section with a heatmap of 'EcoCars' time at power levels, and a 'PLS Details' section showing R-squared values (R2: 0.72, RMSEC: 0.23, RMSECV: 0.23). A 'CORRELATE' button is highlighted in green at the bottom.

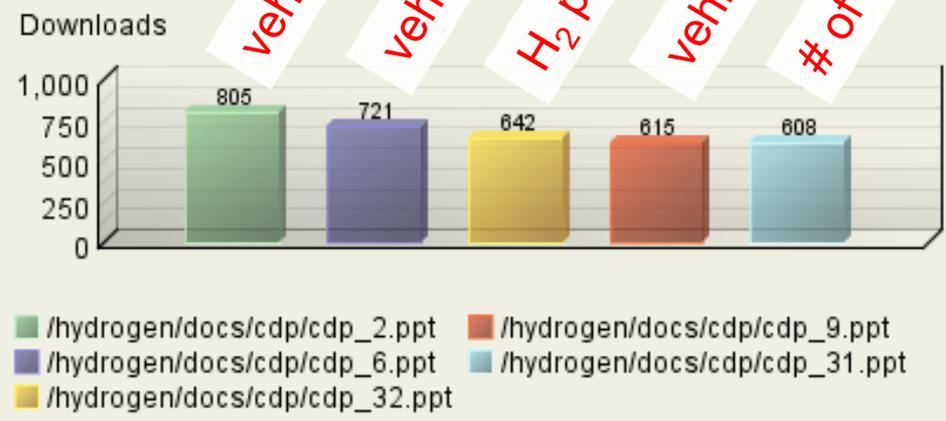
Accomplishment: Successfully Communicating Results, Papers, and Presentations Available to Public through Web Site

Spike in activity after NHA conference



Sustained activity Over the last year at ~100 visitors/month

Top 5 CDPs viewed



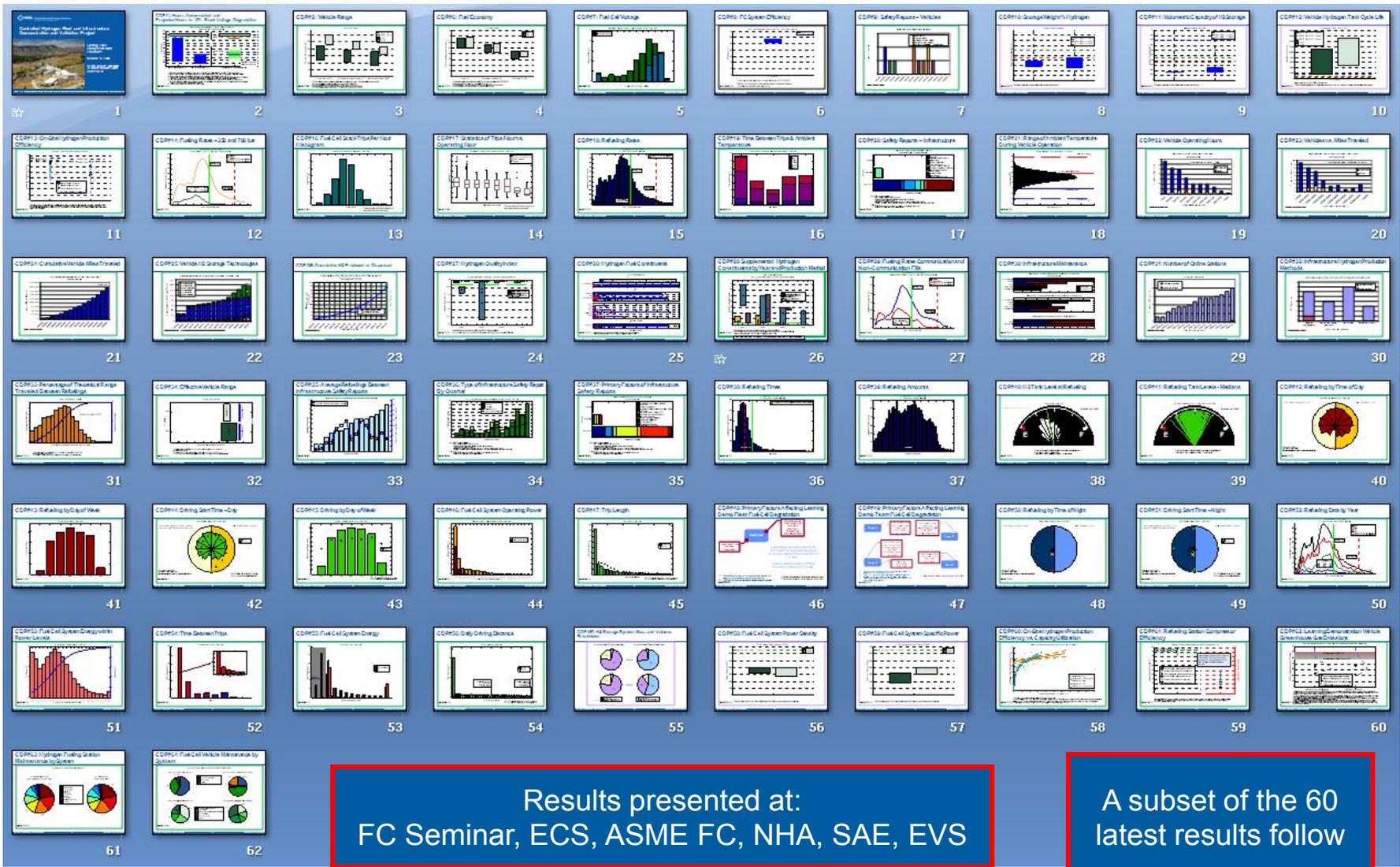
Visitor Summary	
Visitors	1,462
Visitors Who Visited Once	1,266
Visitors Who Visited More Than Once	196
Average Visits per Visitor	1.68

http://www.nrel.gov/hydrogen/cdp_topic.html

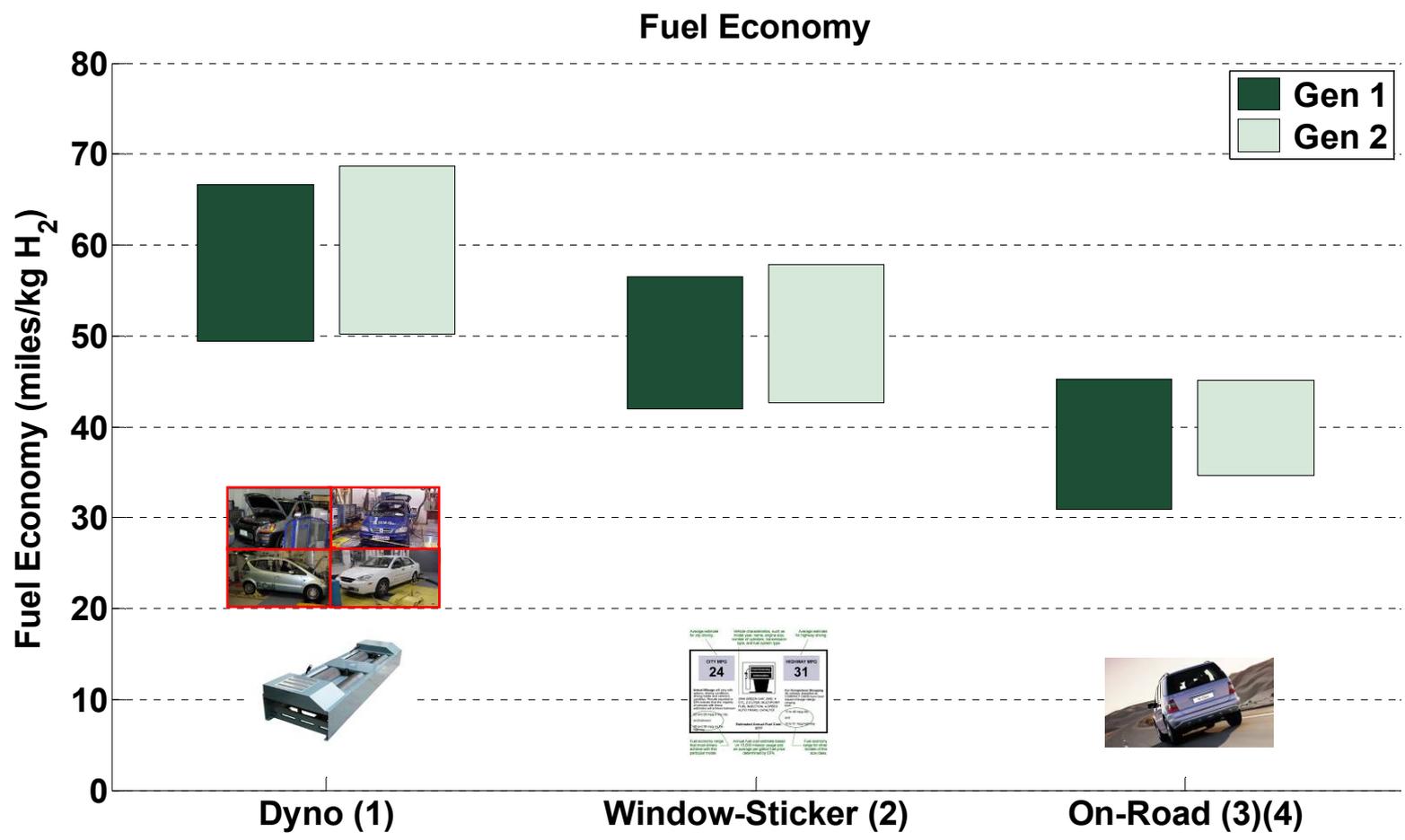
Summer 2007 Learning Demo Progress Report downloaded **2607** times (11th most popular on NREL's H₂ web site)



Accomplishment: 60 Public Composite Data Products Have Been Published; New Results and Updates Every 6 Months



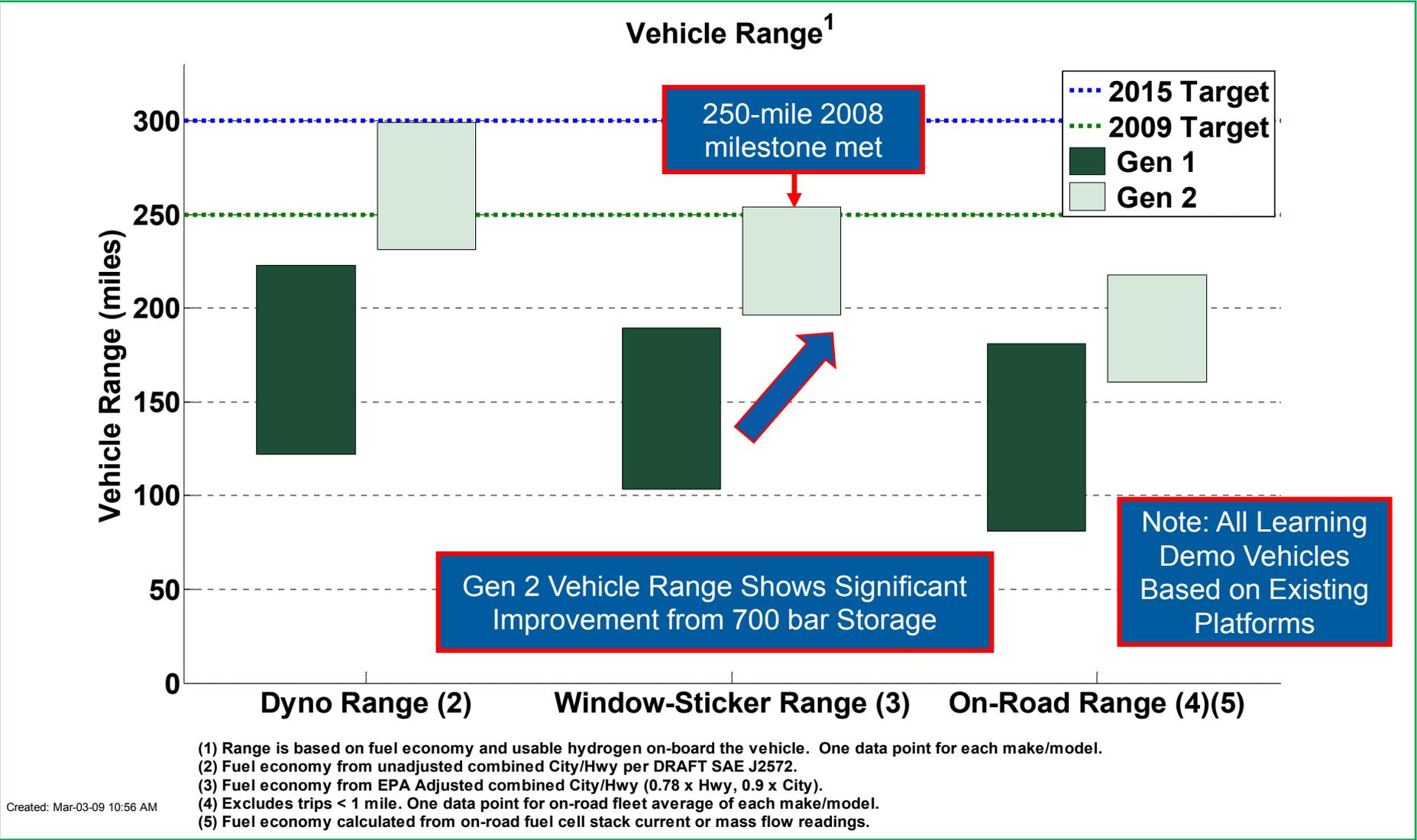
Ranges of Fuel Economy from Dynamometer and On-Road Data Similar for Gen 1 & 2



- (1) One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAE J2572.
- (2) Adjusted combined City/Hwy fuel economy (0.78 x Hwy, 0.9 x City).
- (3) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
- (4) Calculated from on-road fuel cell stack current or mass flow readings.

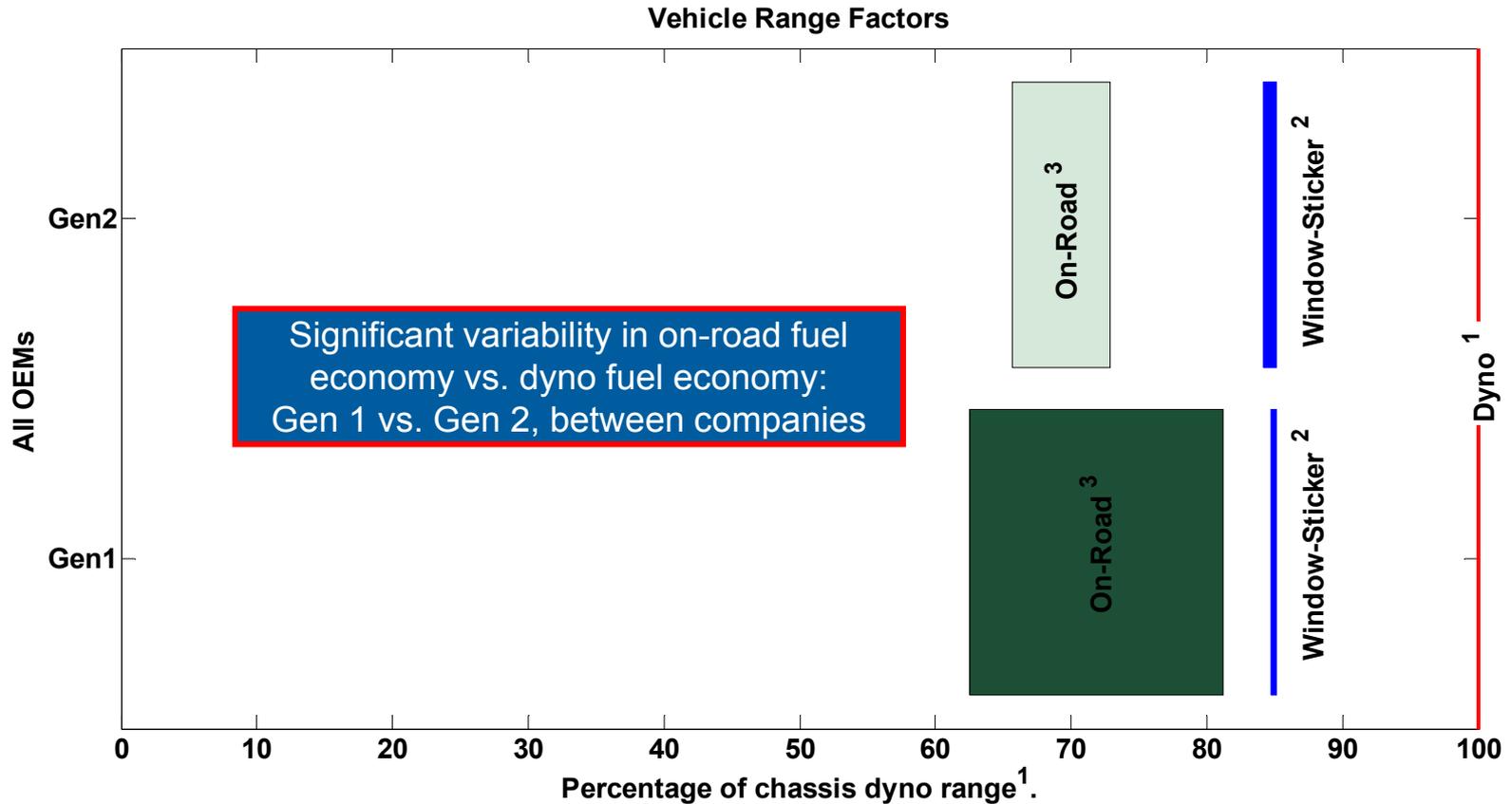
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Driving Range for Gen 1 and Gen 2 Vehicles: Based on Fuel Economy and Usable H₂



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Spread of On-Road Range from Four Teams as a Percentage of Dyno Range

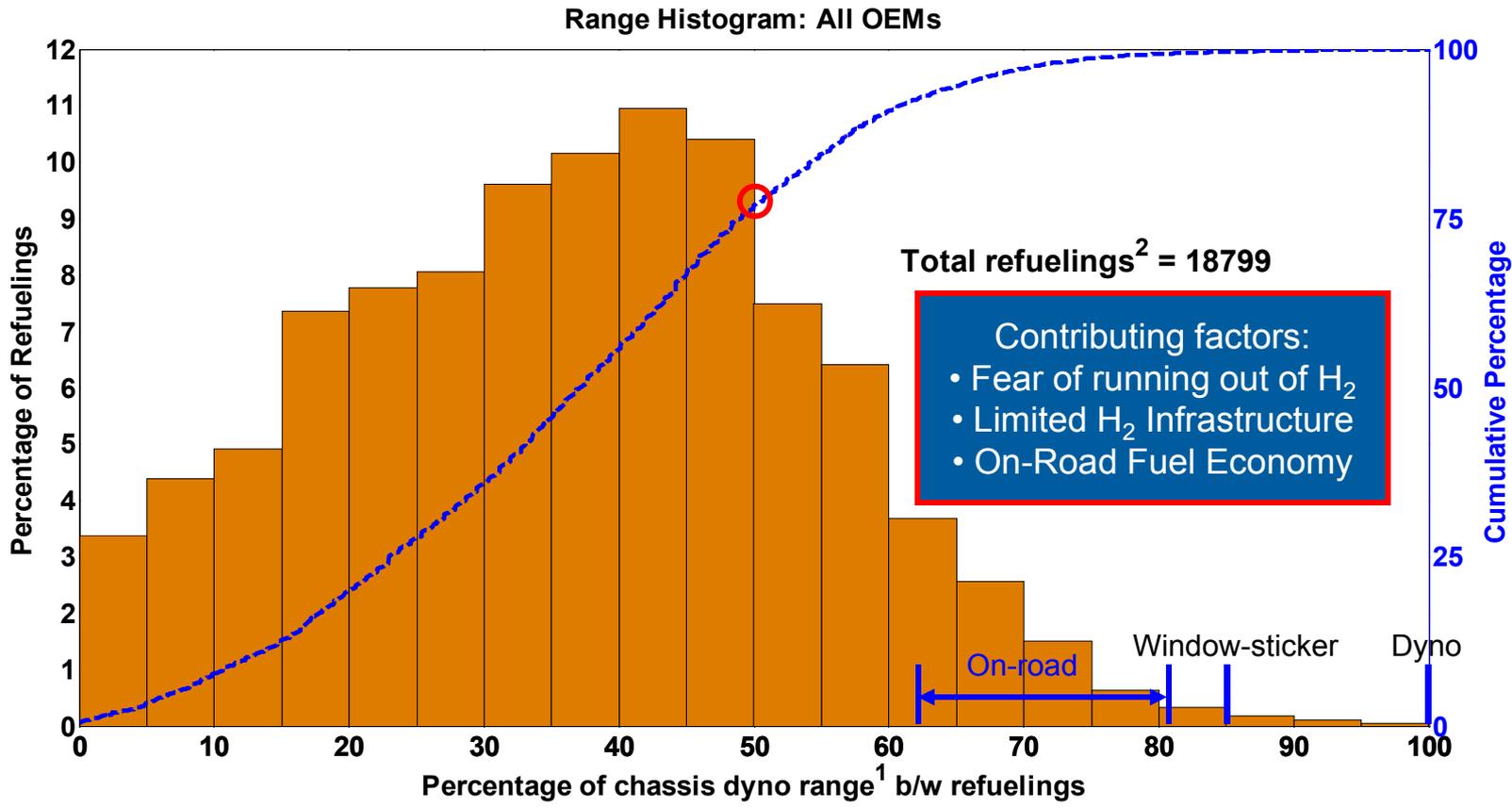


Significant variability in on-road fuel economy vs. dyno fuel economy: Gen 1 vs. Gen 2, between companies

1. Calculated using the combined City/Hwy fuel economy from dyno testing (non-adjusted) and usable fuel on board.
2. Applying window-sticker correction factors for fuel economy: 0.78 x Hwy and 0.9 x City.
3. Using fuel economy from on-road data (excluding trips > 1 mile, consistent with other data products).

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Majority (80%) of Vehicles Travel <1/2 of Dyno Range Between Refuelings



1. Range calculated using the combined City/Hwy fuel economy from dyno testing (not EPA adjusted) and usable fuel on board.
 2. Some refueling events are not detected/reported due to data noise or incompleteness.

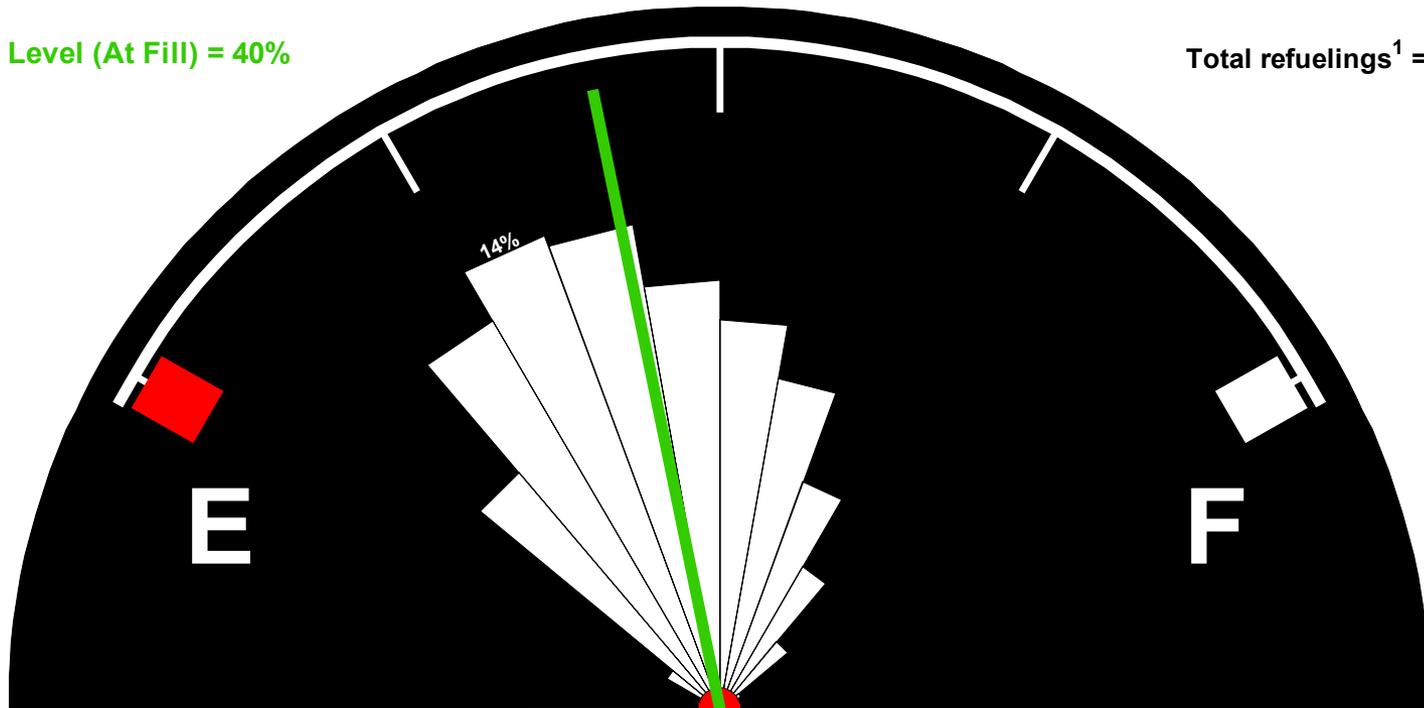
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Large Spread in H₂ Tank Level at Refueling Peak at ~1/4 Full, Median at ~3/8 Full

Tank Levels: DOE Fleet

Median Tank Level (At Fill) = 40%

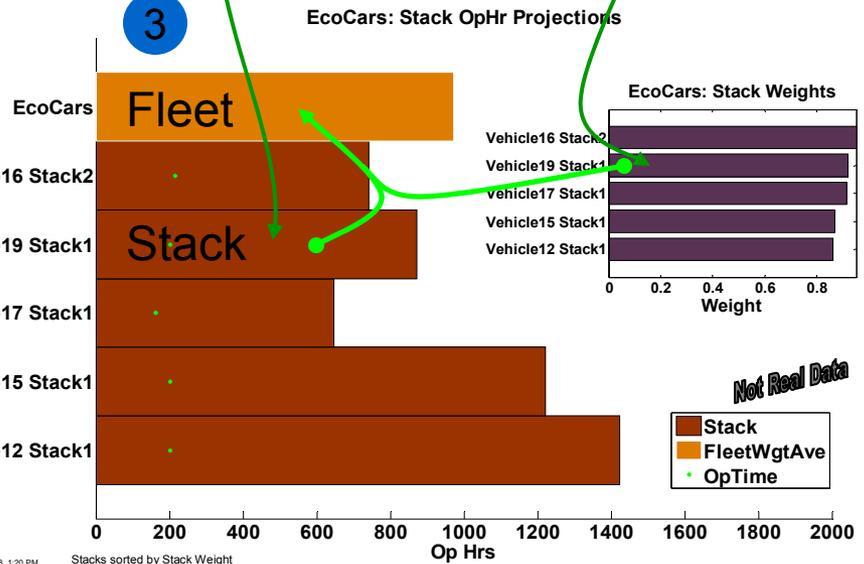
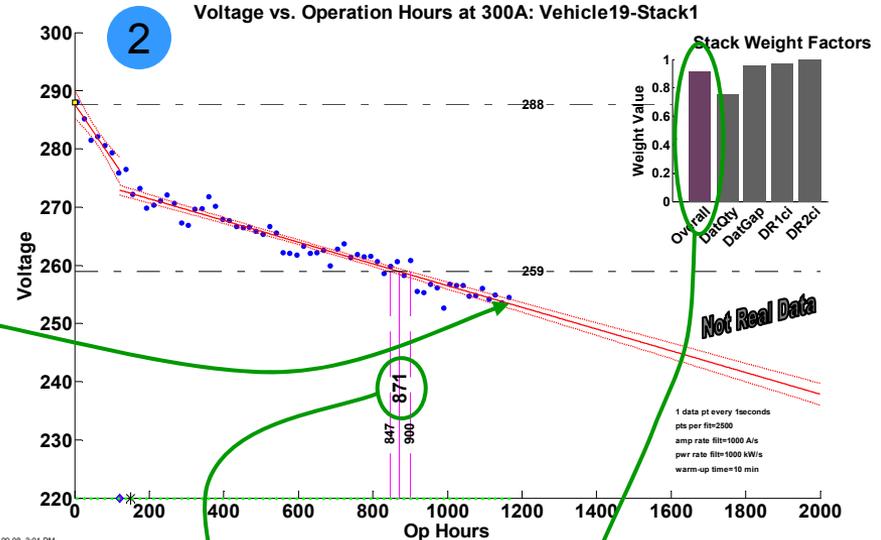
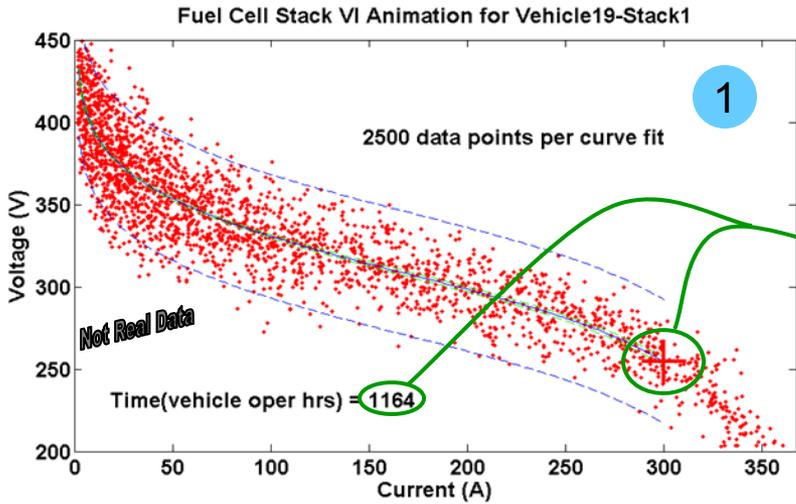
Total refuelings¹ = 20639



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.

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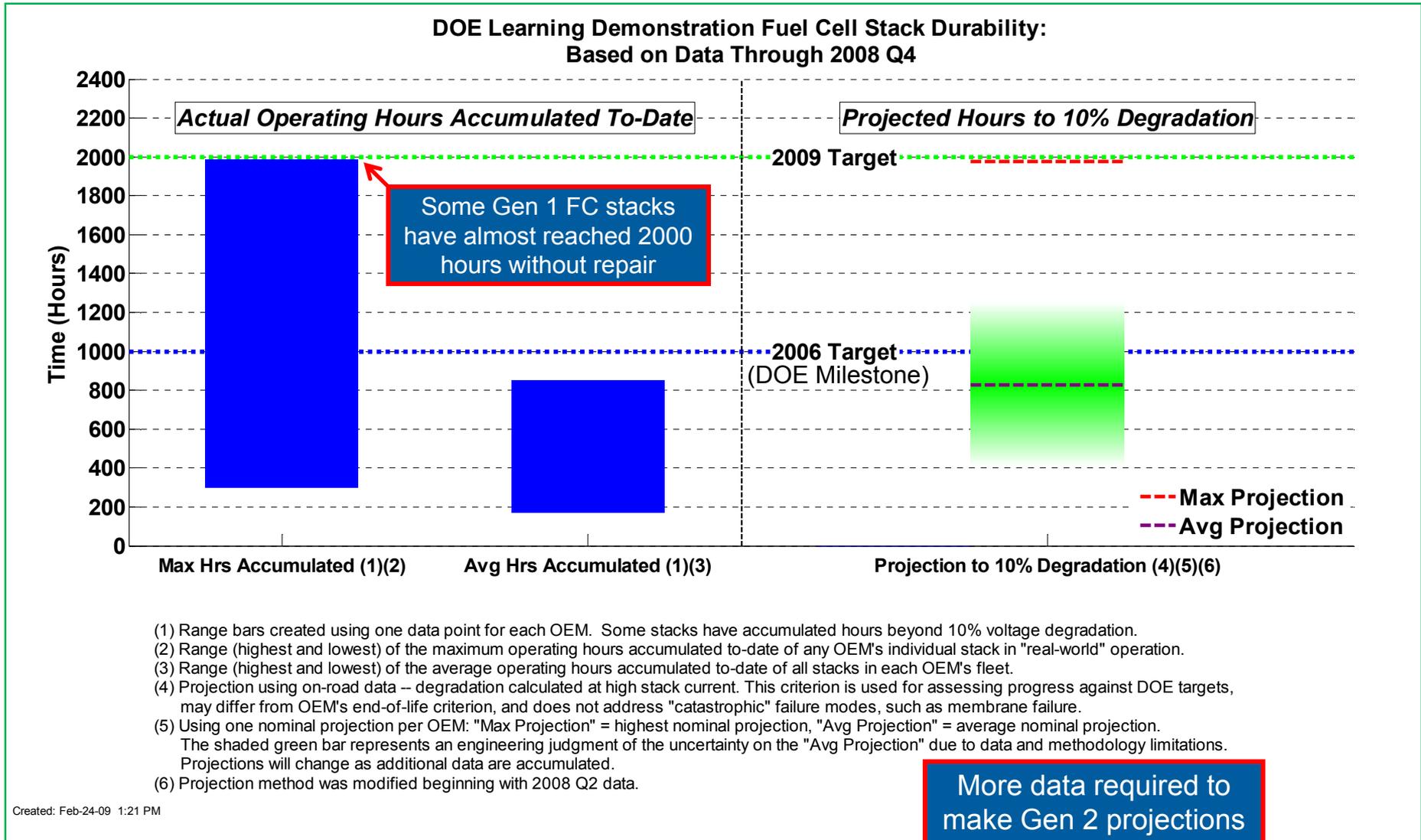
Improved Approach for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet



1. **FC Stack** voltage & current **polarization fit**
2. **FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)
3. **Fleet weighted average** using FC Stack operating hour projections and weights (based on data and confidence in fit)

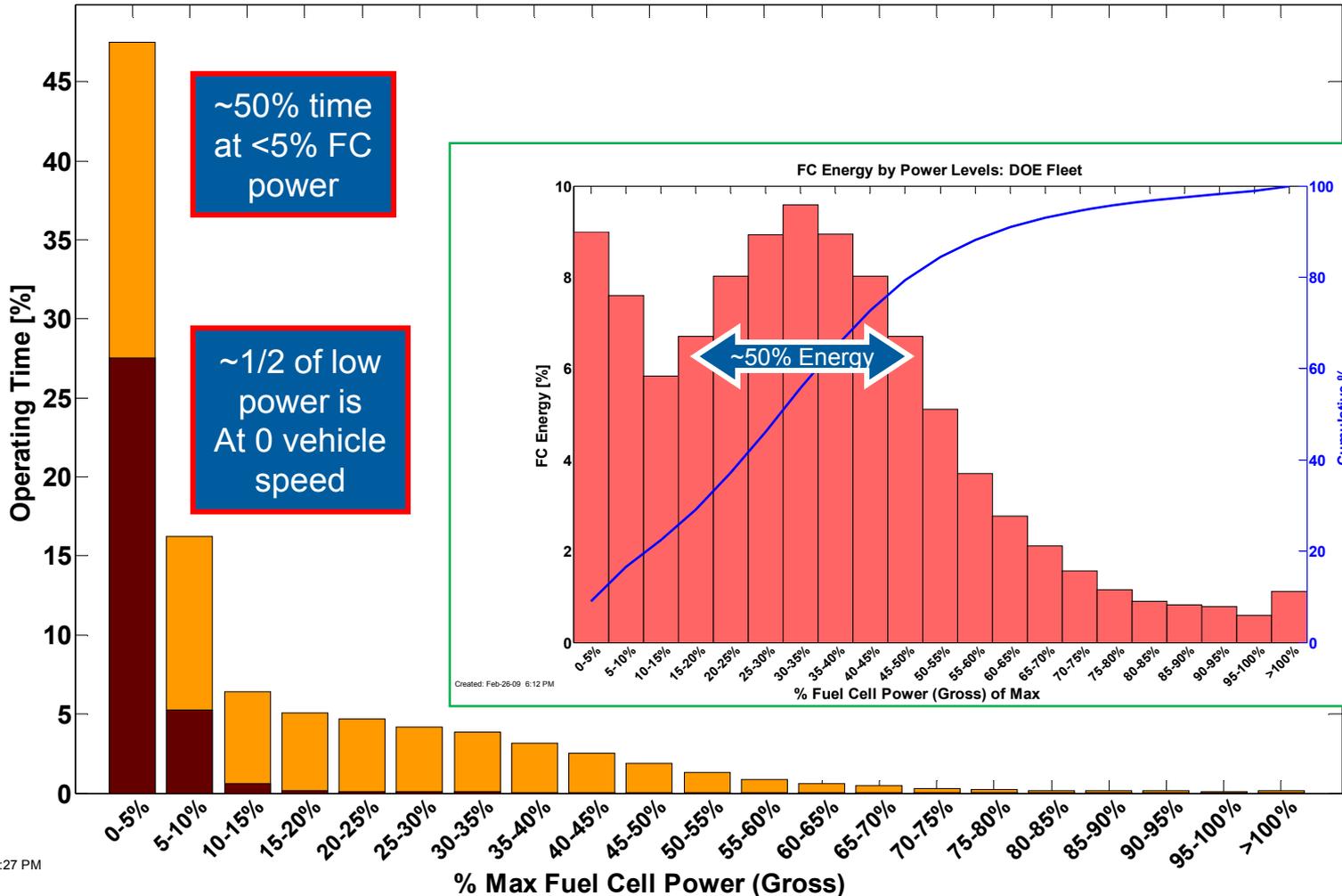
Note, 10% voltage drop is a DOE target/metric, not an indicator of end-of-life

Gen 1 Stack Operating Hours and Projected Time to 10% Voltage Drop



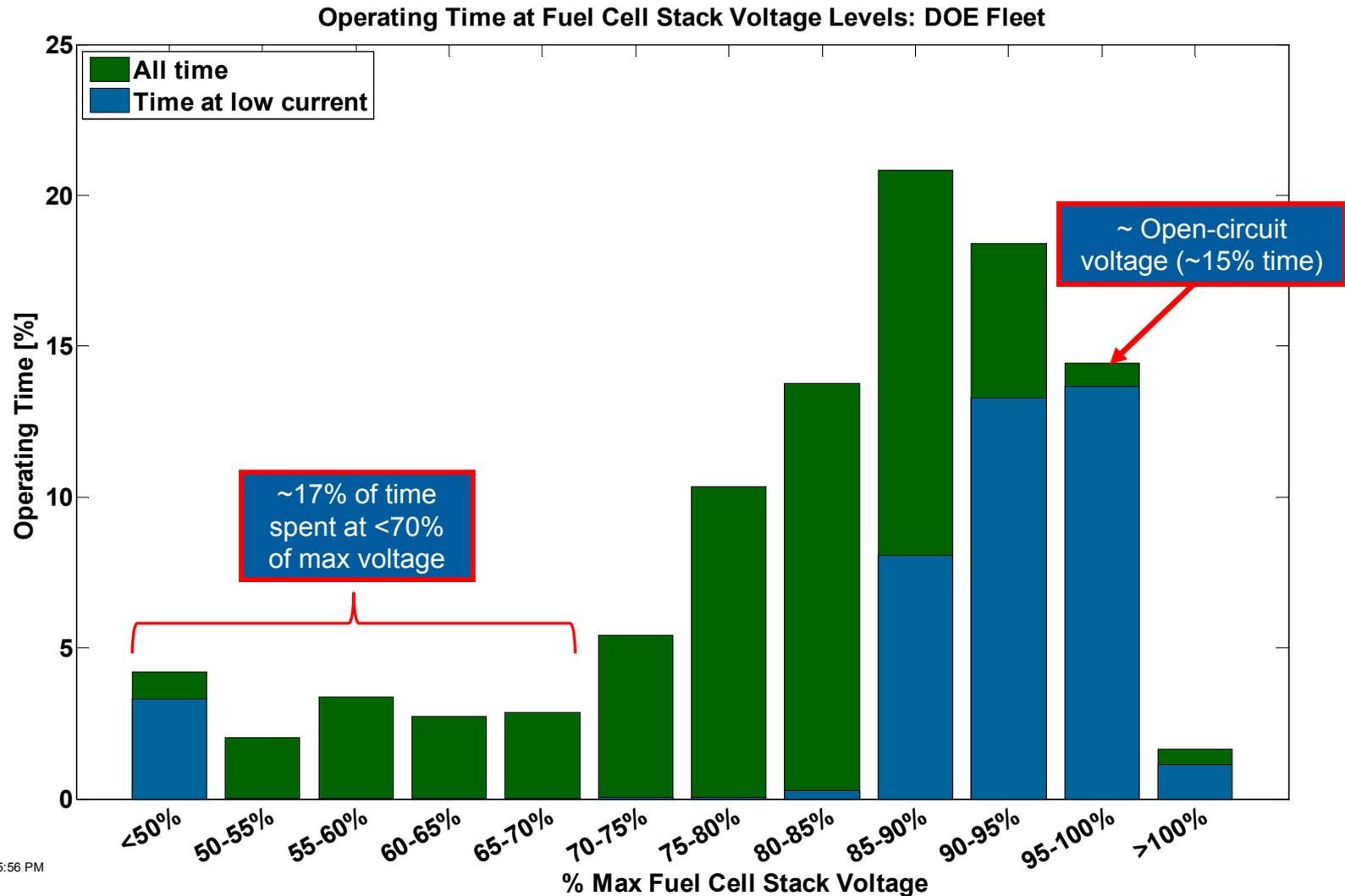
Most of FC Time is Spent at Idle, Bulk of Energy is at 20-50% Power

Time at Fuel Cell Stack Power Levels: DOE Fleet



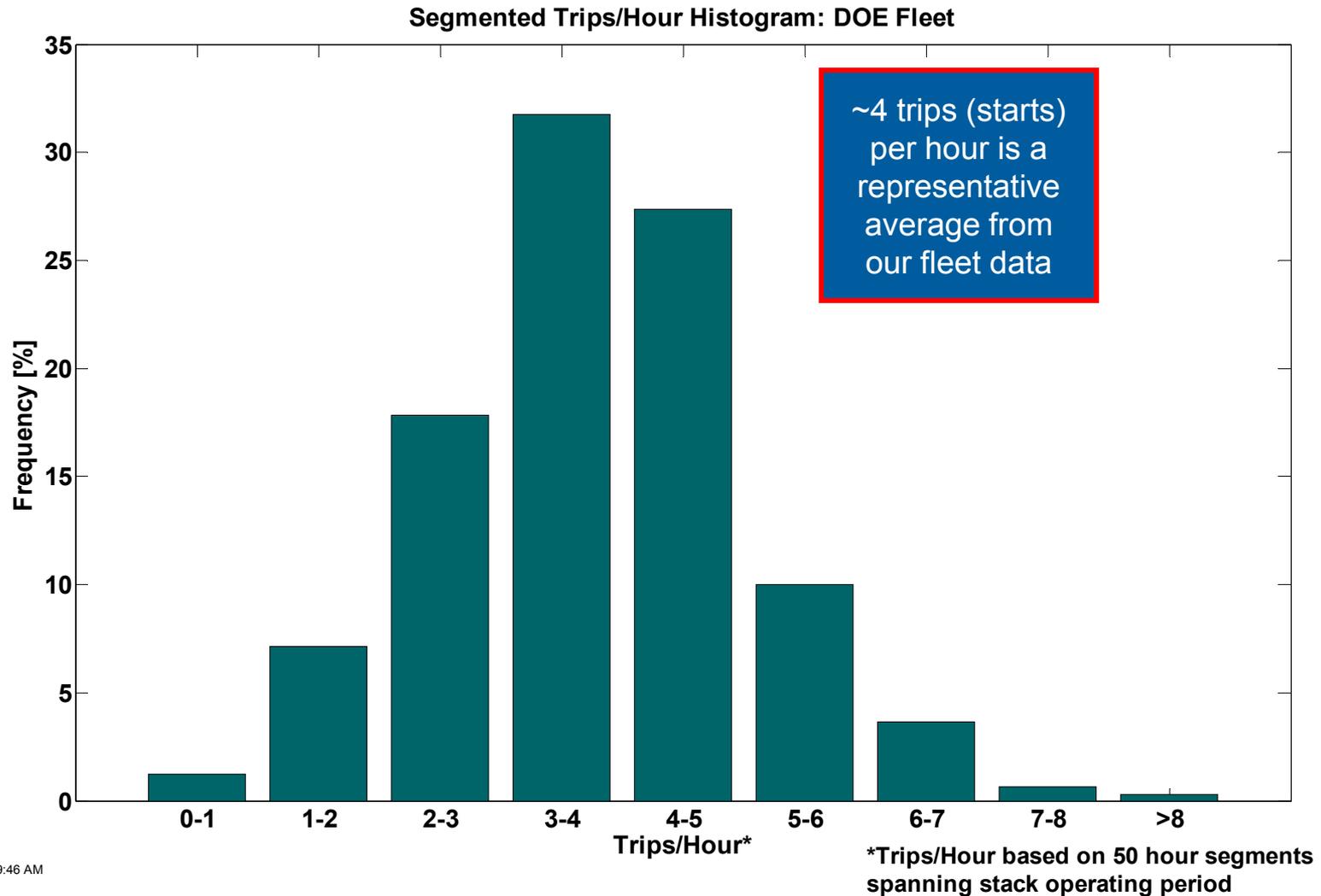
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Stack Duty Cycle: Time Fuel Cell Spends at Various Voltage Levels Was Requested by FC Developers

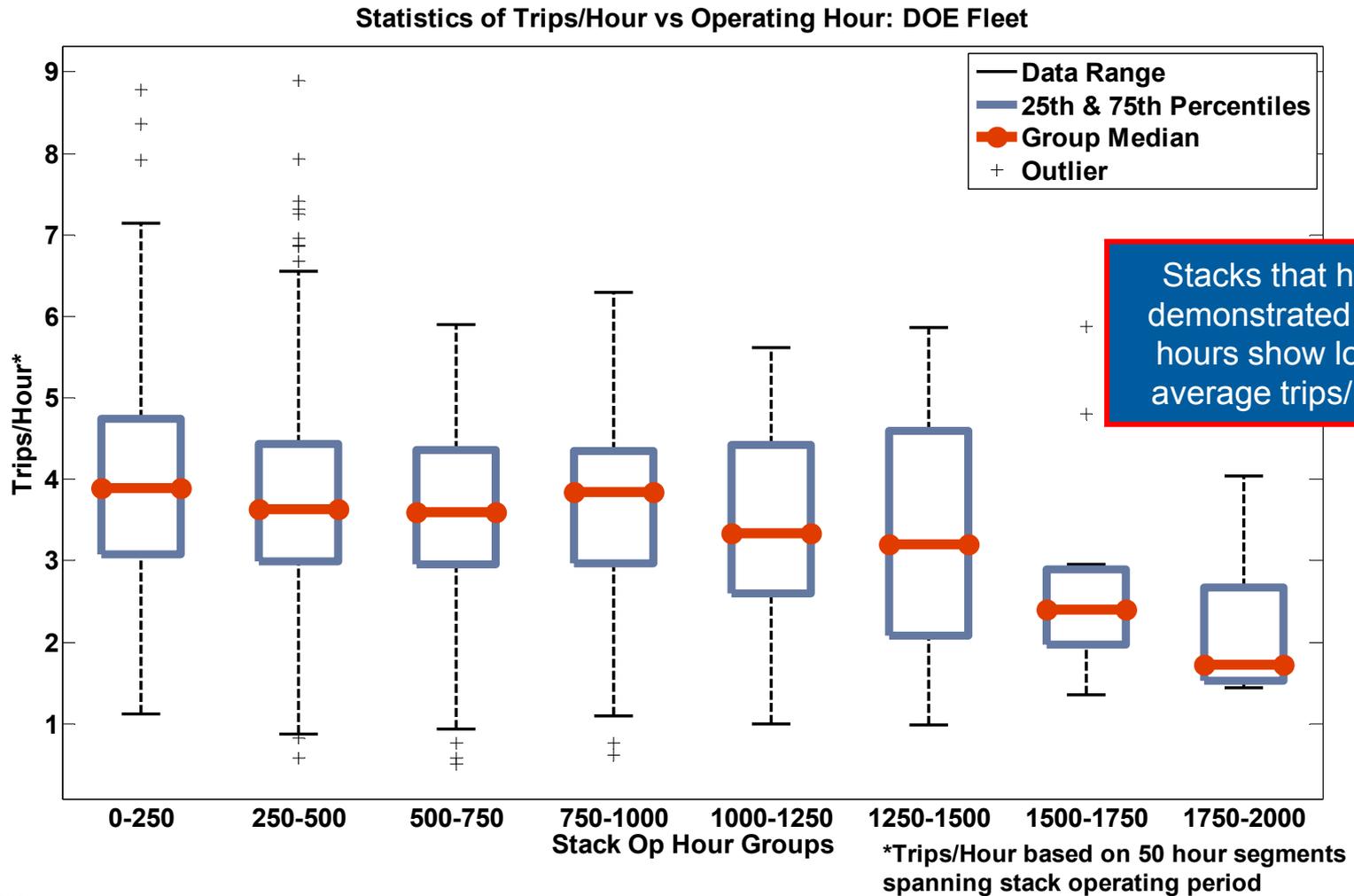


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Fuel Cell Stack Trips Per Hour Histogram Provided to FC Durability Protocol Task Force

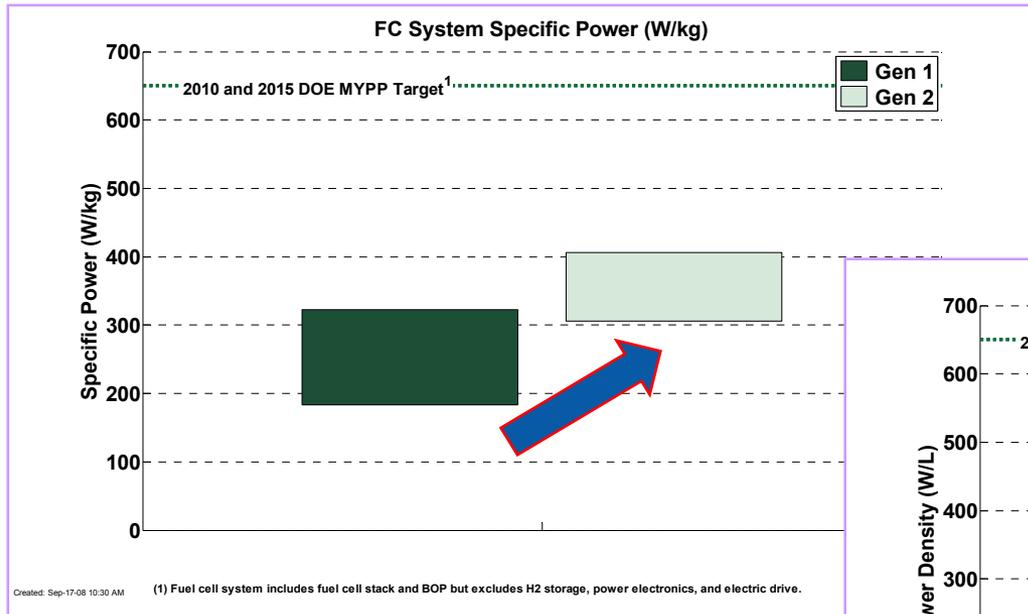


Average Trips/Hour as a Function of Stack Operating Hour



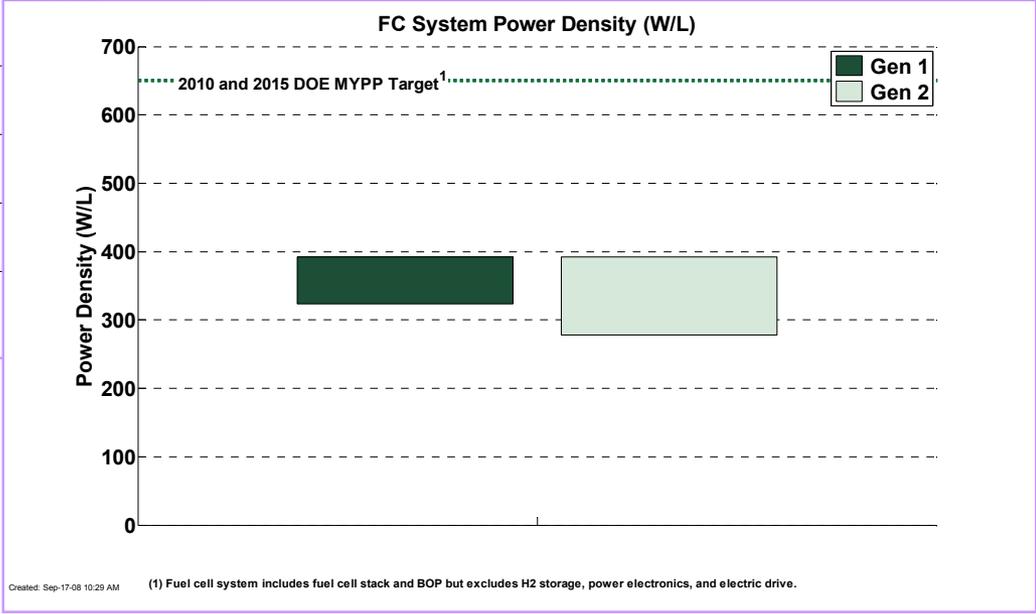
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Comparison of FC System Specific Power and Power Density Between Gen 1 to Gen 2



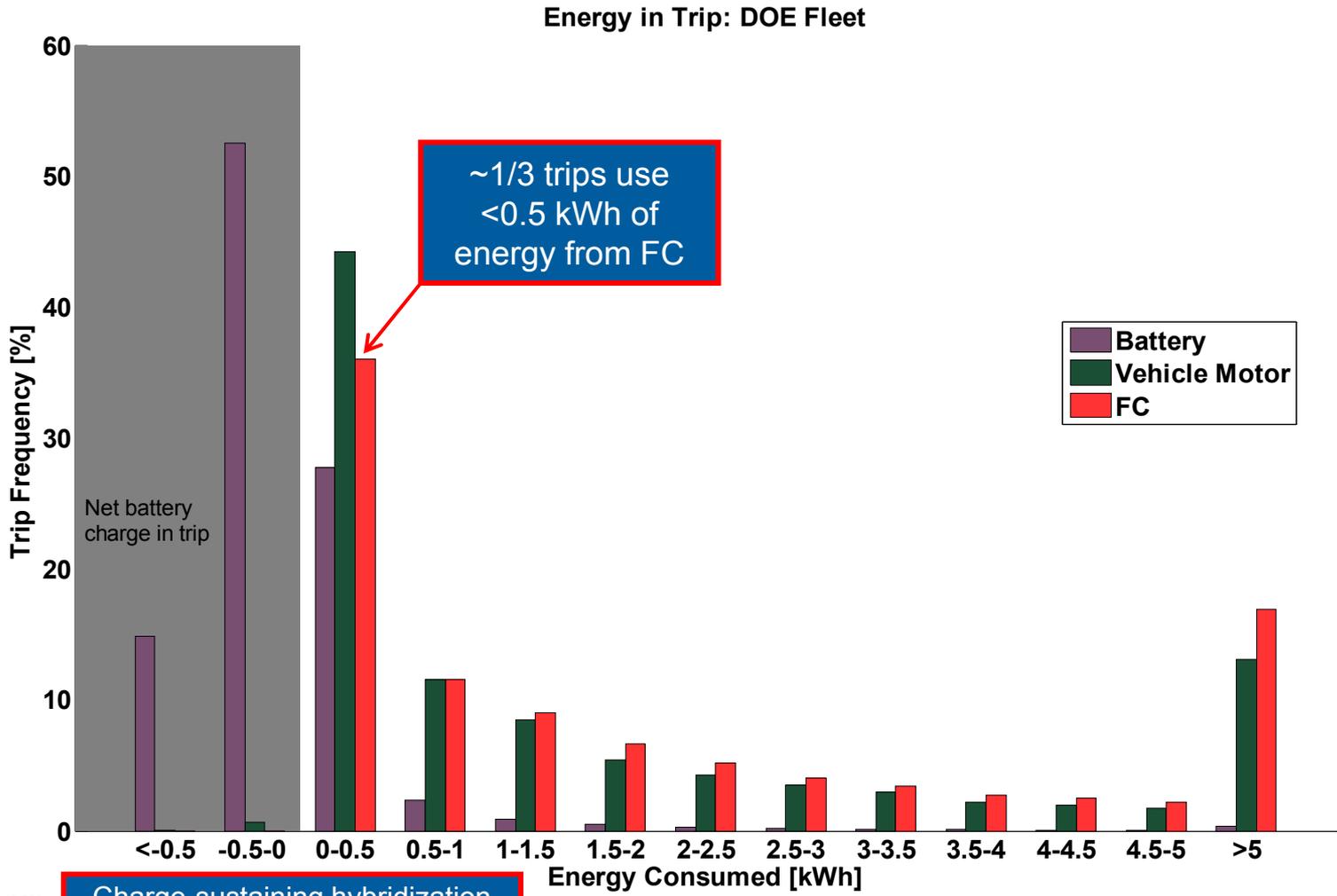
Freeze Capability of Gen 2 Systems May Have Increased Volume

Significant Improvements Seen in Specific Power (...systems getting lighter)



Power Density Did Not Improve Between Gen 1 and Gen 2 (...same size or larger)

Energy Flow Through Major FCV Powertrain Components by Percentage of Trips

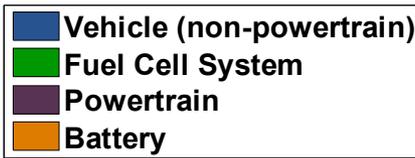
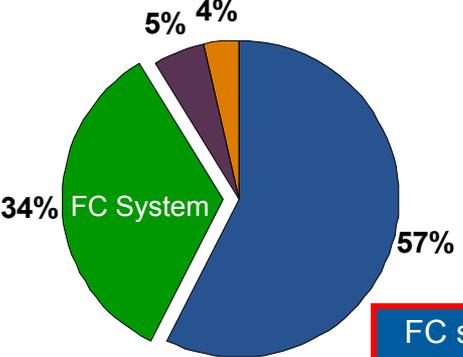


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New Analysis of Vehicle Maintenance Data Highlights Areas for Improvement

Fuel Cell Vehicle Maintenance Events and Labor Hours

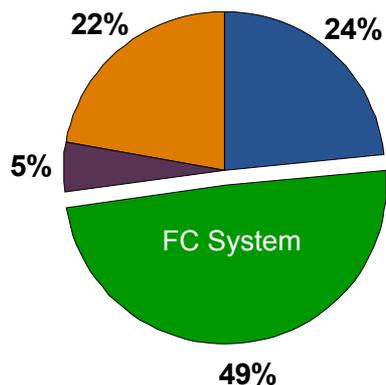
Fuel Cell Vehicle Events (9357)



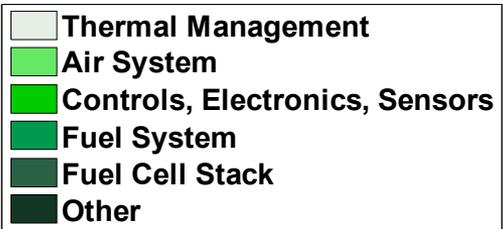
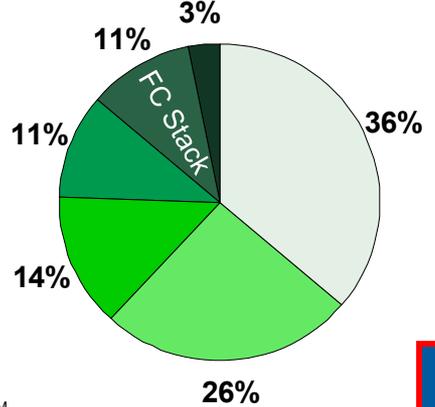
Non-powertrain responsible for >1/2 maintenance events

FC system responsible for 1/3 of maintenance events, which take 1/2 the time

Fuel Cell Vehicle Labor (10216 hours)

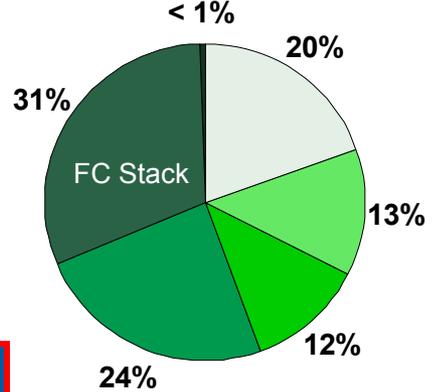


Fuel Cell System Events (3175)



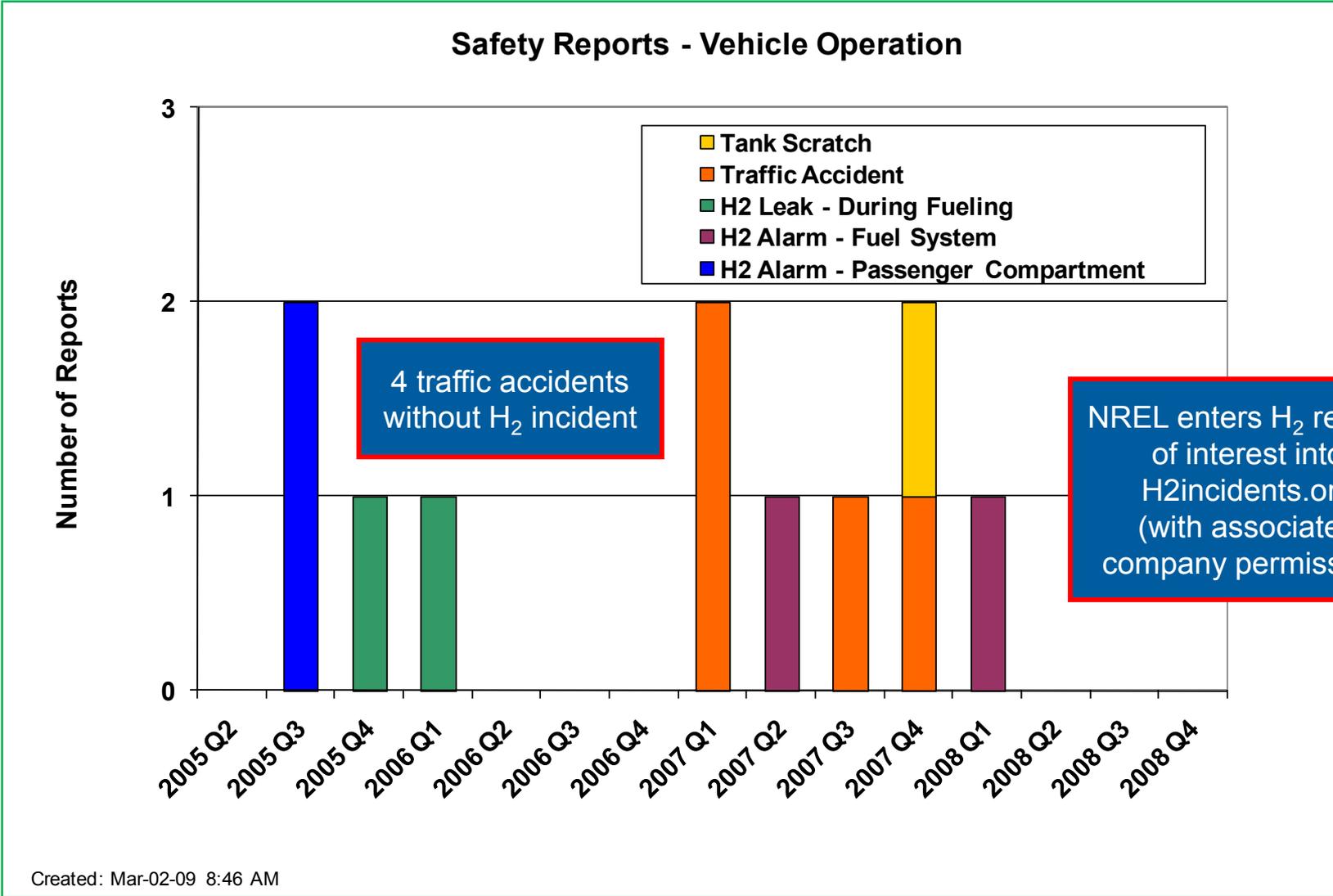
Within FC system, stack is only the 5th most (11%) frequent maintenance, but responsible for 1/3 of repair time

Fuel Cell System Labor (5035 hours)

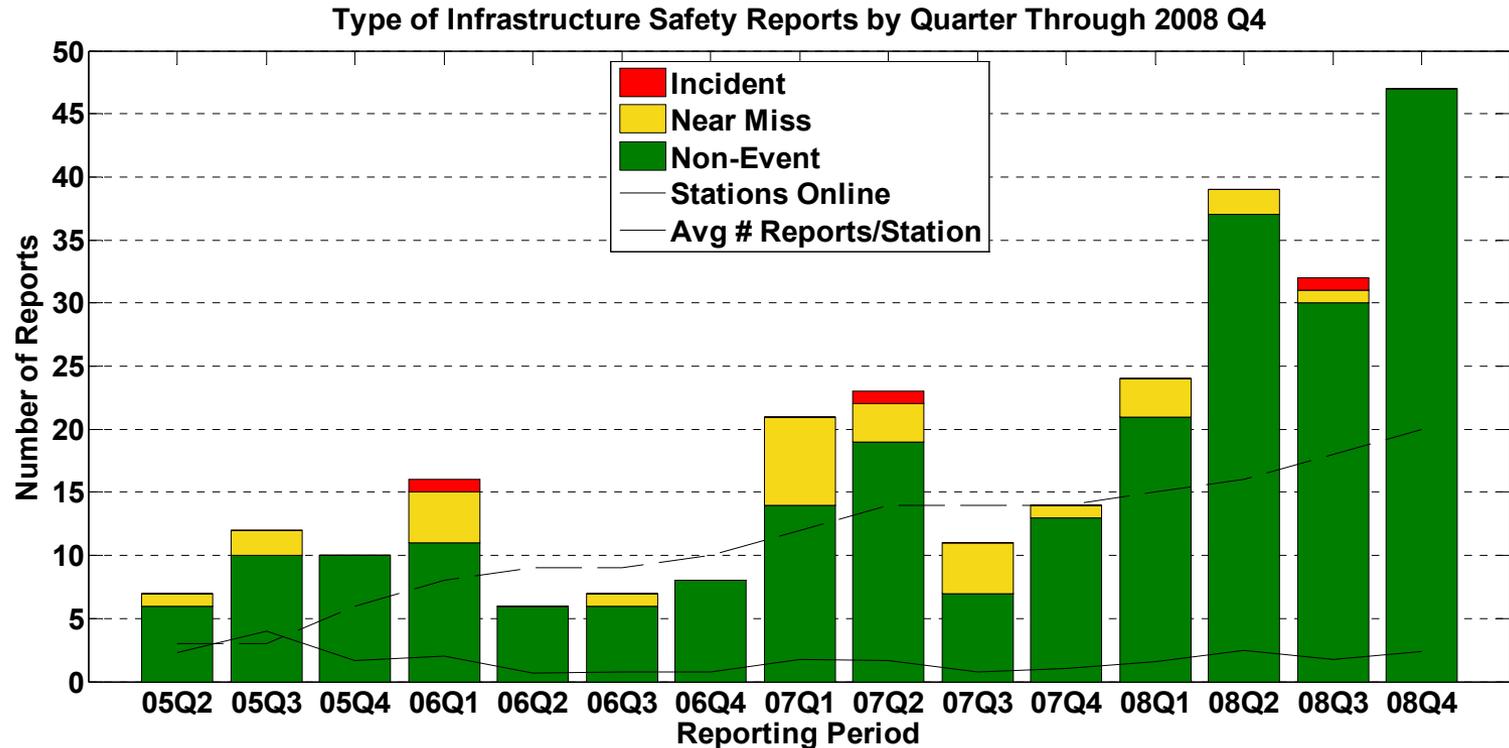


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Minimal Vehicle Safety Reports Continue to Demonstrate a Strong Vehicle Safety Record



Overall Infrastructure Reports Correlated with Increase in New Stations Coming Online



An INCIDENT is an event that results in:

- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

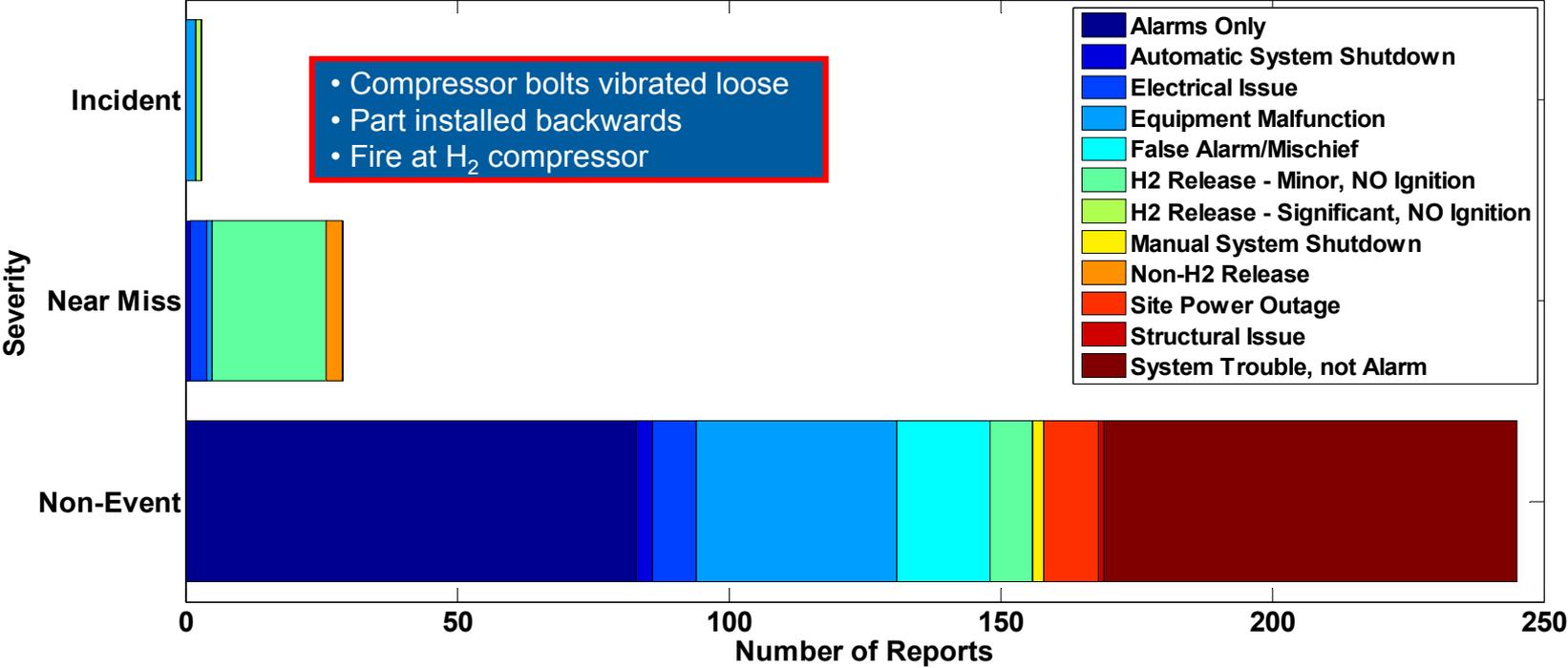
A NEAR-MISS is:

- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

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Most of Infrastructure Safety Reports Continue to Be Non-Events (and Most of Those, Alarms Only)

Total Infrastructure Safety Reports by Severity and Report Type Through 2008 Q4



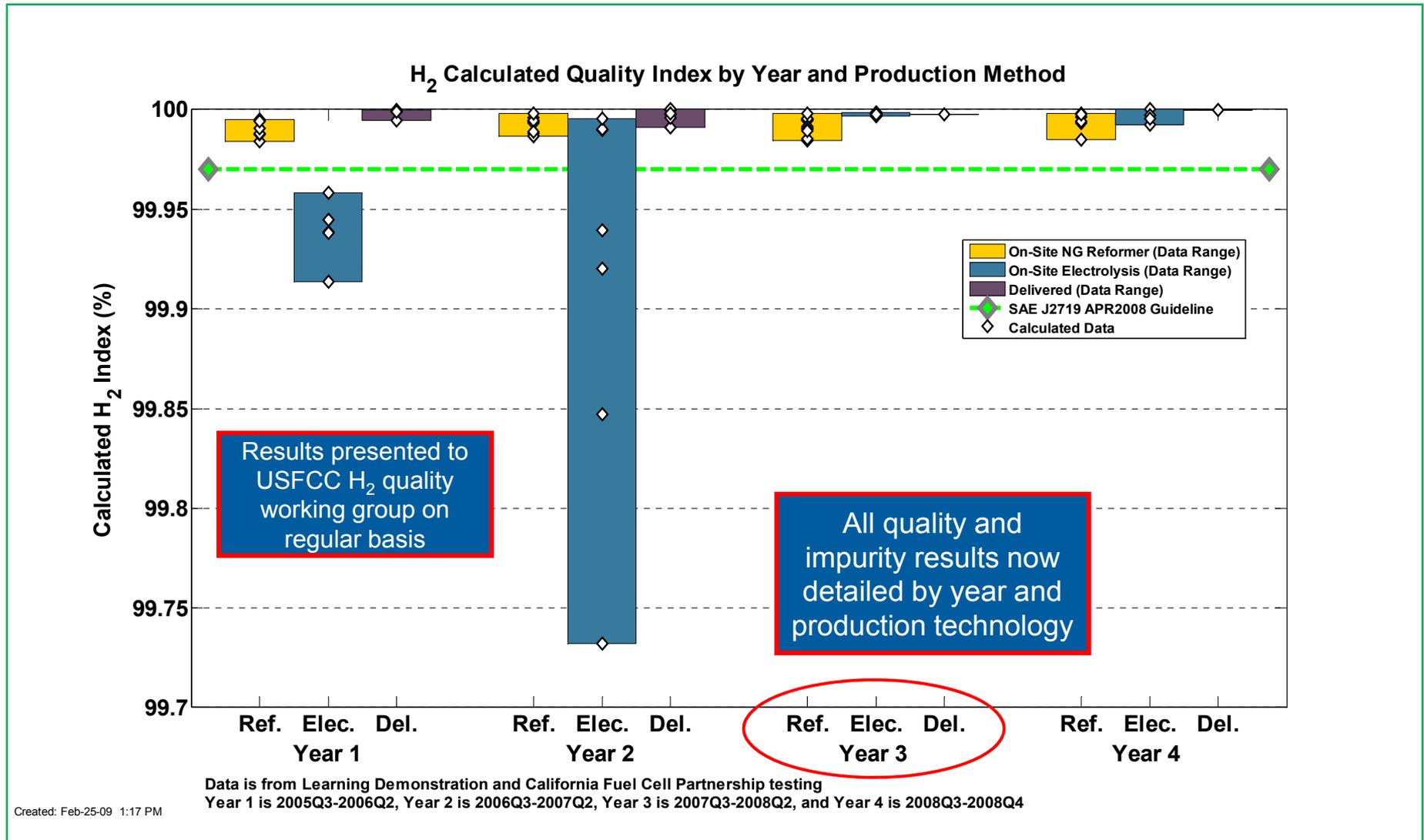
• Compressor bolts vibrated loose
 • Part installed backwards
 • Fire at H₂ compressor

- An INCIDENT is an event that results in:
- a lost time accident and/or injury to personnel
 - damage/unplanned downtime for project equipment, facilities or property
 - impact to the public or environment
 - any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
 - release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)
- A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
 - unplanned H₂ release insufficient to sustain a flame

Note: All "incidents" are reported to H2incidents.org (with associated company permission)

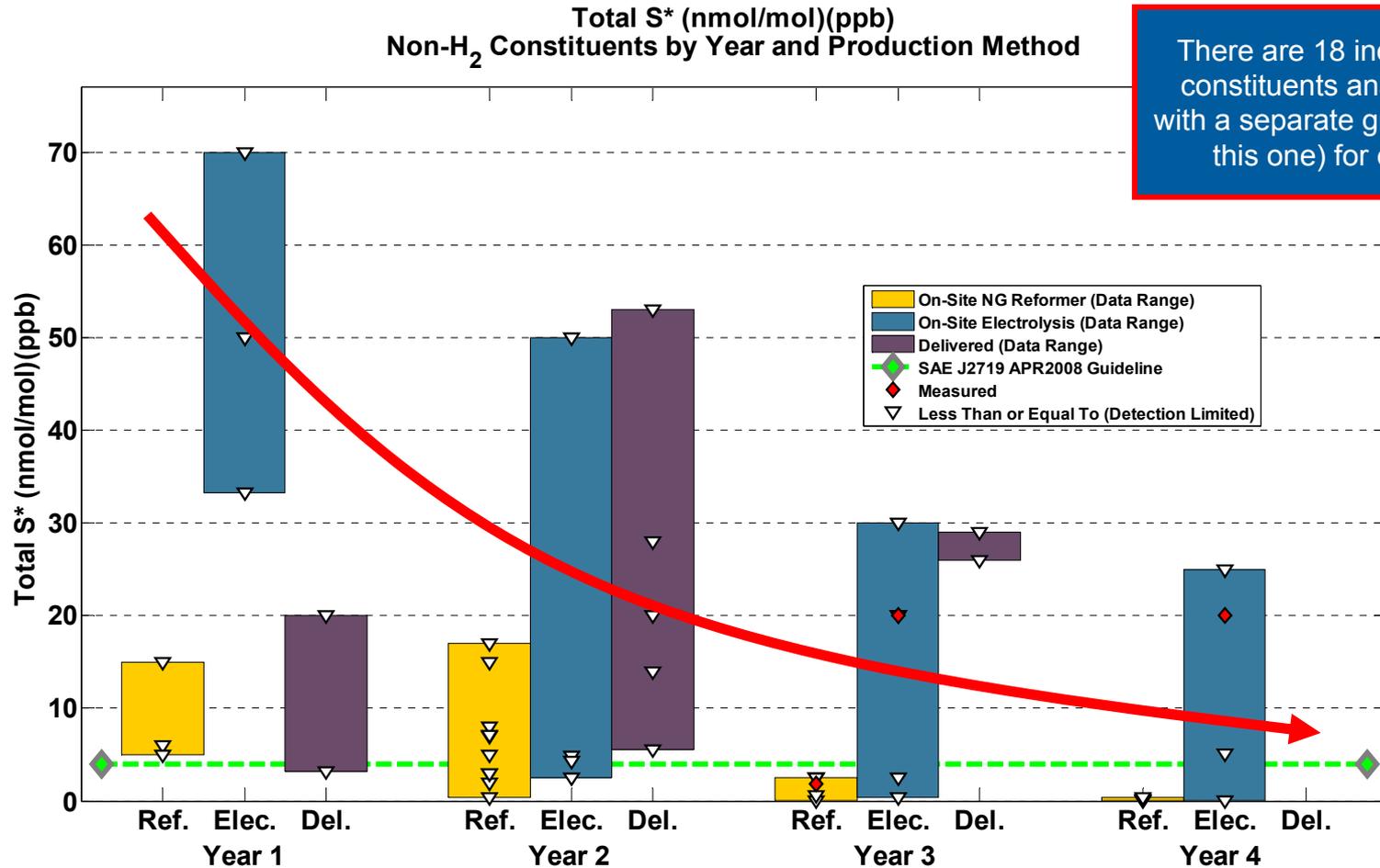
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New Hydrogen Quality Results Show that the Overall Quality Index Met the Target for Last 2 Years



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Hydrogen Constituents by Year and Production Method – Example of Sulfur



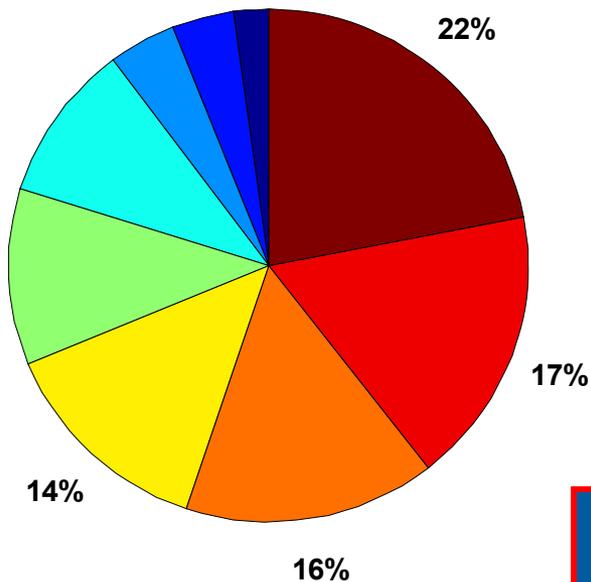
Data is from Learning Demonstration and California Fuel Cell Partnership testing
 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, Year 3 is 2007Q3-2008Q2, and Year 4 is 2008Q3-2008Q4
 *Total S calculated from SO₂, COS, H₂S, CS₂, and Methyl Mercaptan (CH₃SH).

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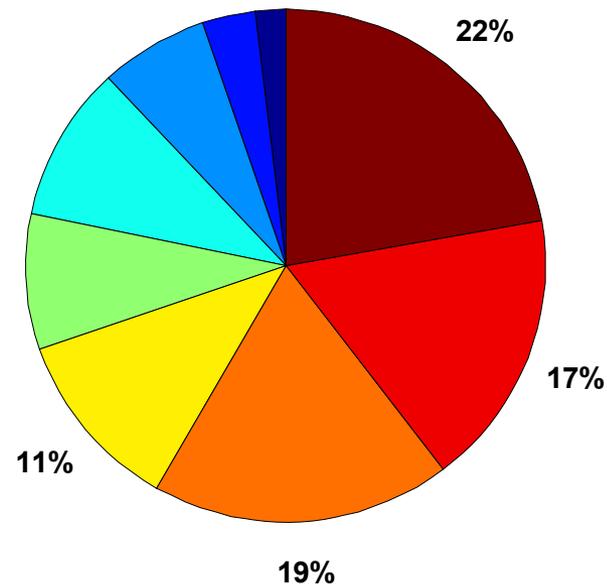
Hydrogen Fueling Station Maintenance by System Shows ~Equal Responsibility of Major Components

Hydrogen Fueling Station Maintenance

By Number of Events
Total Number of Events = 1860

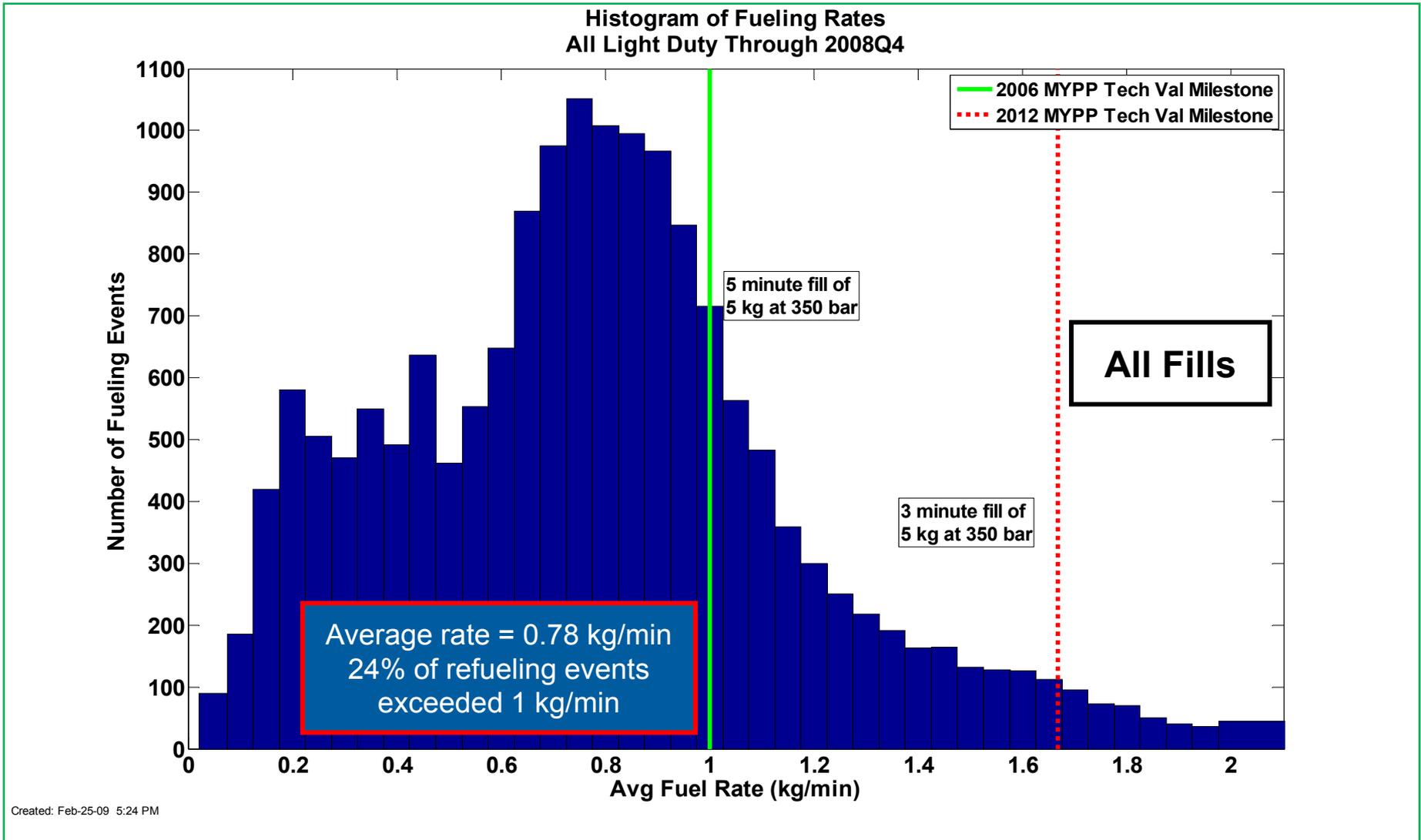


By Labor Hours
Total Hours = 9093

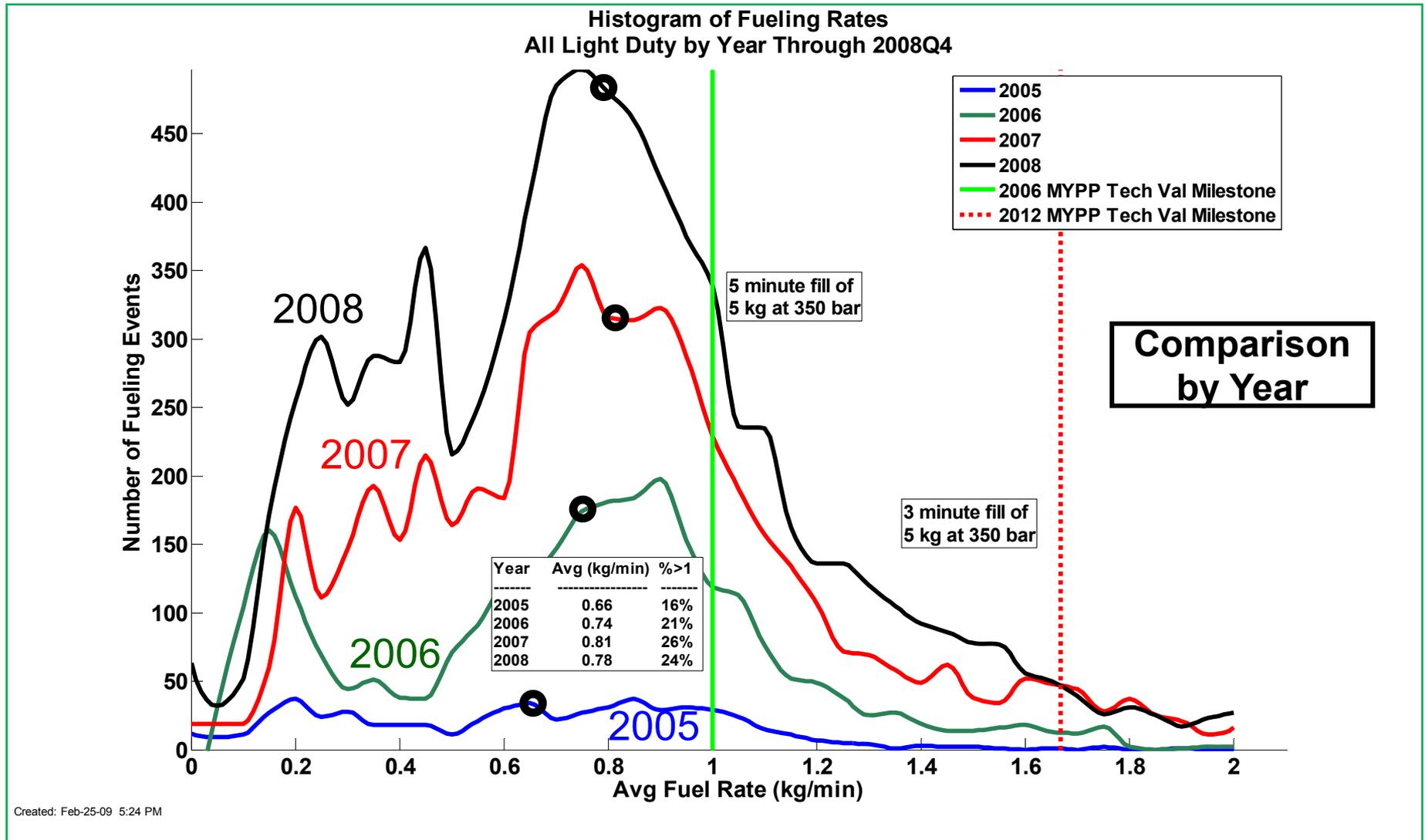


Note that "system control and safety" cause more issues than the production components

Actual Vehicle Refueling Rates from 16,000 Events: Measured by Stations or by Vehicles

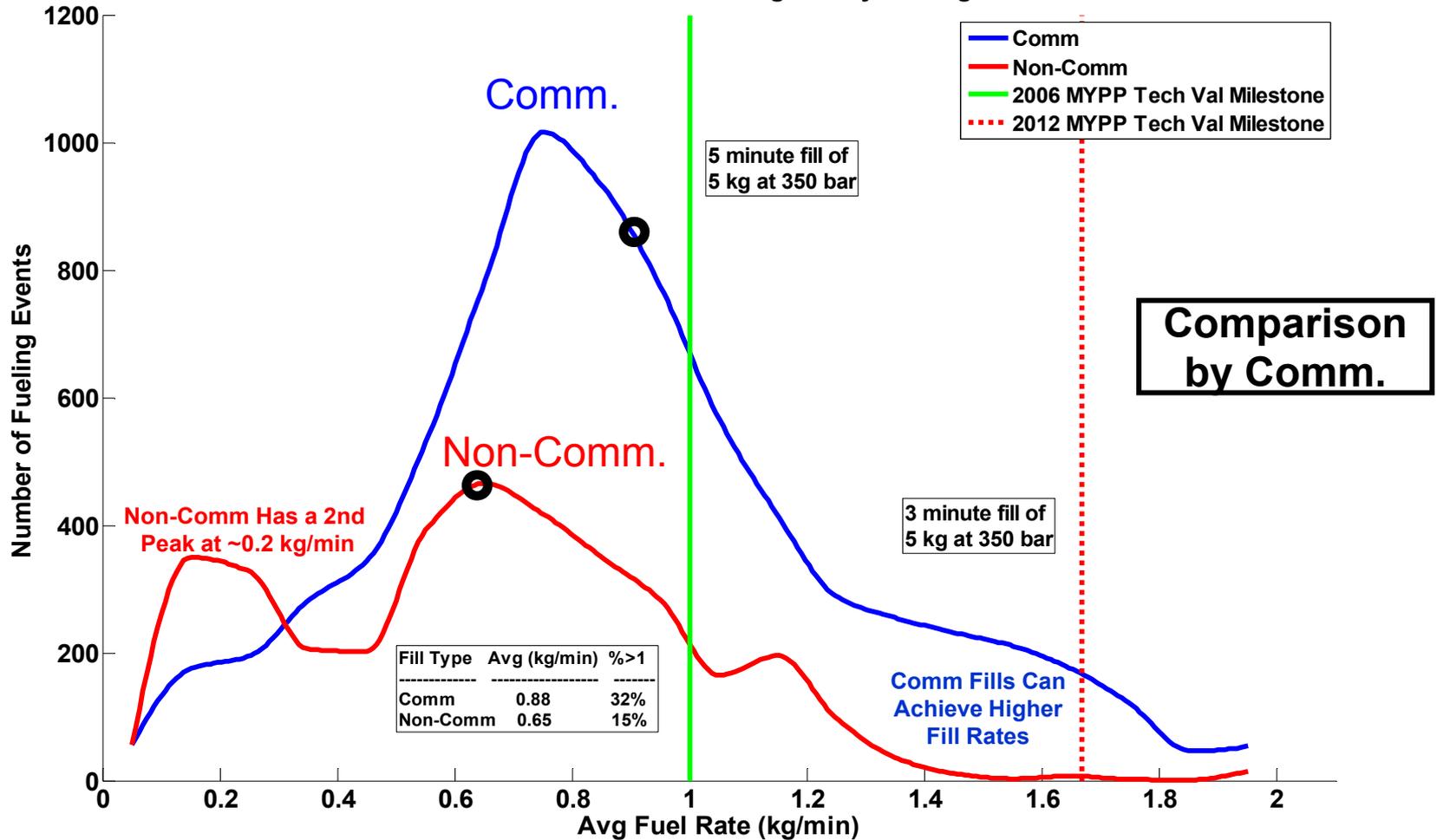


Refueling Rates by Year: Highest Number of Fills in 2008; ~1/4 Now Exceed 1 kg/min



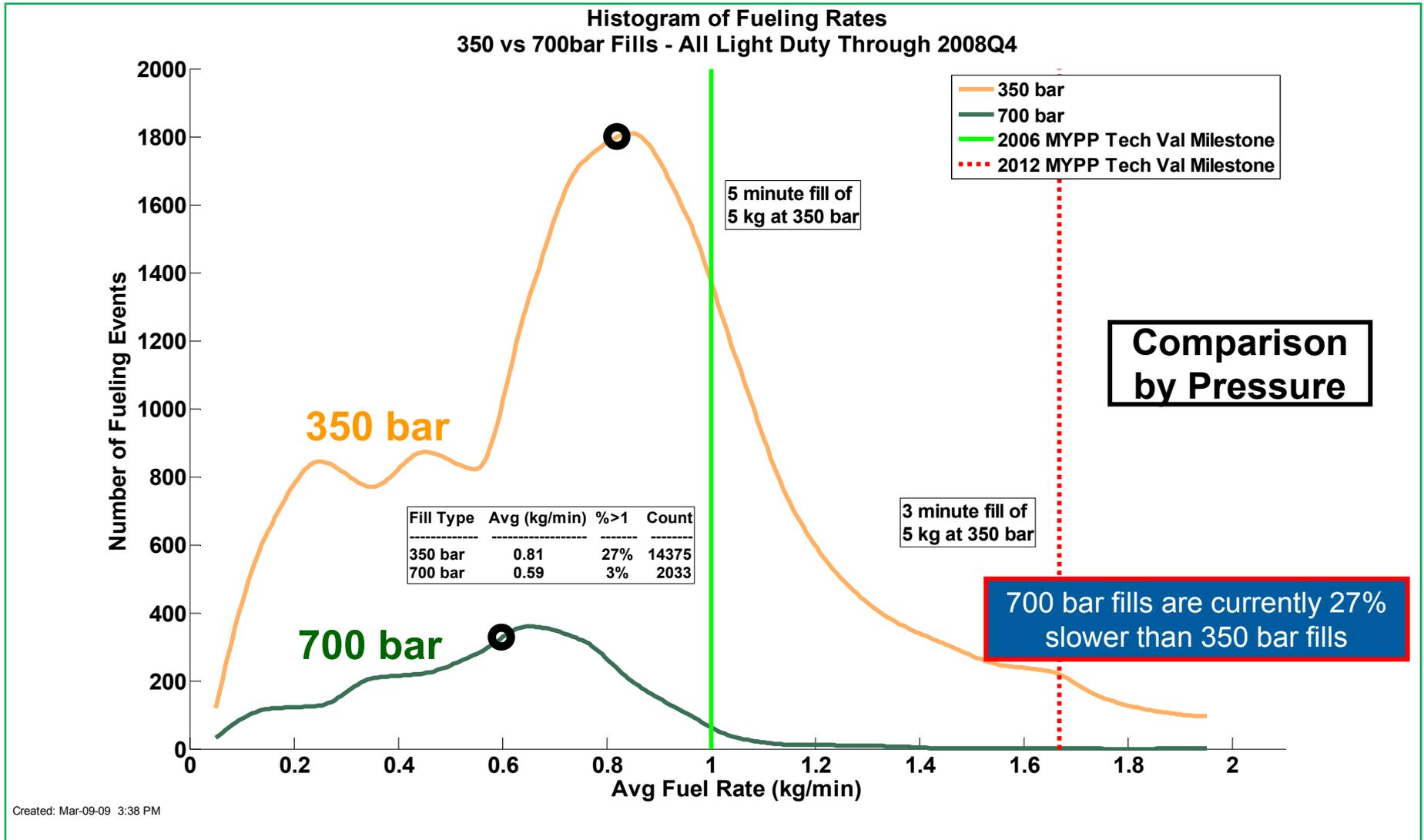
Communication H₂ Fills Achieving 35% Higher Average Fill Rate than Non-Communication

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2008Q4

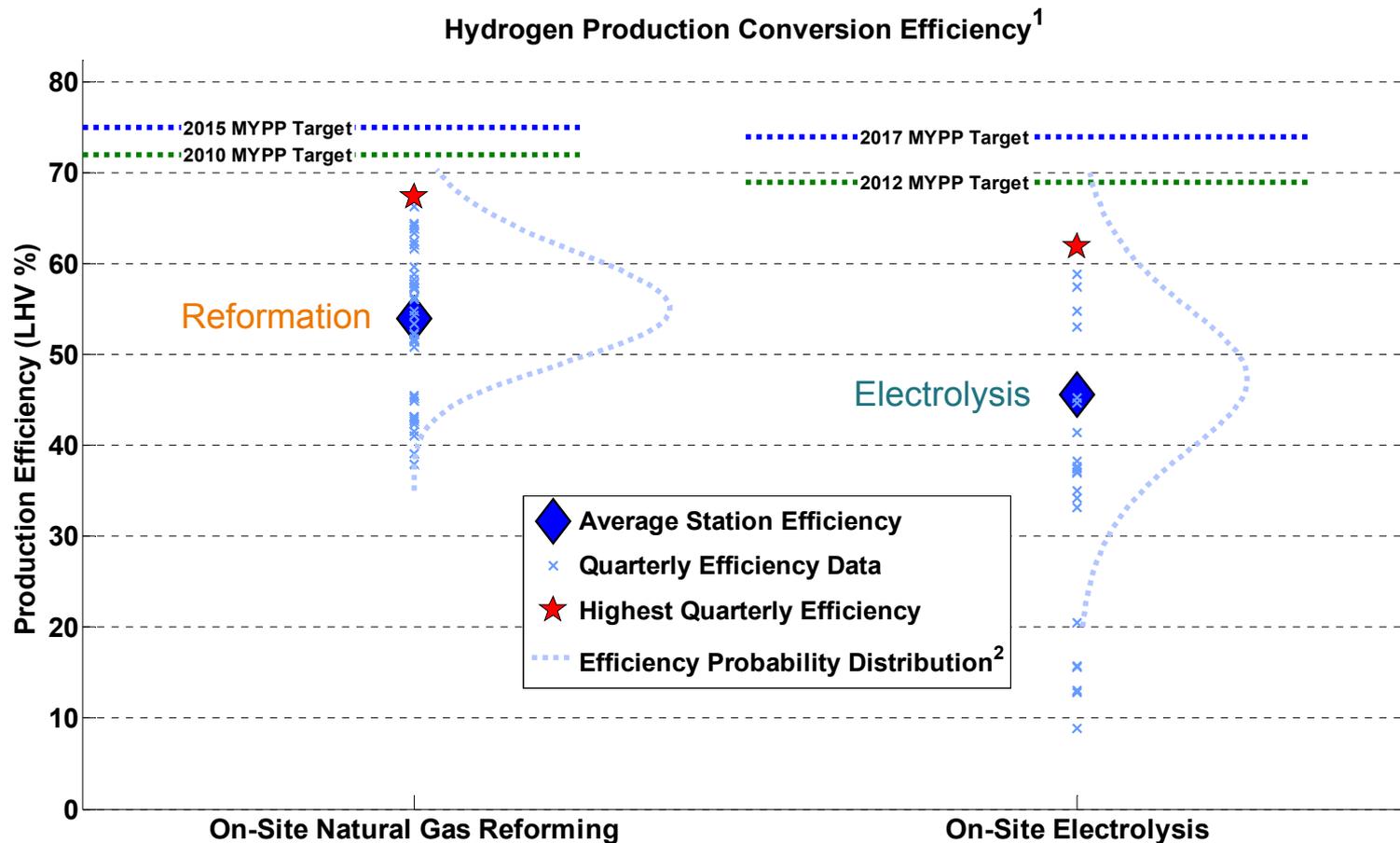


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Comparison of Fueling Rates for 350 and 700 bar Pressure Fueling Events



On-Site Production Efficiency from Natural Gas Reformation and Electrolysis Compared to Targets

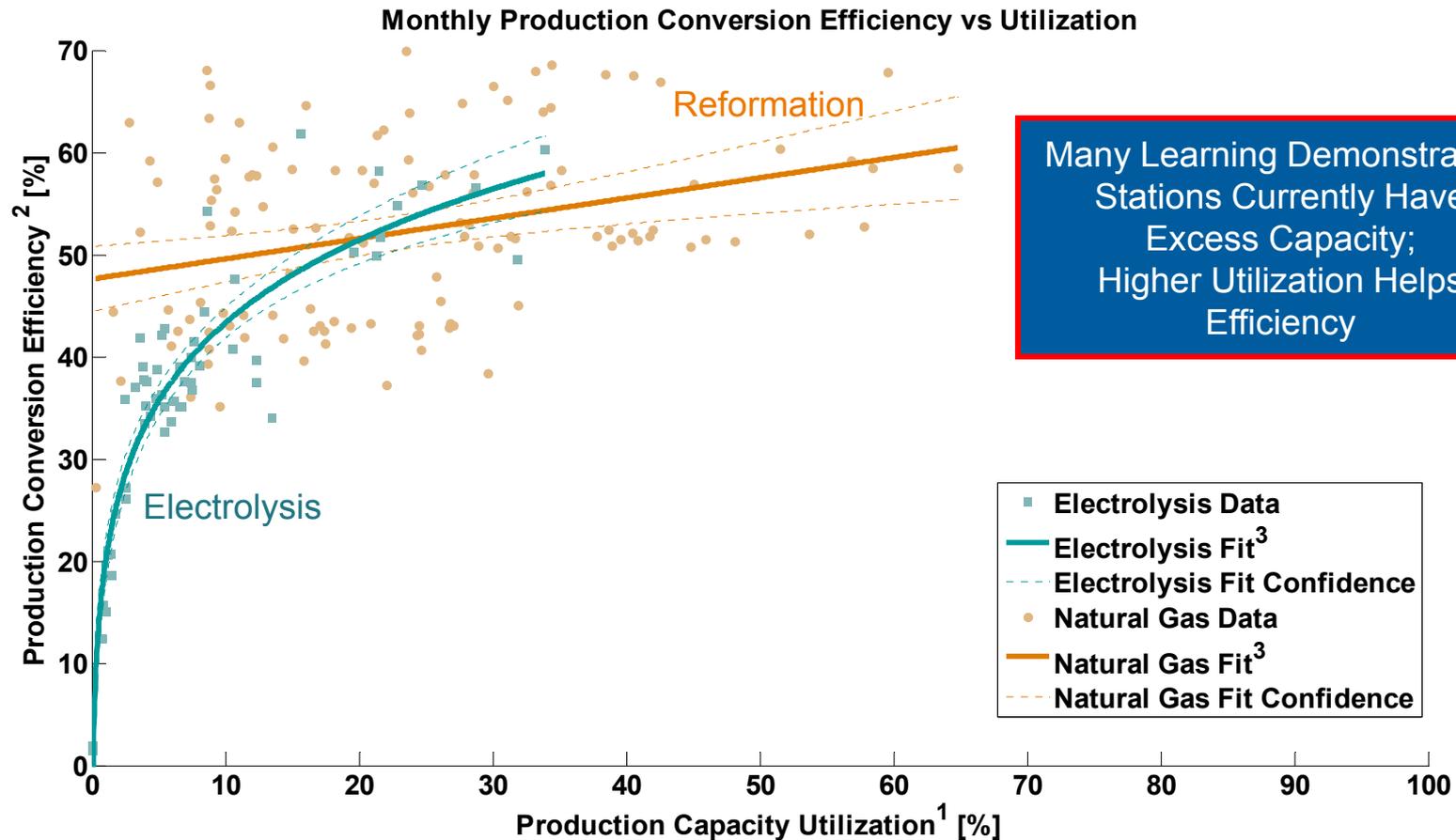


¹Production conversion efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.

²The efficiency probability distribution represents the range and likelihood of hydrogen production conversion efficiency based on monthly conversion efficiency data from the Learning Demonstration.

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On-Site Hydrogen Production Efficiency vs. Capacity Utilization



1) 100% production utilization assumes operation 24 hrs a day, 7 days a week

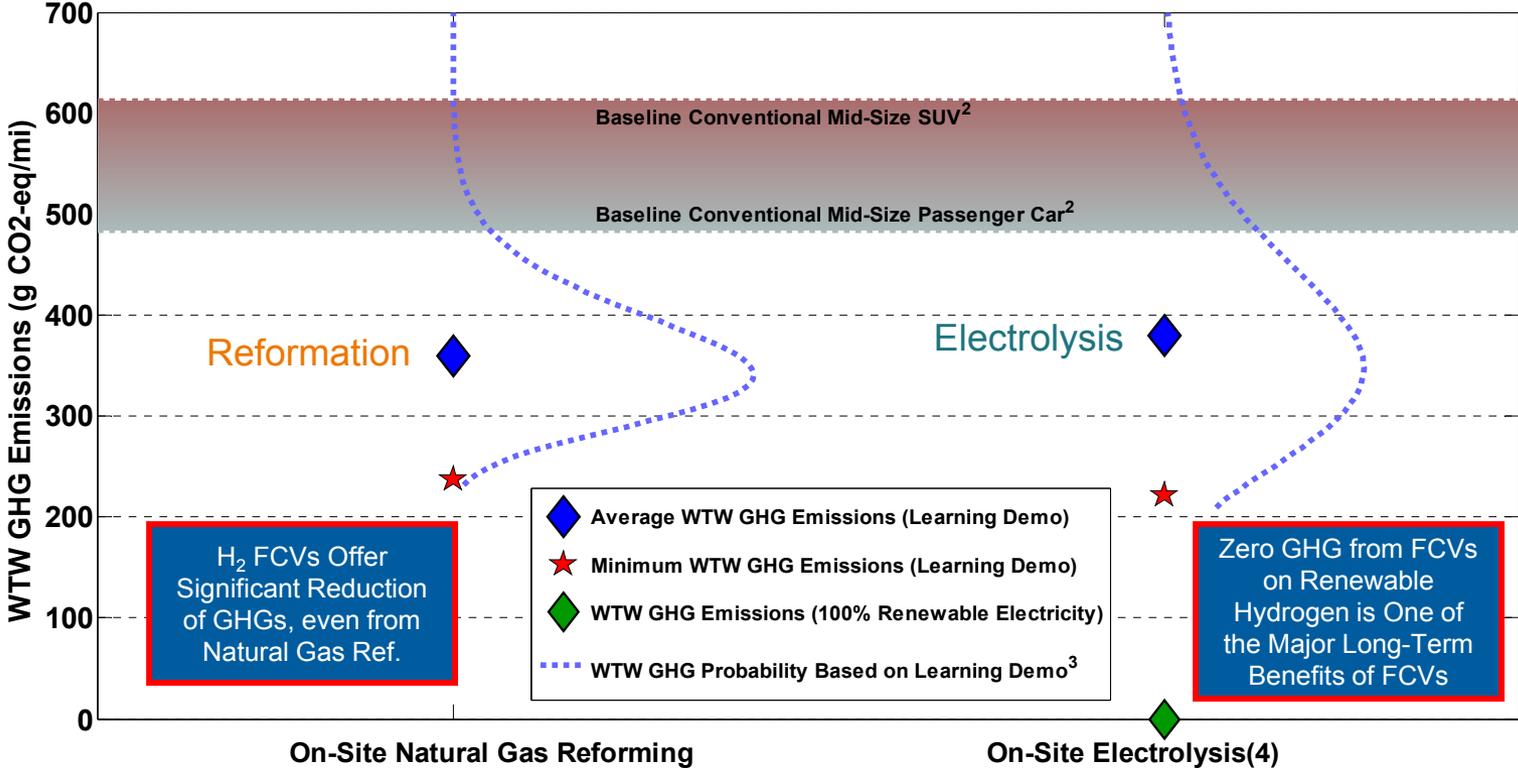
2) Production conversion efficiency is defined as the energy of the hydrogen out of the process (on a LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.

3) High correlation with electrolysis data ($R^2 = 0.87$) & low correlation with natural gas data ($R^2 = 0.018$)

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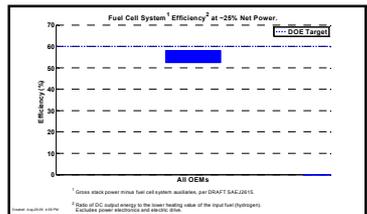
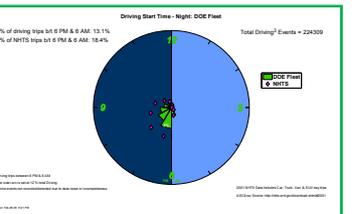
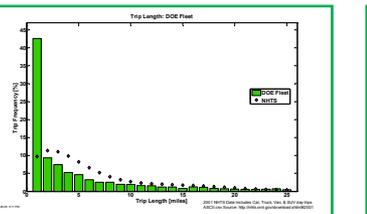
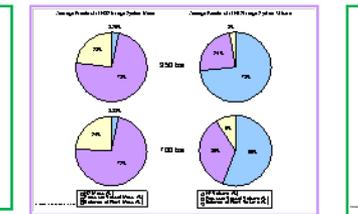
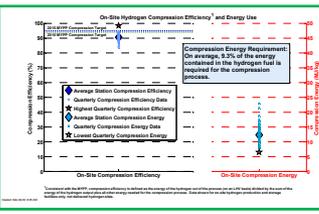
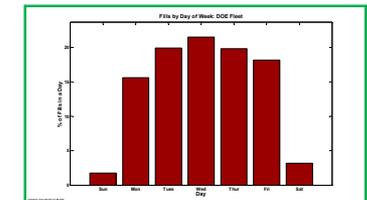
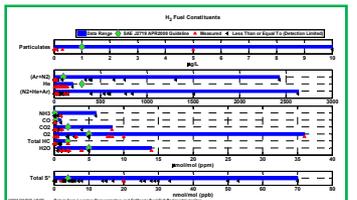
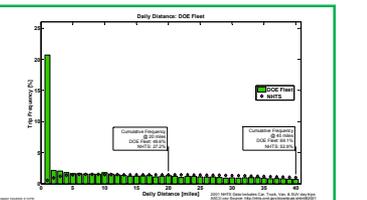
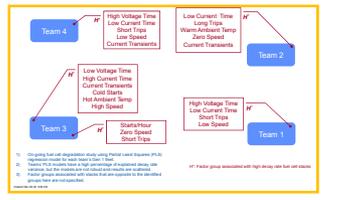
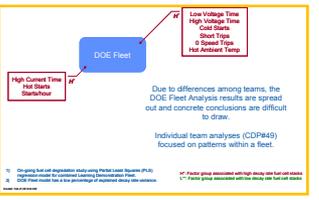
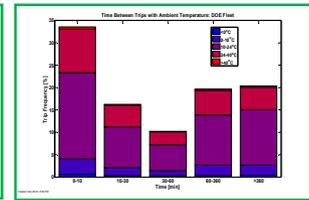
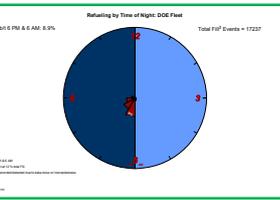
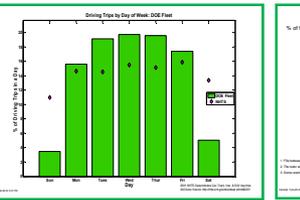
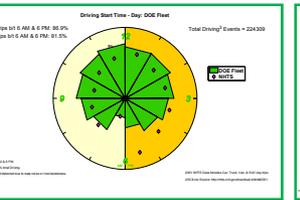
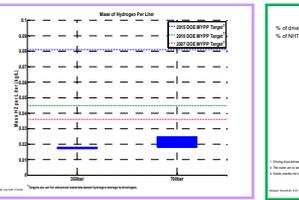
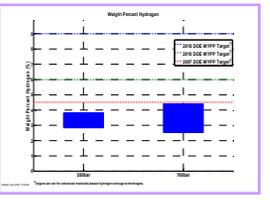
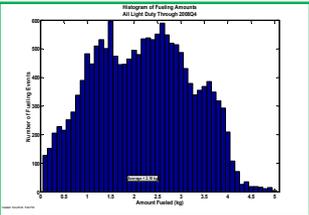
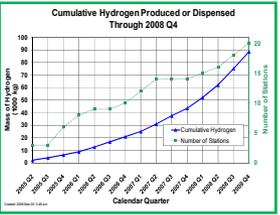
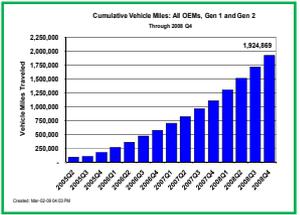
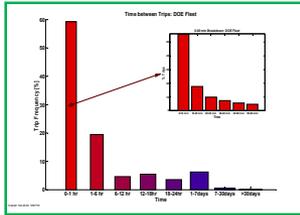
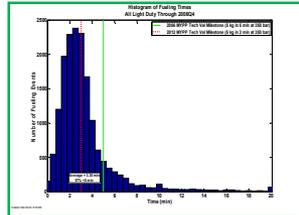
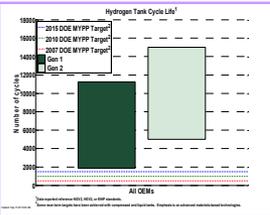
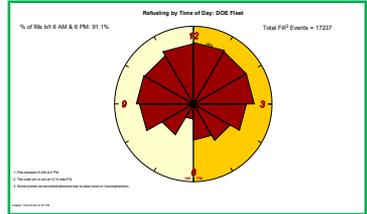
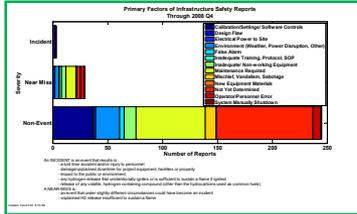
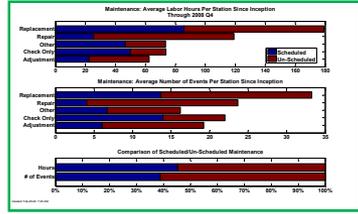
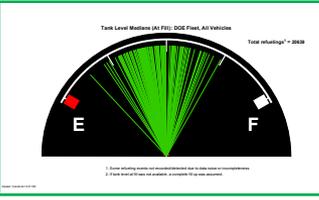
Learning Demonstration Vehicle Greenhouse Gas Emissions Using Actual Production Efficiencies and Fuel Economies

Learning Demonstration Fuel Cycle Well-to-Wheels Greenhouse Gas Emissions¹



1. Well-to-Wheels greenhouse gas emissions based on DOE's GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all teams (as used in CDP #6); conversion efficiency values are the production efficiency data used in CDP #13.
 2. Baseline conventional passenger car and light duty truck GHG emissions are determined by GREET 1.8b, based on the EPA window-sticker fuel economy of a conventional gasoline mid-size passenger car and mid-size SUV, respectively. The Learning Demonstration fleet includes both passenger cars and SUVs.
 3. The Well-to-Wheels GHG probability distribution represents the range and likelihood of GHG emissions resulting from the hydrogen FCV fleet based on window-sticker fuel economy data and monthly conversion efficiency data from the Learning Demonstration.
 4. On-site electrolysis GHG emissions are based on the average mix of electricity production used by the Learning Demonstration production sites, which includes both grid-based electricity and renewable on-site solar electricity. GHG emissions associated with on-site production of hydrogen from electrolysis are highly dependent on electricity source. GHG emissions from a 100% renewable electricity mix would be zero, as shown. If electricity were supplied from the U.S. average grid mix, average GHG emissions would be 1241 g/mile.

Other CDP Results Not Discussed Here Today



Highlights of Interactions and Collaborations in the Last Year

Auto/Energy Industry Partners

- Site visits with industry (at OEM site or NREL) to discuss detailed results and NREL methodology
- Focused on 2-way sharing of voltage degradation calculations and multivariate analyses
- Completed implementation for producing detailed data results and CDPs at same time for easier industry review



FreedomCAR and Fuel Technical Teams

- Fuel Cell (7/08, 4/09) and H₂ Storage (10/08, 4/09) Tech Teams



US Fuel Cell Council Technical Working Groups

- Transportation Working Group
- Joint H₂ Quality Task Force
- FC Durability Testing Protocol Working Group



California Organizations

- CaFCP: NREL now includes H₂ impurity test results in CDPs
- CARB: Agreement for data from new stations to be sent to NREL



Department of Defense (DLA)

- Leveraging experience to evaluate FC forklifts and backup power



Future Work

Remainder of FY09:

- Create new and updated composite data products (CDPs) based on data through June 2009 (Fall 2009 CDPs)
 - Prepare results for publication at 2009 Fuel Cell Seminar
- Key upcoming September 2009 DOE MYPP and Joule milestones on:
 - Hydrogen production cost from project compared to \$3/gge target
 - Gen 2 stack voltage degradation time to 10% compared to target of 2000 hours
 - Gen 2 vehicle freeze capability and start-up energy requirements compared to targets
- Support OEMs, energy companies, and state organizations in California in coordinating early infrastructure plans

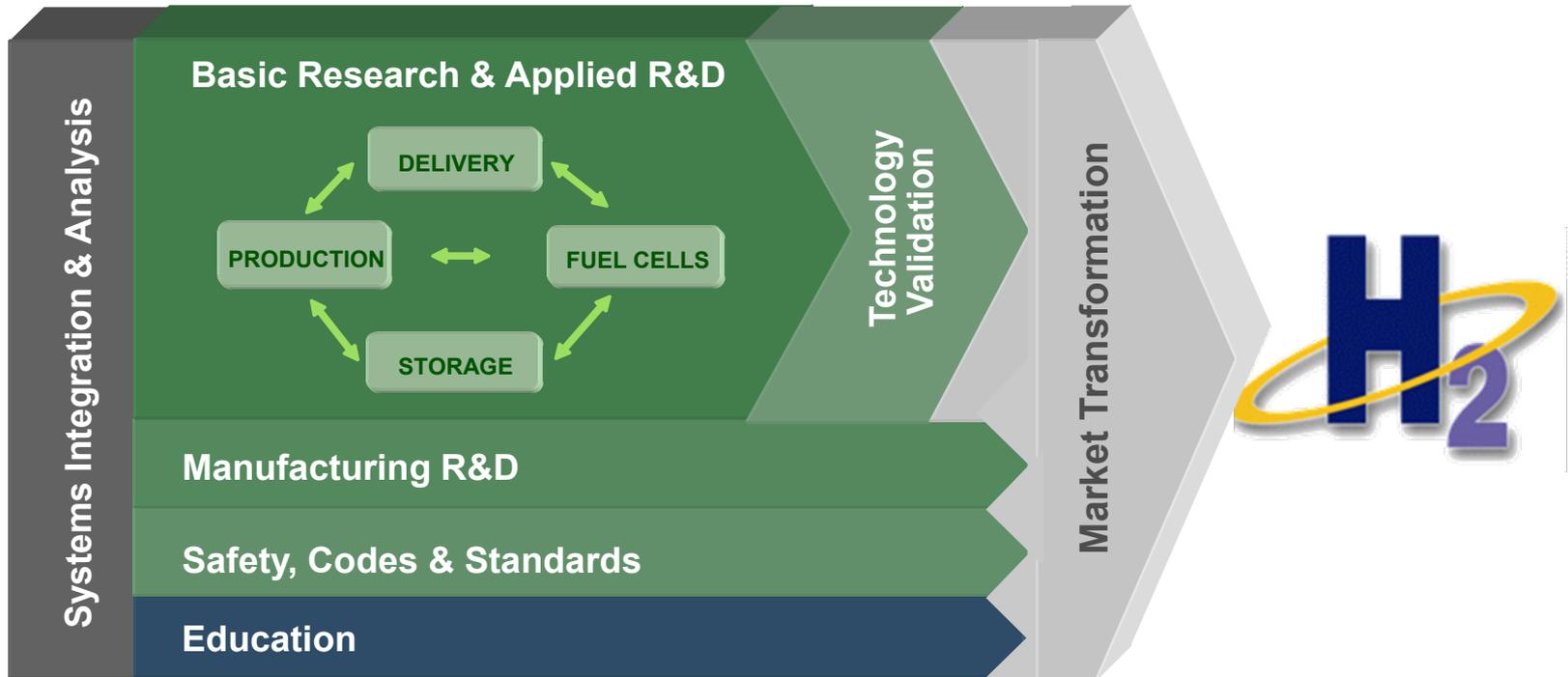
FY10:

- Continue to identify opportunities to feed findings from project back into VT/H₂ programs and industry R&D activities to maintain project as a “learning demonstration”
- Publish Spring 2010, Fall 2010 composite data products as the last anticipated results from the project
- Write final summary report for the project

Summary

- Learning Demo evaluation is ~80% complete
 - 140 vehicles and 20 stations deployed
 - 1.9 million miles traveled, 90,000 kg H₂ produced or dispensed
 - 346,000 individual vehicle trips analyzed
 - Project to continue through 2010
- Many new technical results since last AMR presentation
 - All but 2 updated since last AMR
 - 52 new/updated results since Fall 2008, 8 unchanged (total of 60)
 - H₂ production efficiency, compressor efficiency, vehicle GHG emissions
 - 350 vs. 700 bar refueling rates
 - Several new FC stack usage statistics
 - Time between trips & ambient temperature
 - H₂ fueling station maintenance by system
 - Fuel cell vehicle maintenance by system
 - All results available on web site
- Roll-out of 2nd generation vehicles is now complete
- Station deployment nearing completion

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