

Fuel Cell Vehicle Learning Demonstration: Early Second-Generation Vehicle Results and Hydrogen Production Efficiency



**2008 Fuel Cell Seminar
and Exposition**

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Outline

- Objectives and Partners
- NREL's Role in the Project and Methodology
- How to Access Complete Results
- Vehicle Results (Gen 1 vs. Gen 2)
- Infrastructure Results (Efficiency, GHG)
- Summary

Fuel Cell Vehicle Learning Demonstration

Project Objectives and Targets

Objectives

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

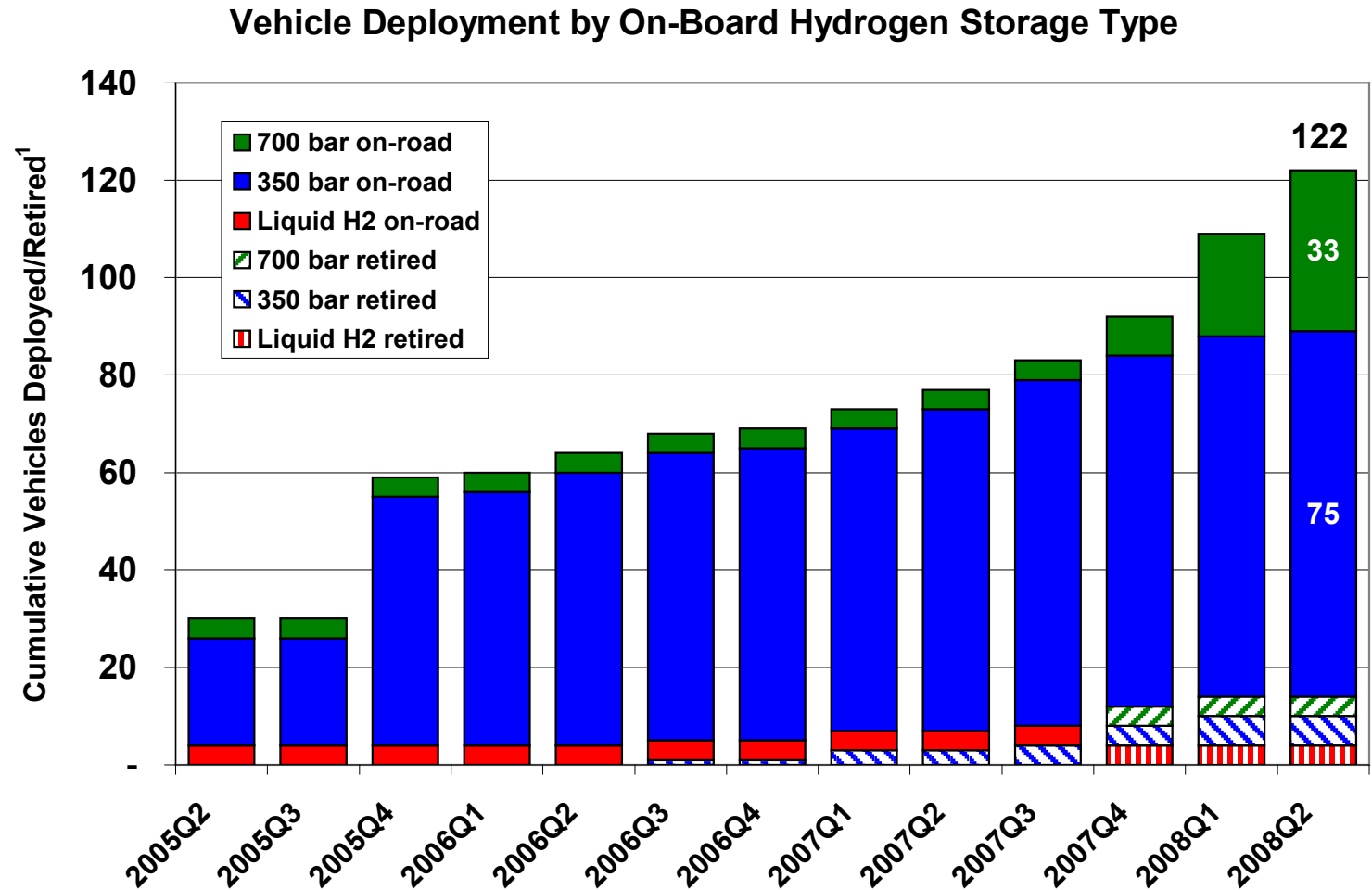


Photo: NREL

Industry Partners: 4 Automaker/Energy-Supplier Teams



Significant Number of Gen 2 Vehicles Now Deployed, Some Early Vehicles Retired

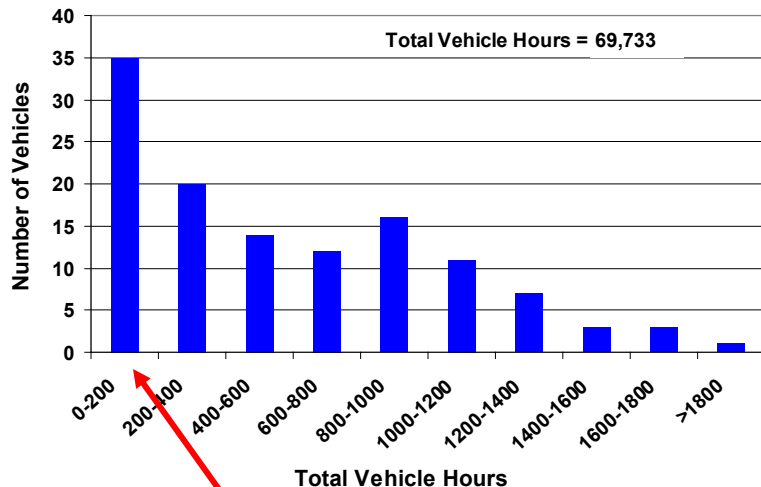


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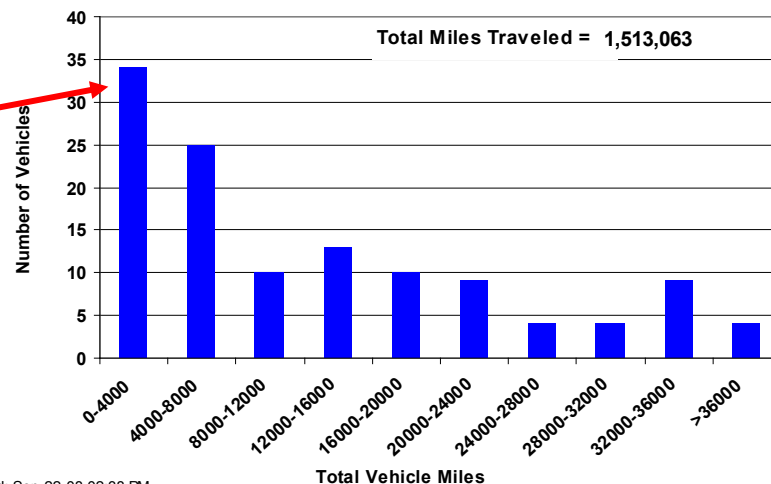
(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL

DOE Learning Demo Fleet Has Surpassed 69,000 Vehicle Hours and 1.5 Million Miles

Vehicle Hours: All OEMs, Gen 1 and Gen 2
Through 2008 Q2

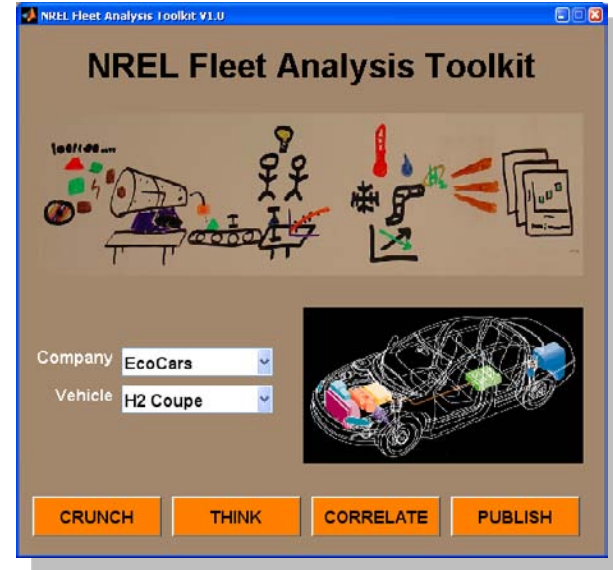
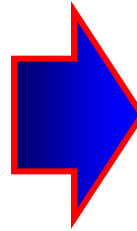
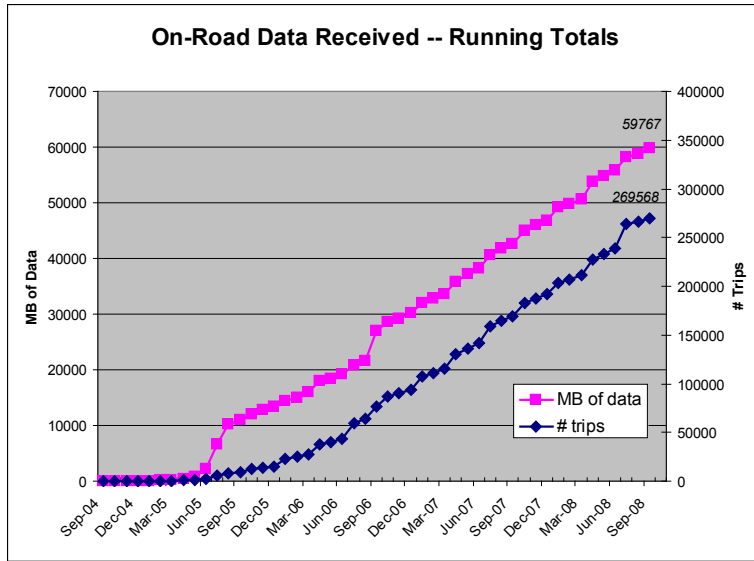


Vehicle Miles: All OEMs, Gen 1 and Gen 2
Through 2008 Q2

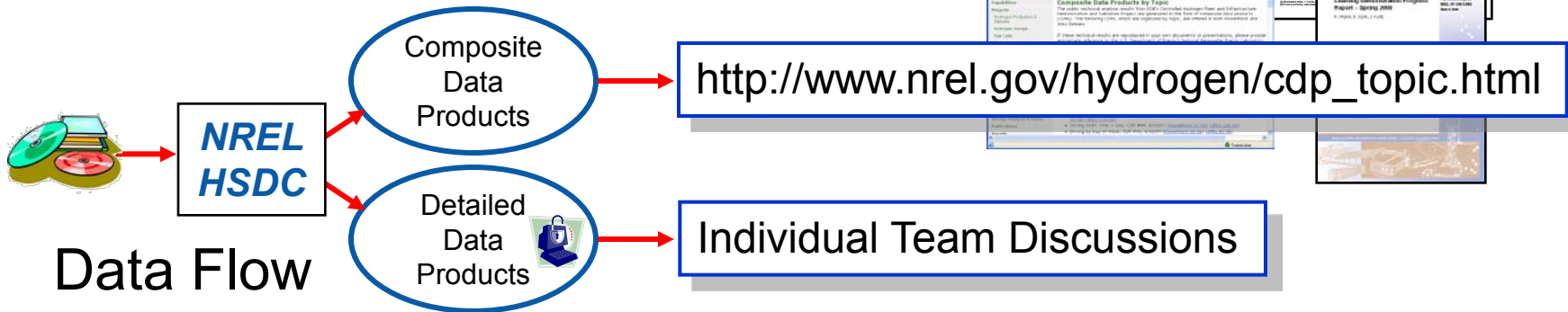


Gen 2 vehicle introduction now appears as the 2nd bulge at low hours/miles

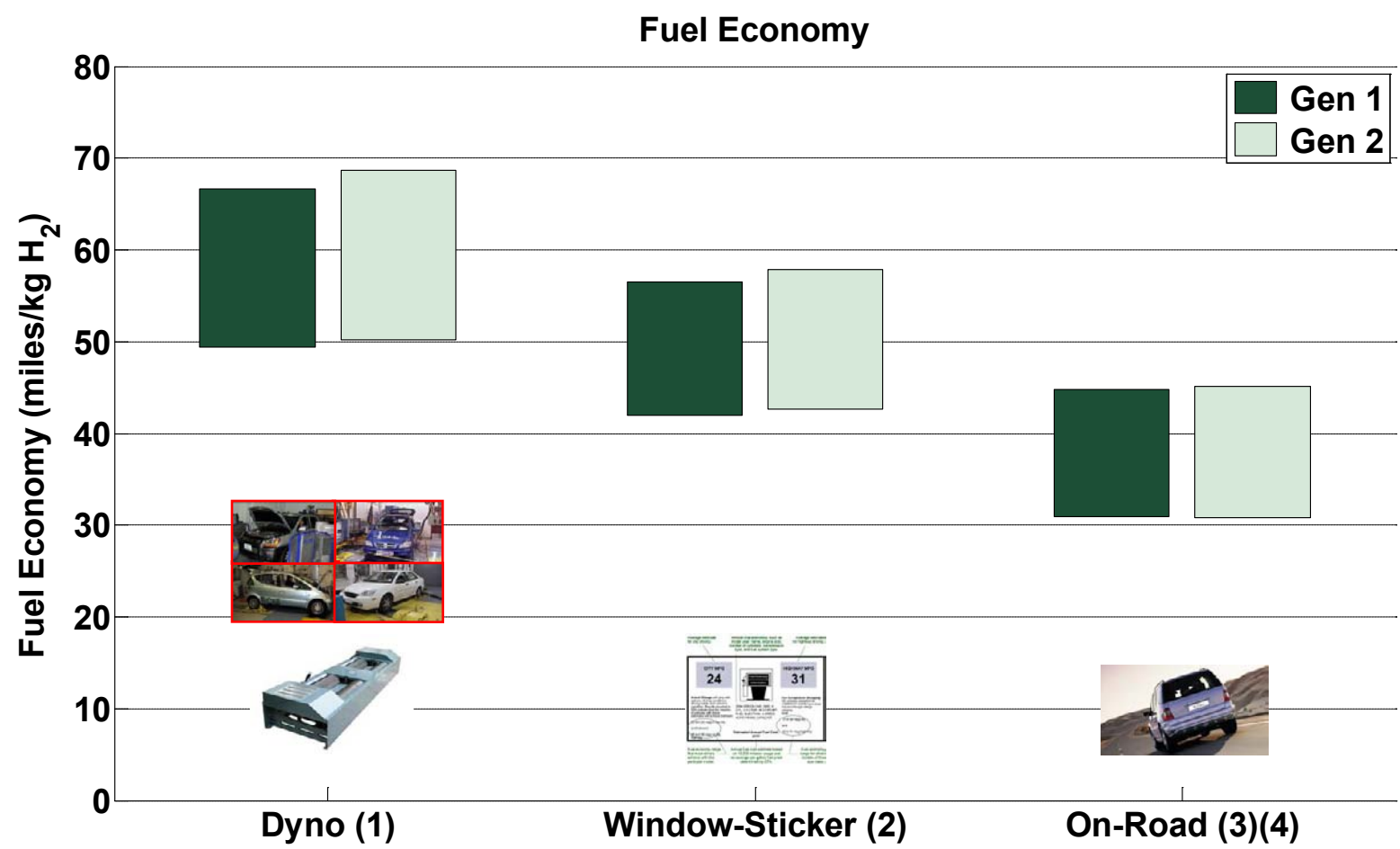
Large Data Sets Processed with NREL Tools; Two Types of Results Serve a Diverse Audience



Through September 2008:
270,000 individual vehicle trips
60 GB of on-road data



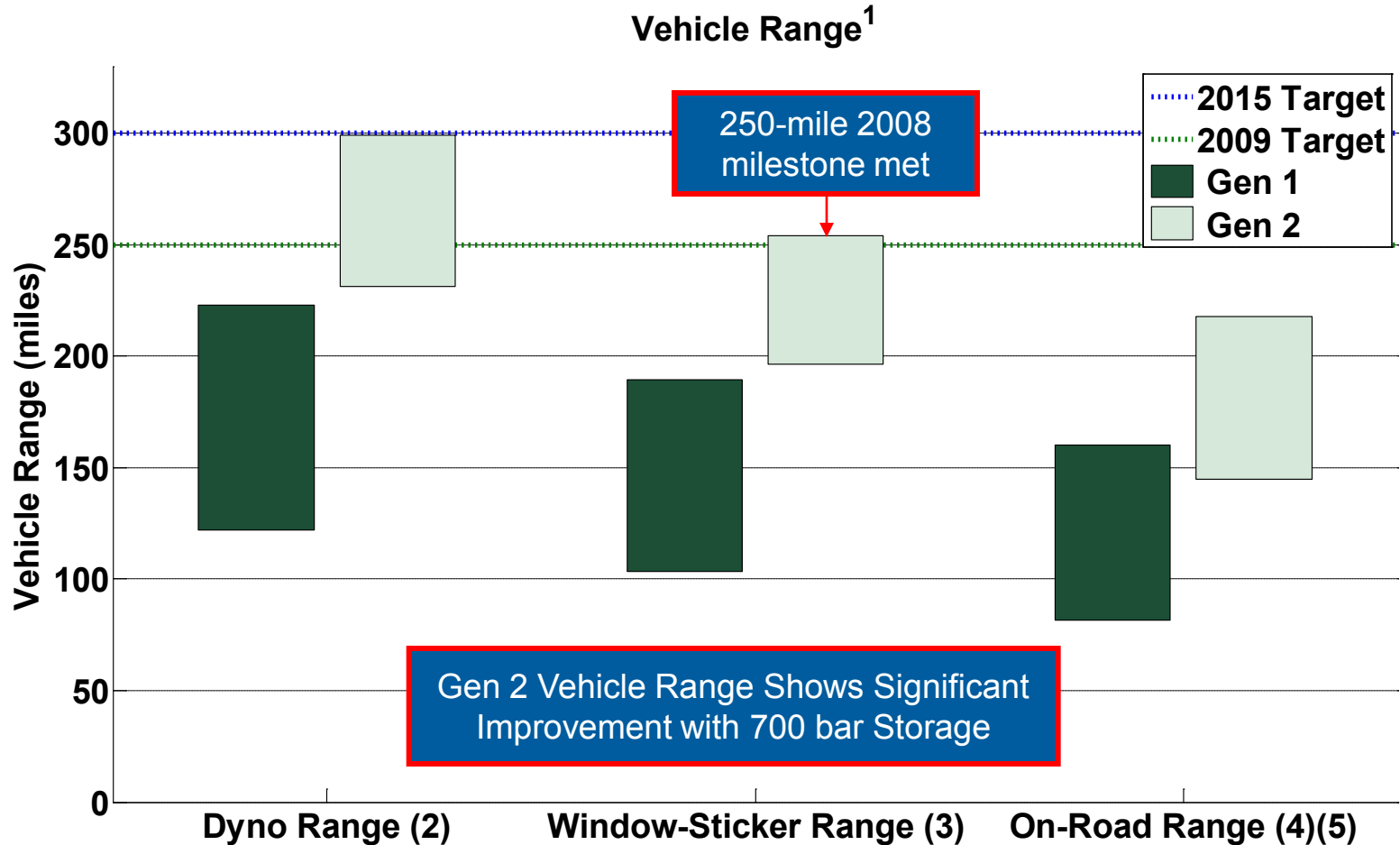
Ranges of Fuel Economy from Dynamometer and On-Road Data Similar for Gen 1 & 2



- (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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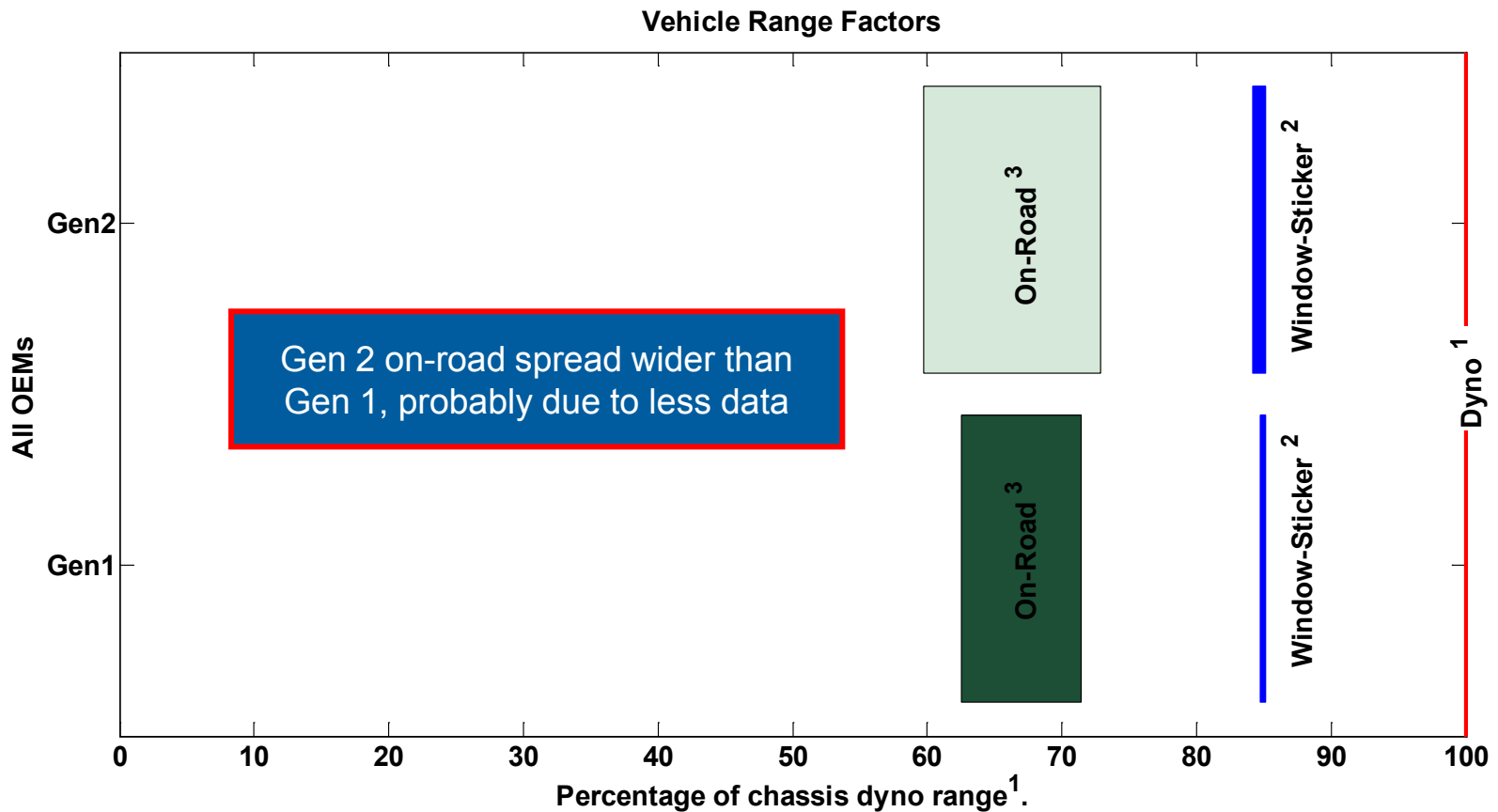
Vehicle Range Based on Dyno Results and Usable H2 Fuel Stored On-Board



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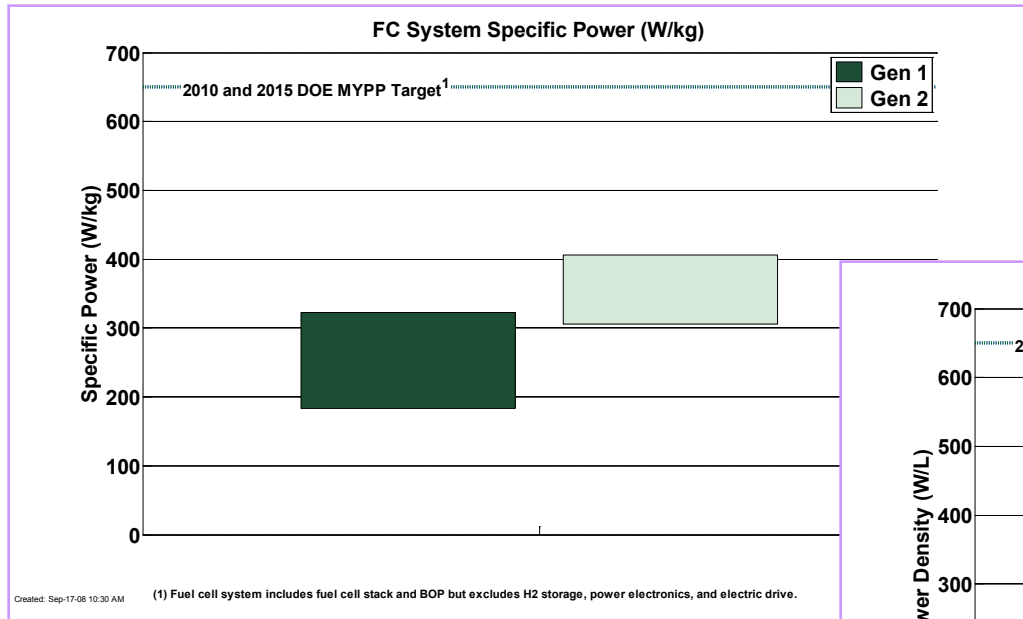
Spread of On-Road Range from Four Teams as a % of Dyno Range



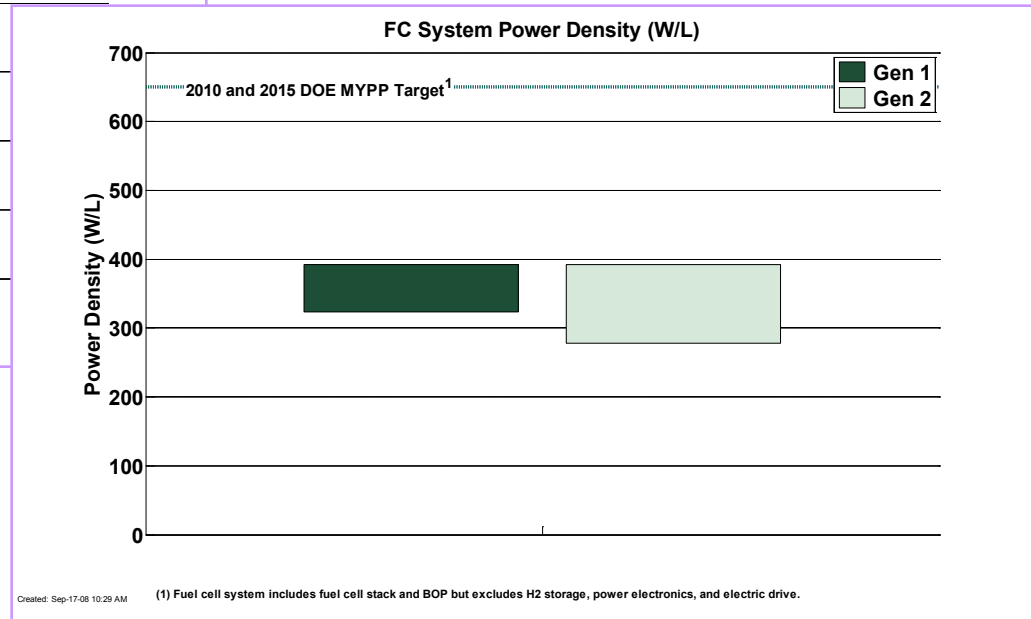
1. Calculated using the combined City/Hwy fuel economy from dyno testing (non-adjusted) and usable fuel on board.
2. Applying window-sticker correction factors for fuel economy: 0.78 x Hwy and 0.9 x City.
3. Using fuel economy from on-road data (excluding trips > 1 mile, consistent with other data products).

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

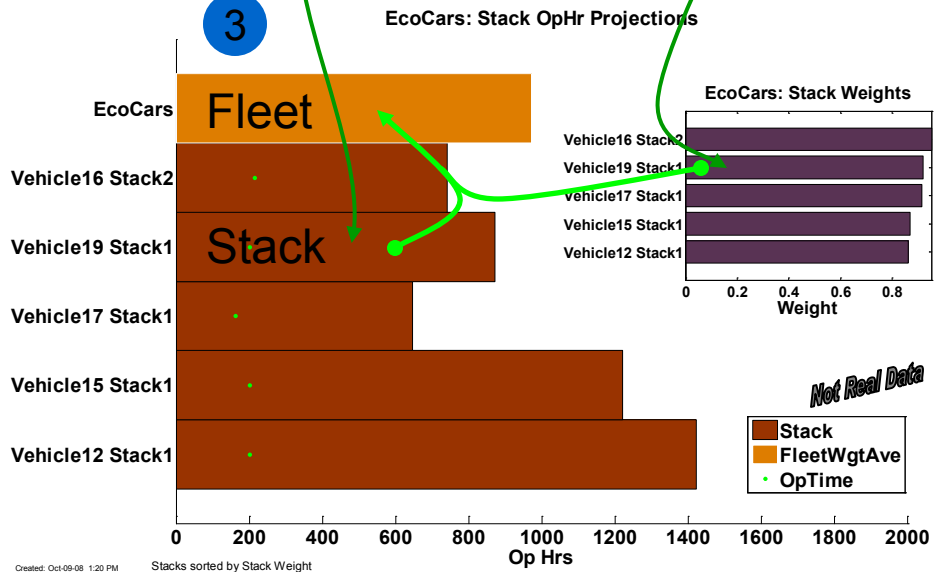
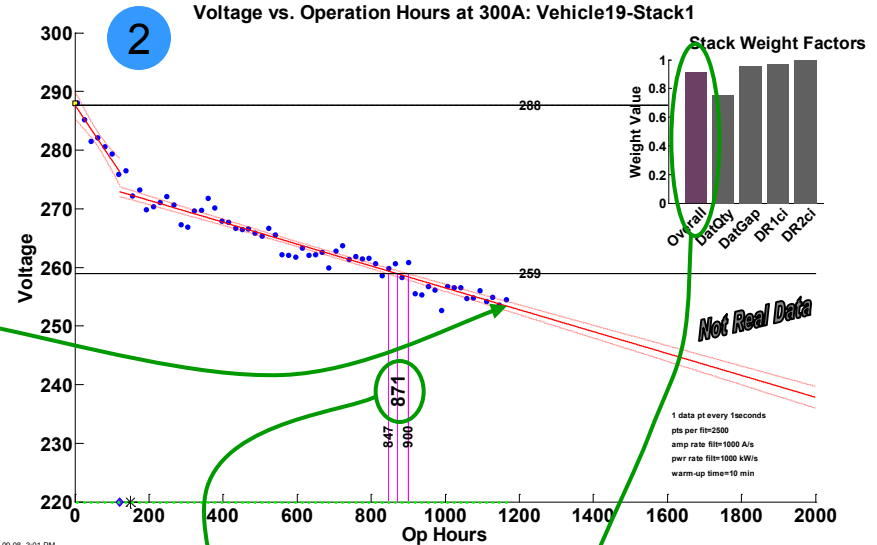
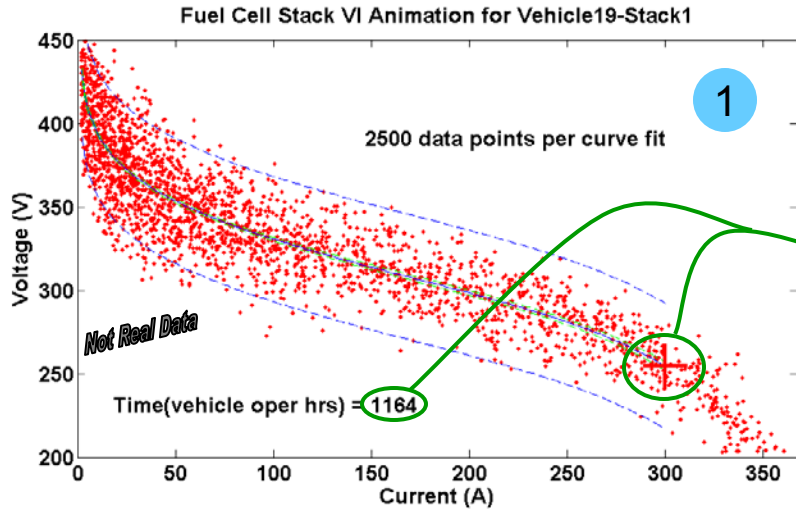


Significant Improvements Seen in Specific Power (...systems getting lighter)



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

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

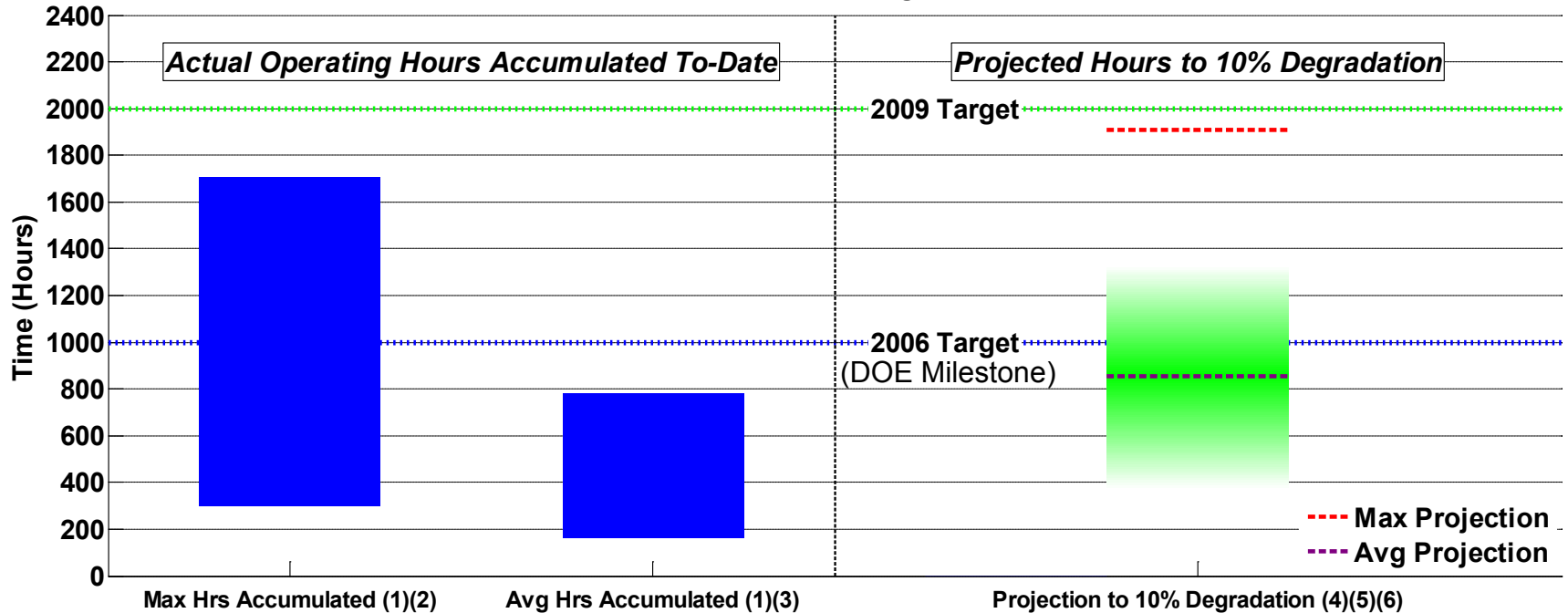


- FC Stack** voltage & current polarization fit
- FC Stack** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)
- Fleet** weighted average using FC Stack operating hour projections and weights (based on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

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

Some Gen 1 FC Stacks Have Now Accumulated a Significant Number of Hours Without Repair

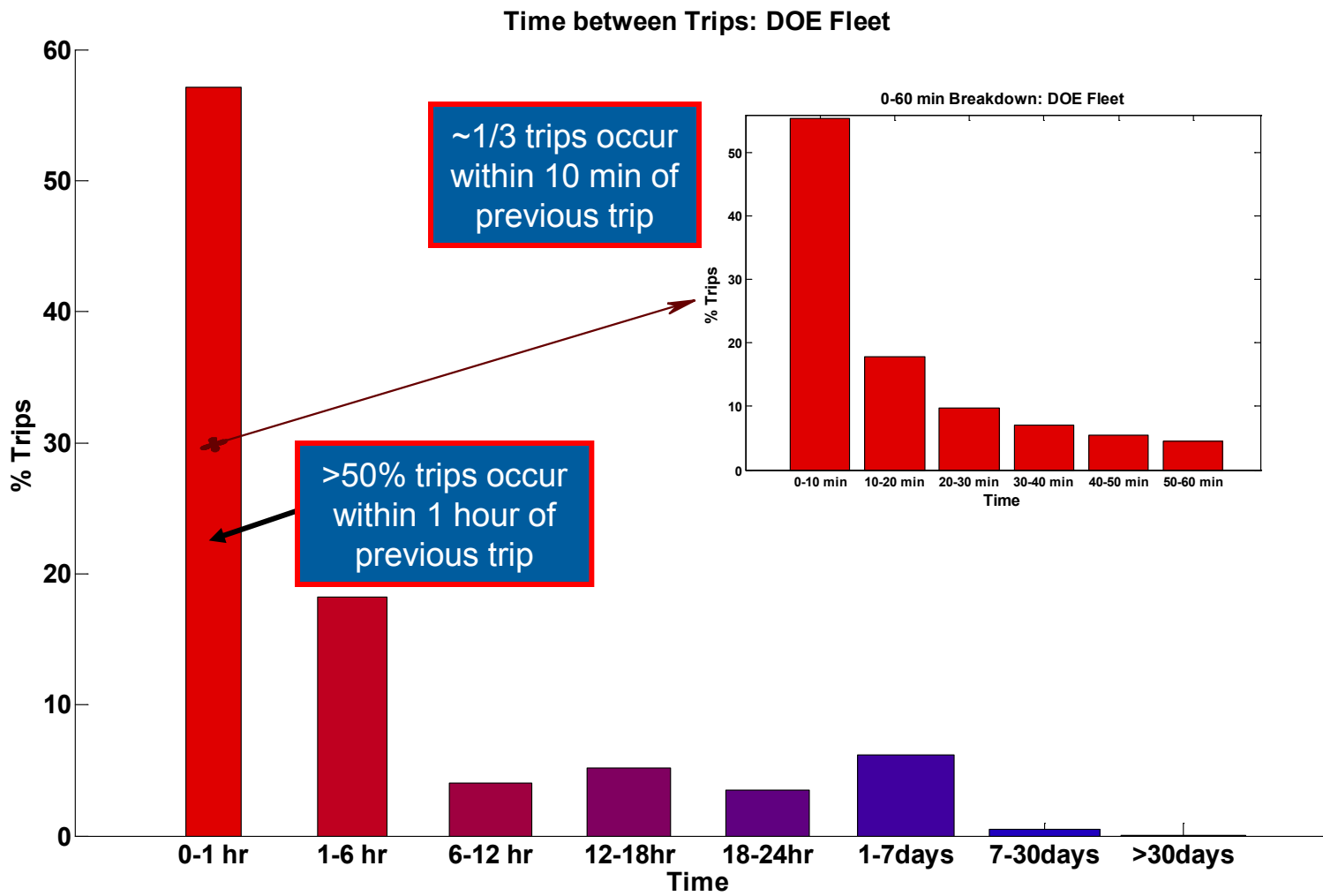
DOE Learning Demonstration Fuel Cell Stack Durability:
Based on Data Through 2008 Q2



- (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 green bar 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 2008 Q2 data.

More data required
to make Gen 2
projections (2009)

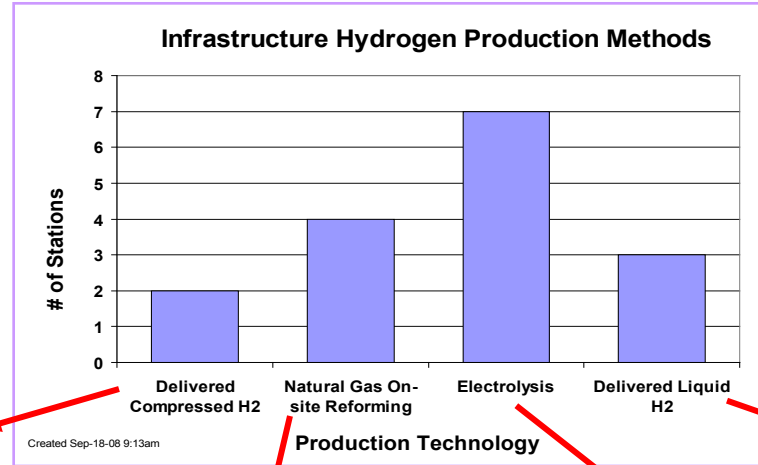
Examining Time Between Trips Shows Fuel Cells Experiencing Large Number of Hot Starts



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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



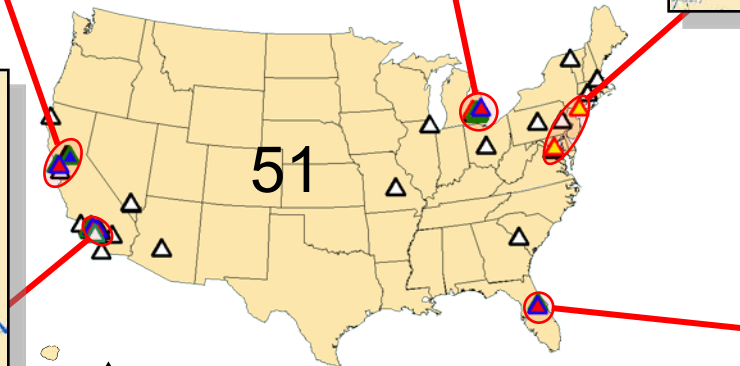
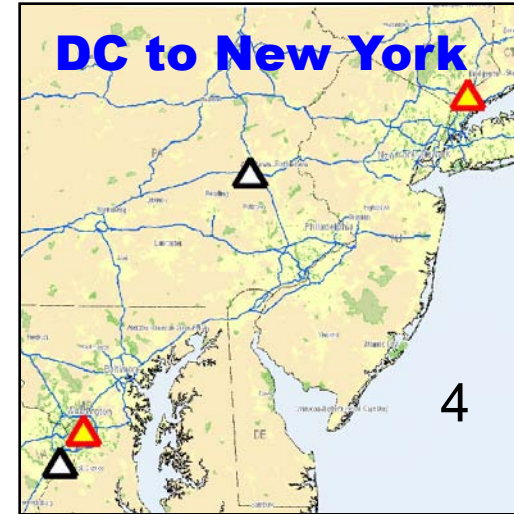
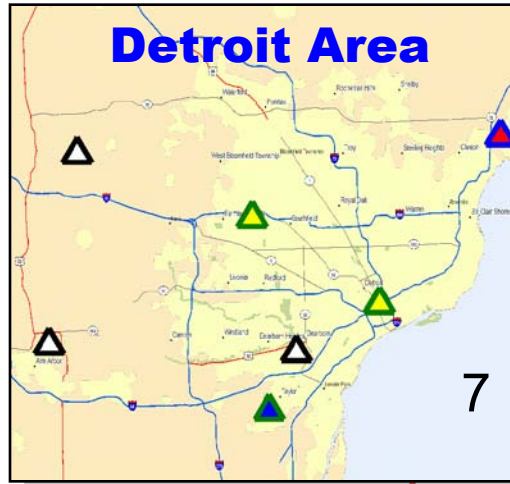
Water Electrolysis
Santa Monica, CA



Total of >60,000 kg H2 produced or dispensed

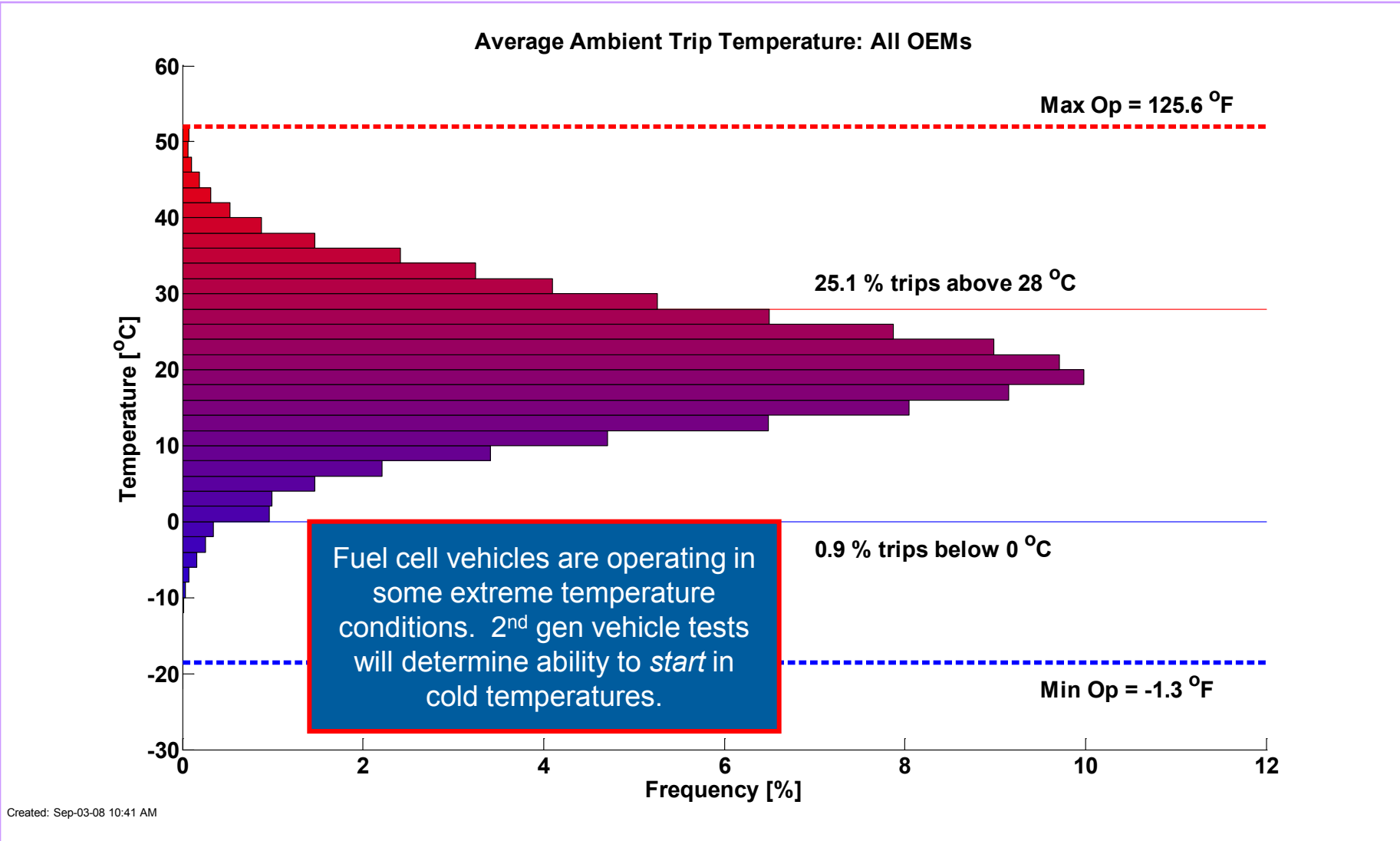
Recent station addition:
Santa Monica Blvd. (Shell)
16 stations now deployed

Refueling Stations Test Performance in Various Climates; Learning Demo Comprises ~1/4 of all US Stations



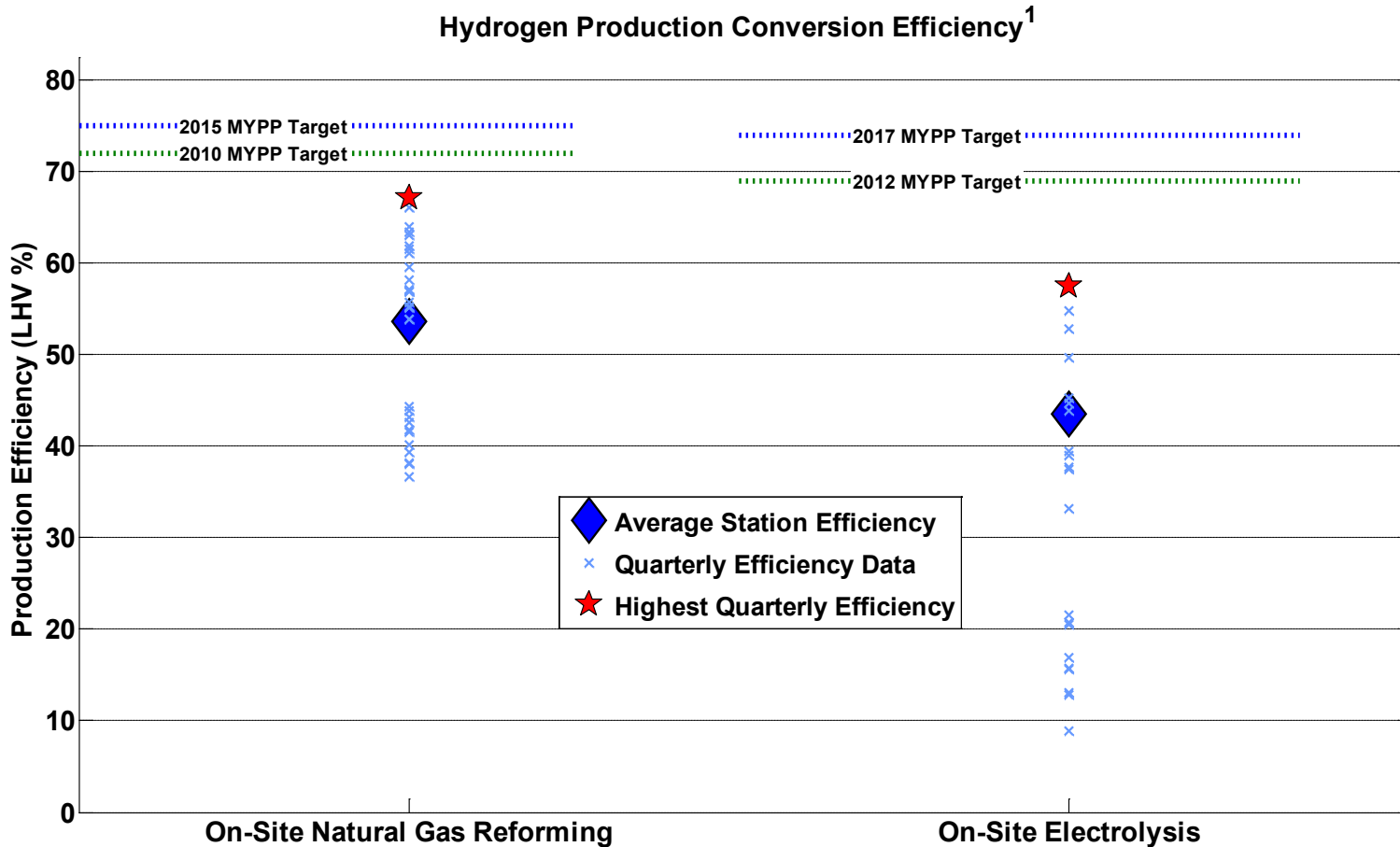
- Legend**
- ▲ Chevron & Hyundai/Kia
 - ▲ DaimlerChrysler & BP
 - ▲ Ford & BP
 - ▲ General Motors & Shell
 - ▲ Air Products
 - ▲ Other Companies

Range of Average Ambient Temperatures During Vehicle Operation



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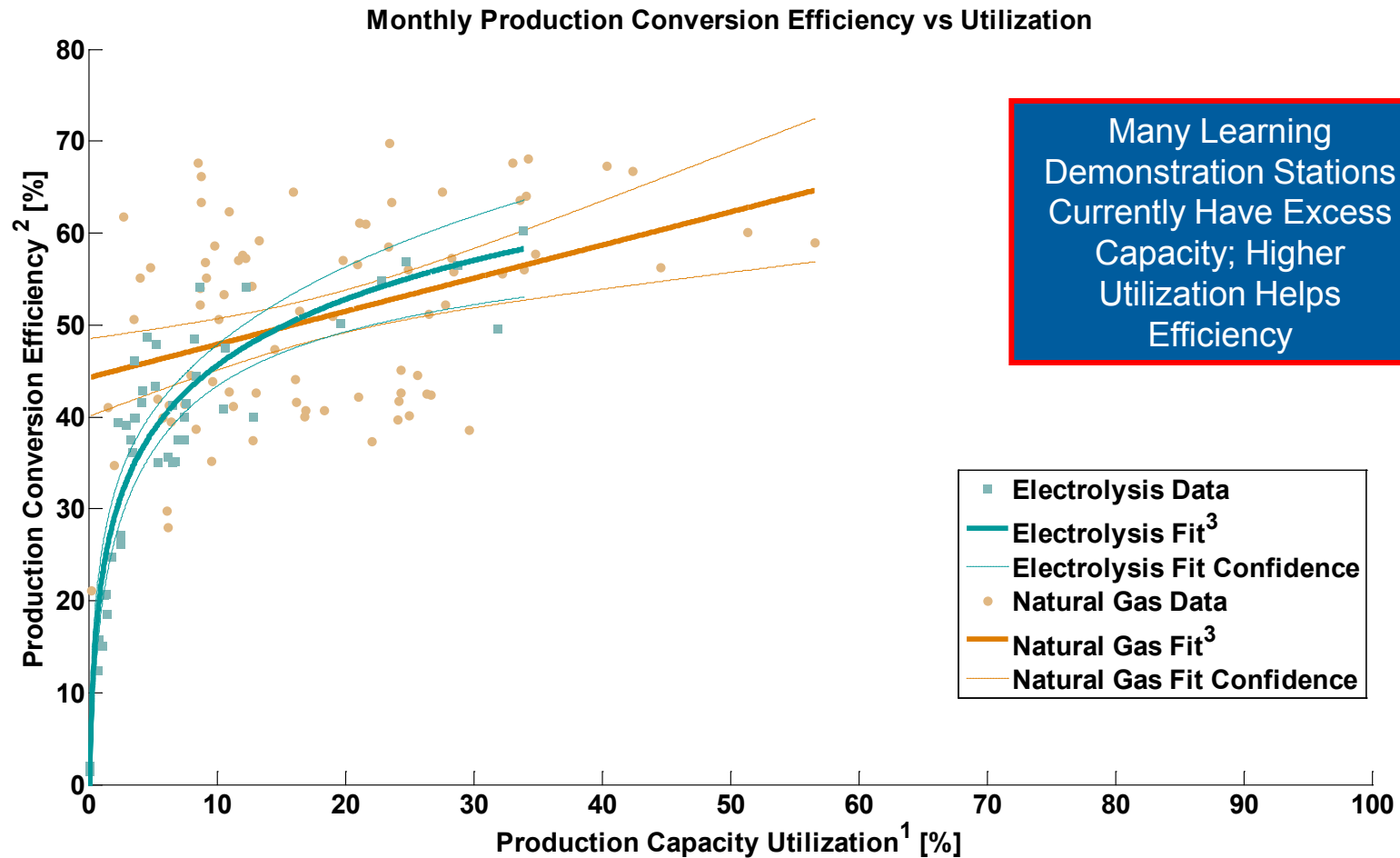
On-Site Production Efficiency from Natural Gas Reformation and Electrolysis Compared to Targets



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.

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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

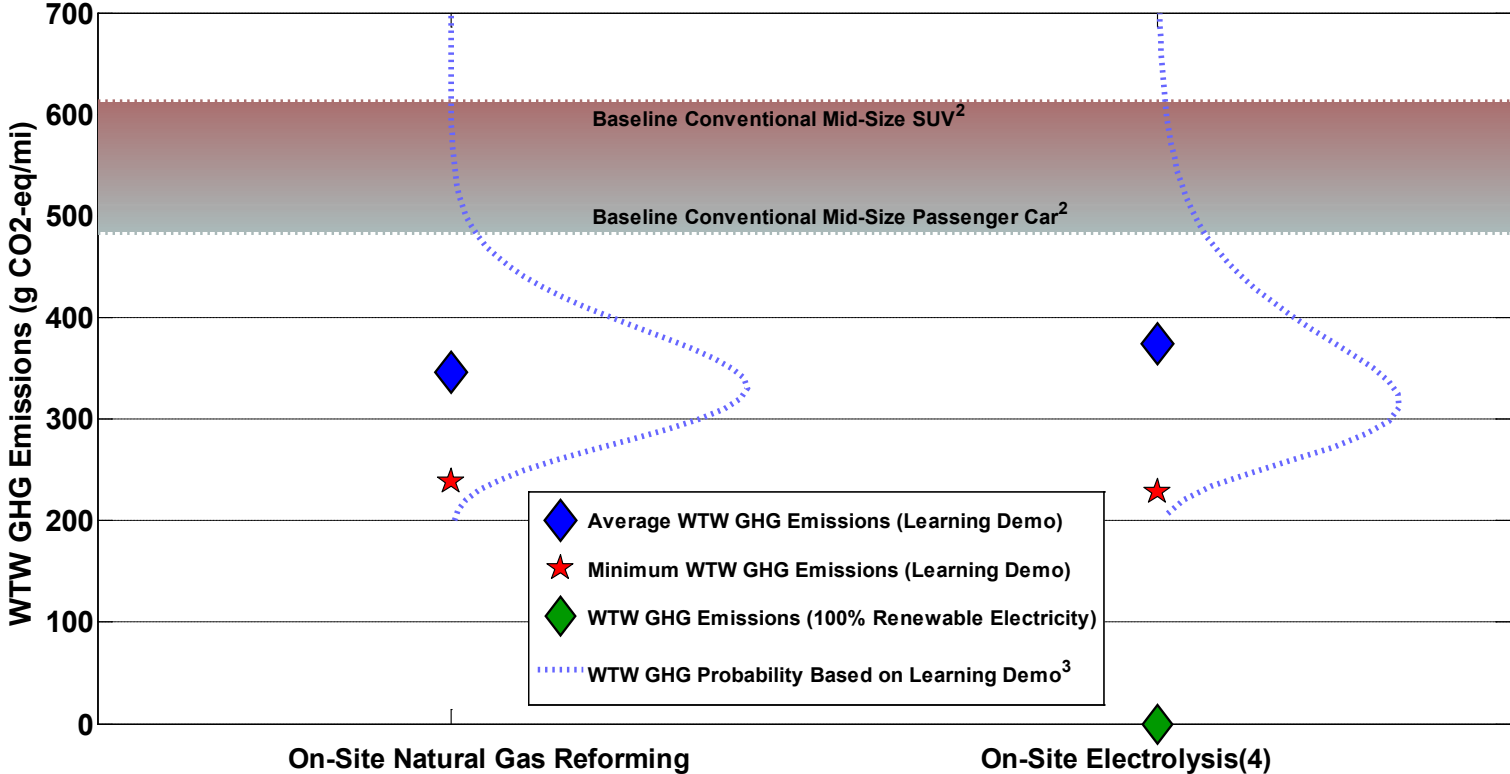
2) Production conversion efficiency is defined as the energy of the hydrogen out of the process (on a LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage,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

3) High correlation with electrolysis data ($R^2 = 0.81$) & low correlation with natural gas data ($R^2 = 0.058$)

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

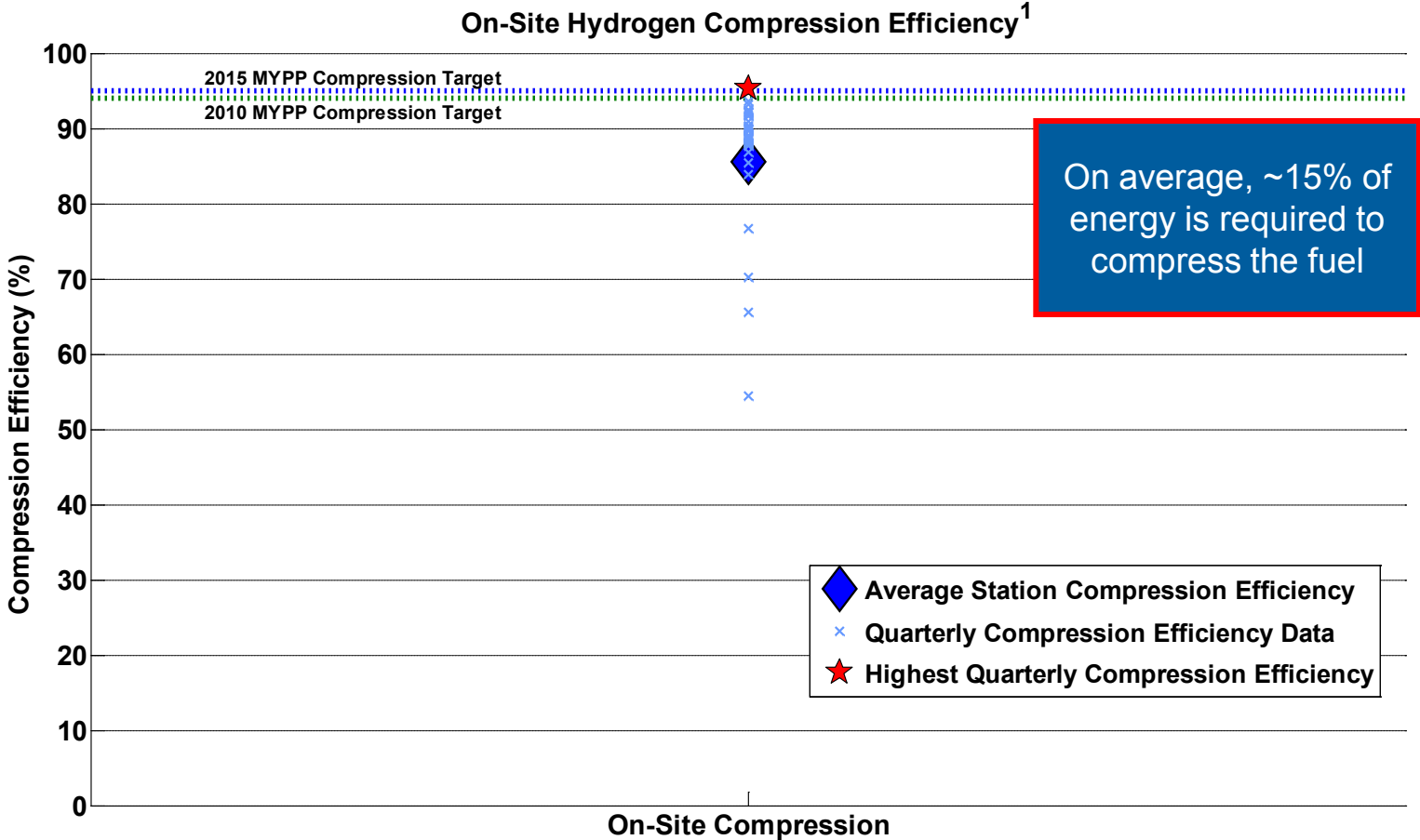
Learning Demonstration Fuel Cycle Well-to-Wheels Greenhouse Gas Emissions¹



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 1296 g/mile.

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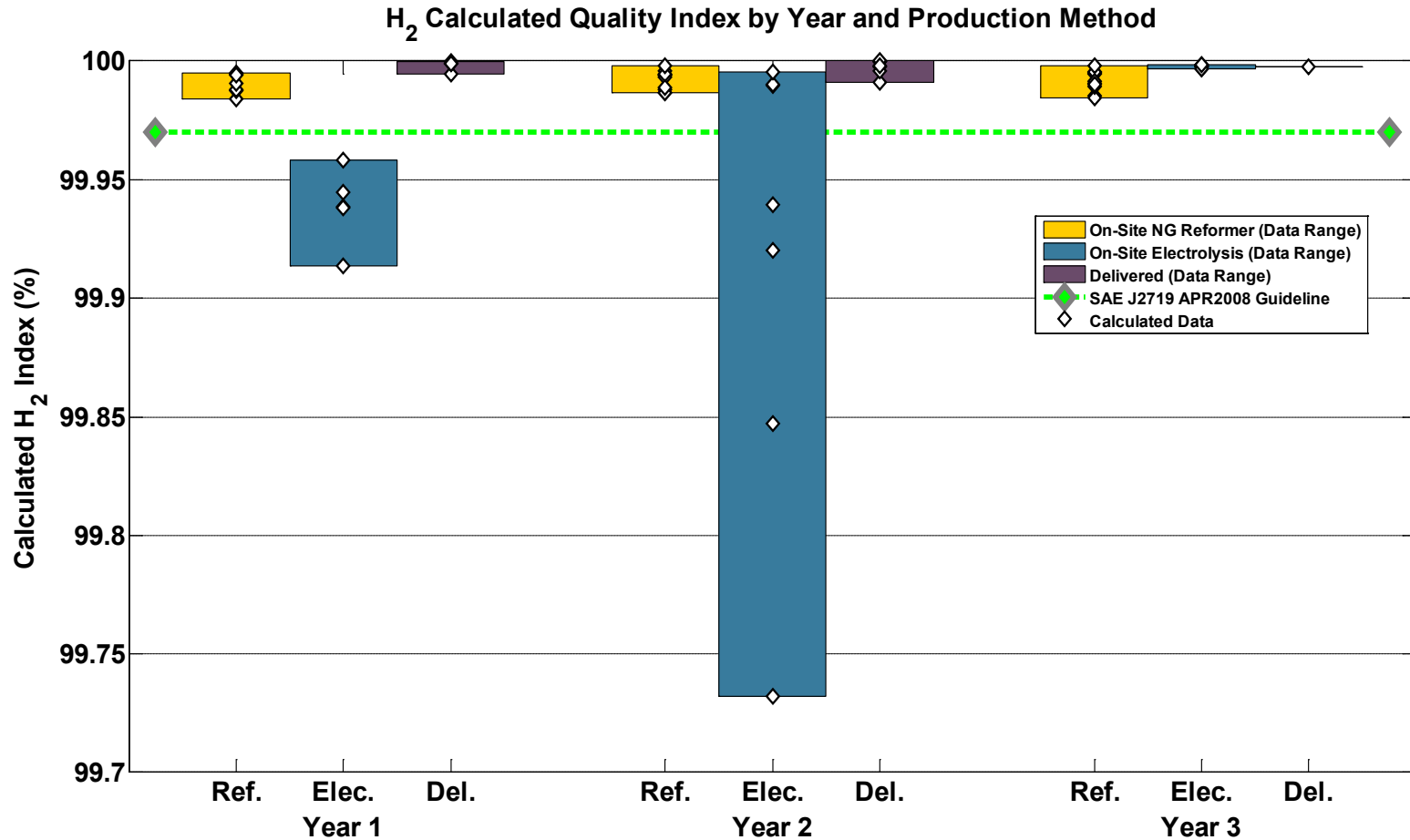
Hydrogen Refueling Station Compressor Efficiency Compared to Targets



¹Consistent with the MYPP, compression efficiency is defined as the energy of the hydrogen out of the process (on an LHV basis) divided by the sum of the energy of the hydrogen output plus all other energy needed for the compression process. Data shown for on-site hydrogen production and storage facilities only, not delivered hydrogen sites.

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Hydrogen Quality Index Close to Target Except for Some High Inert Gas Measurements

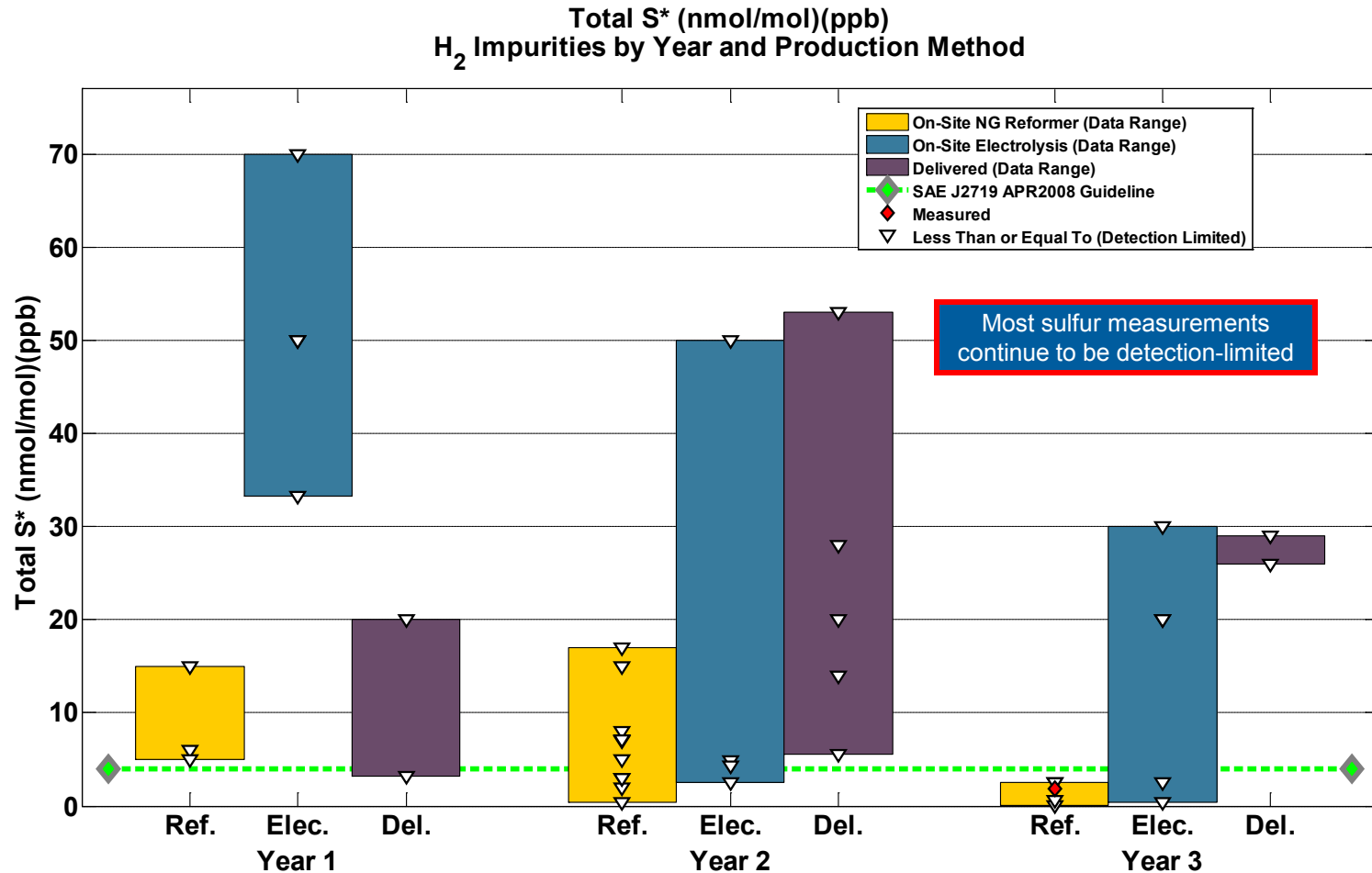


Data is from Learning Demonstration and California Fuel Cell Partnership testing
 Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, and Year 3 is 2007Q3-2008Q2

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Hydrogen Impurities by Year and Production Method

Method – Total Sulfur



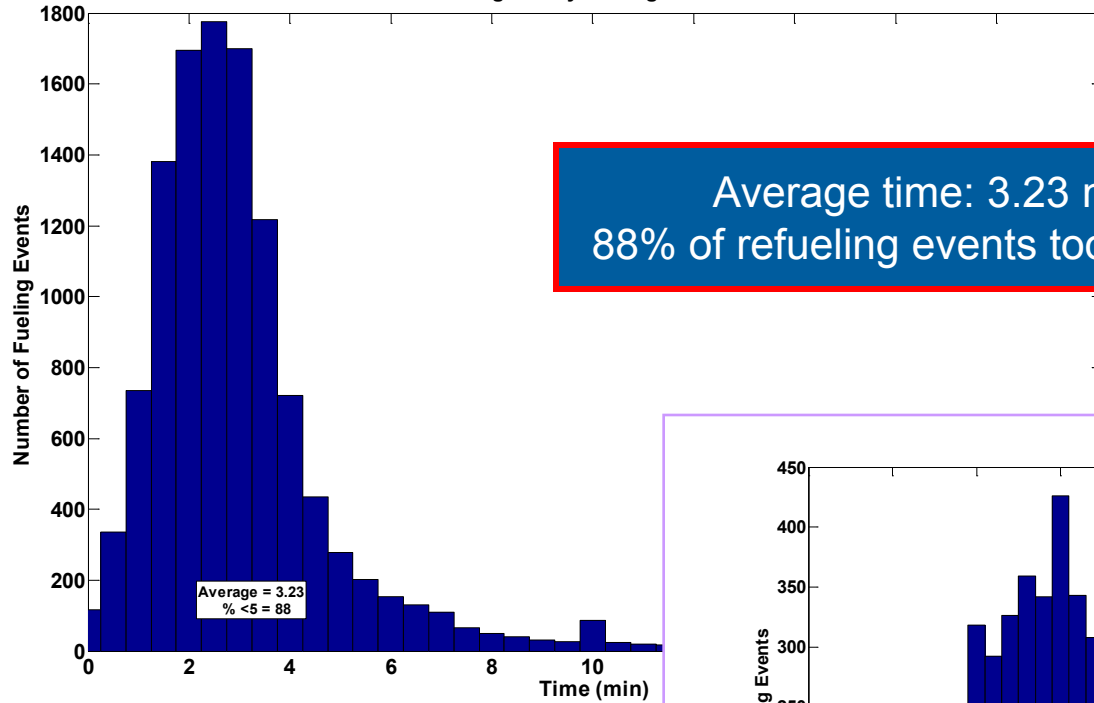
Most sulfur measurements continue to be detection-limited

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

This is 1 of over a dozen impurities now reported by time and production technology

Actual Vehicle Refueling *Times* and *Amounts* from 11,500 Events: Measured by Stations or by Vehicles

Histogram of Fueling Times
All Light Duty Through 2008Q2

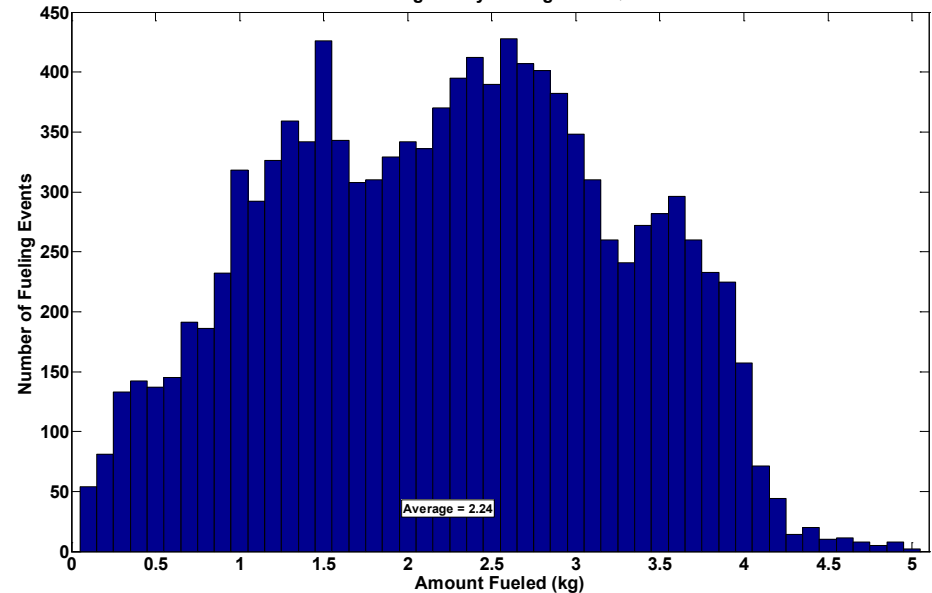


Average time: 3.23 min
88% of refueling events took <5 min

Average fill amount: 2.24 kg

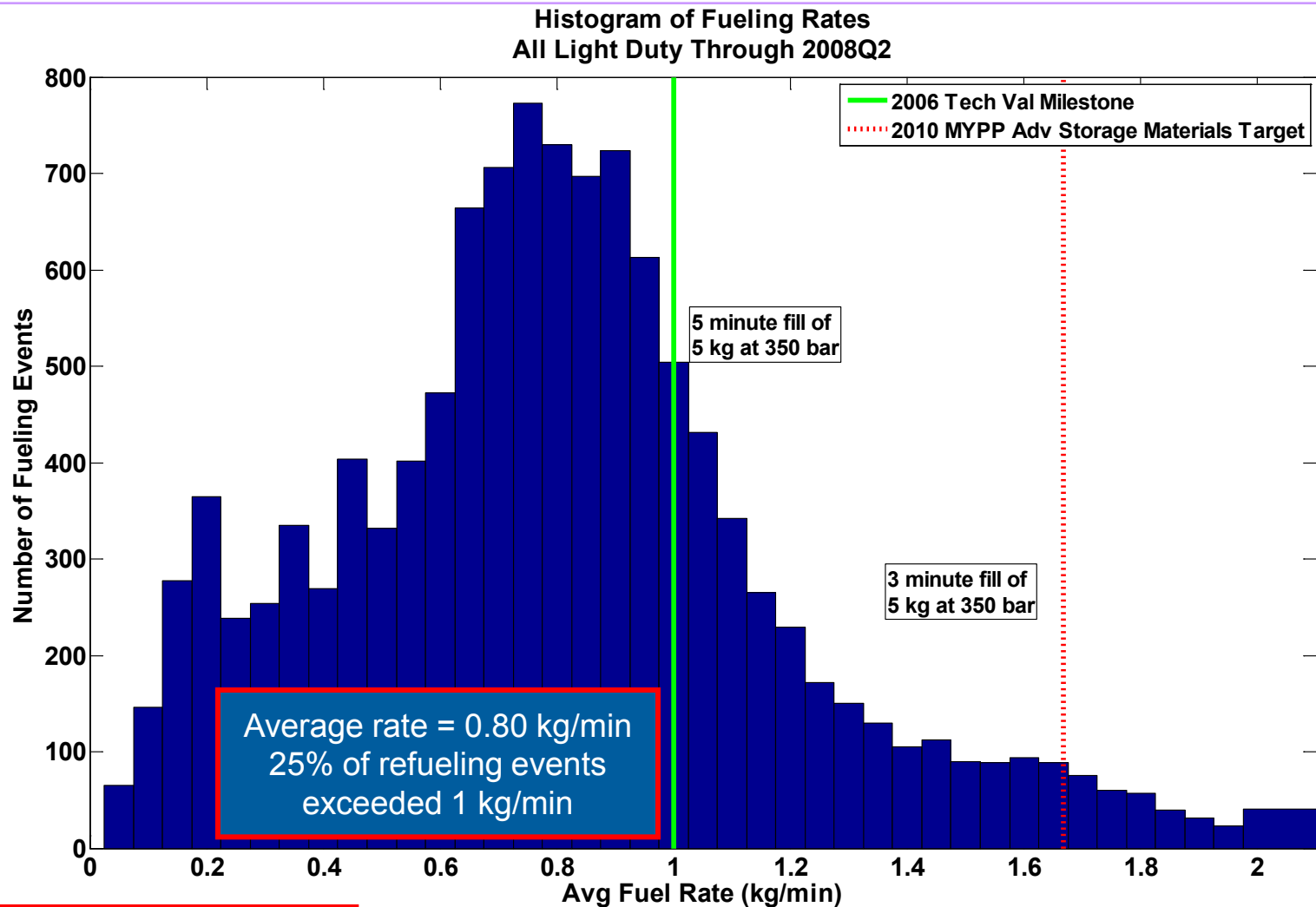
Includes Communication and
Non-Communication Fills

Histogram of Fueling Amounts
All Light Duty Through 2008Q2



Average = 2.24

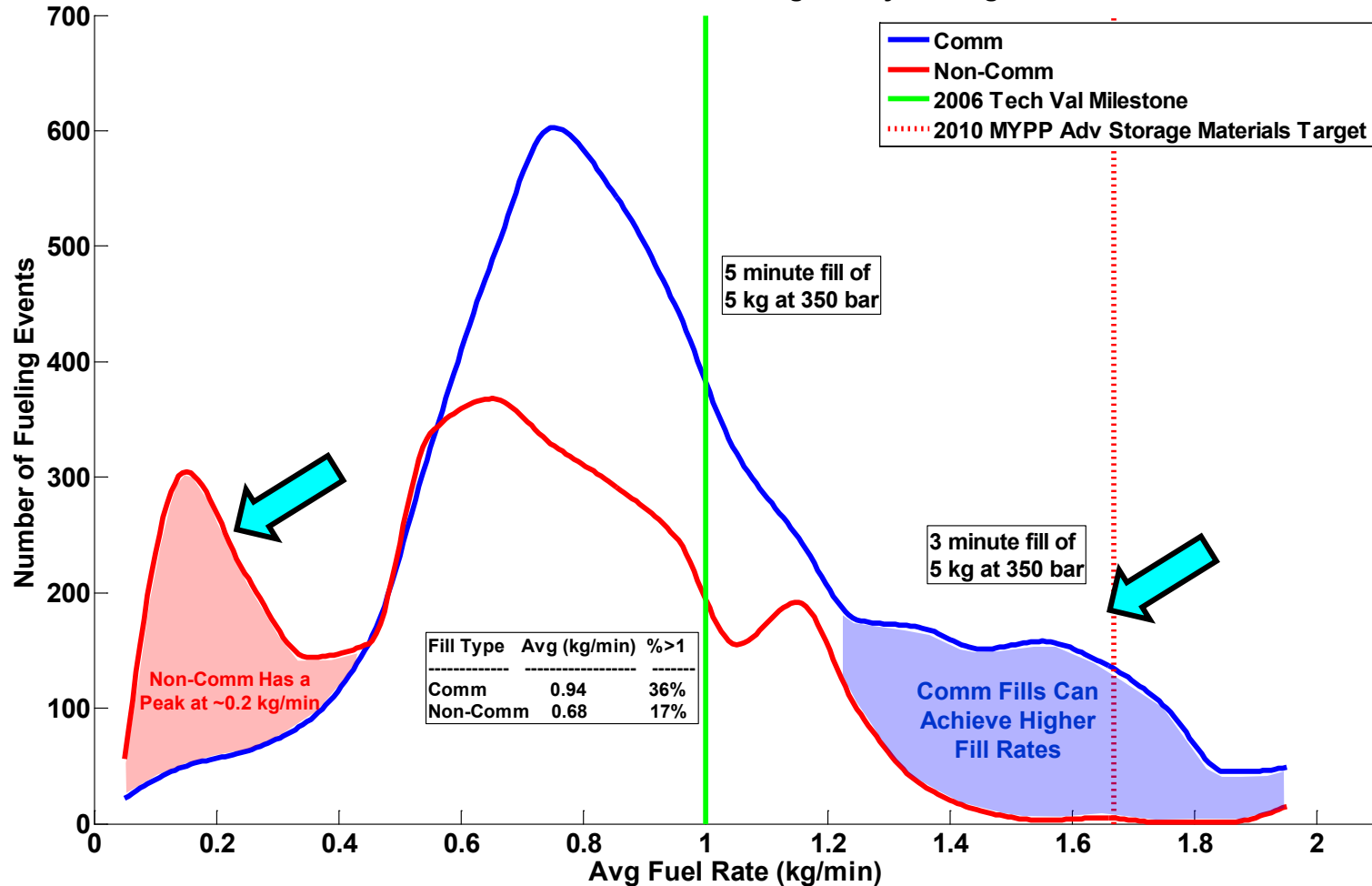
Actual Vehicle Refueling Rates from 11,500 Events: Measured by Stations or by Vehicles



Includes Communication and Non-Communication Fills

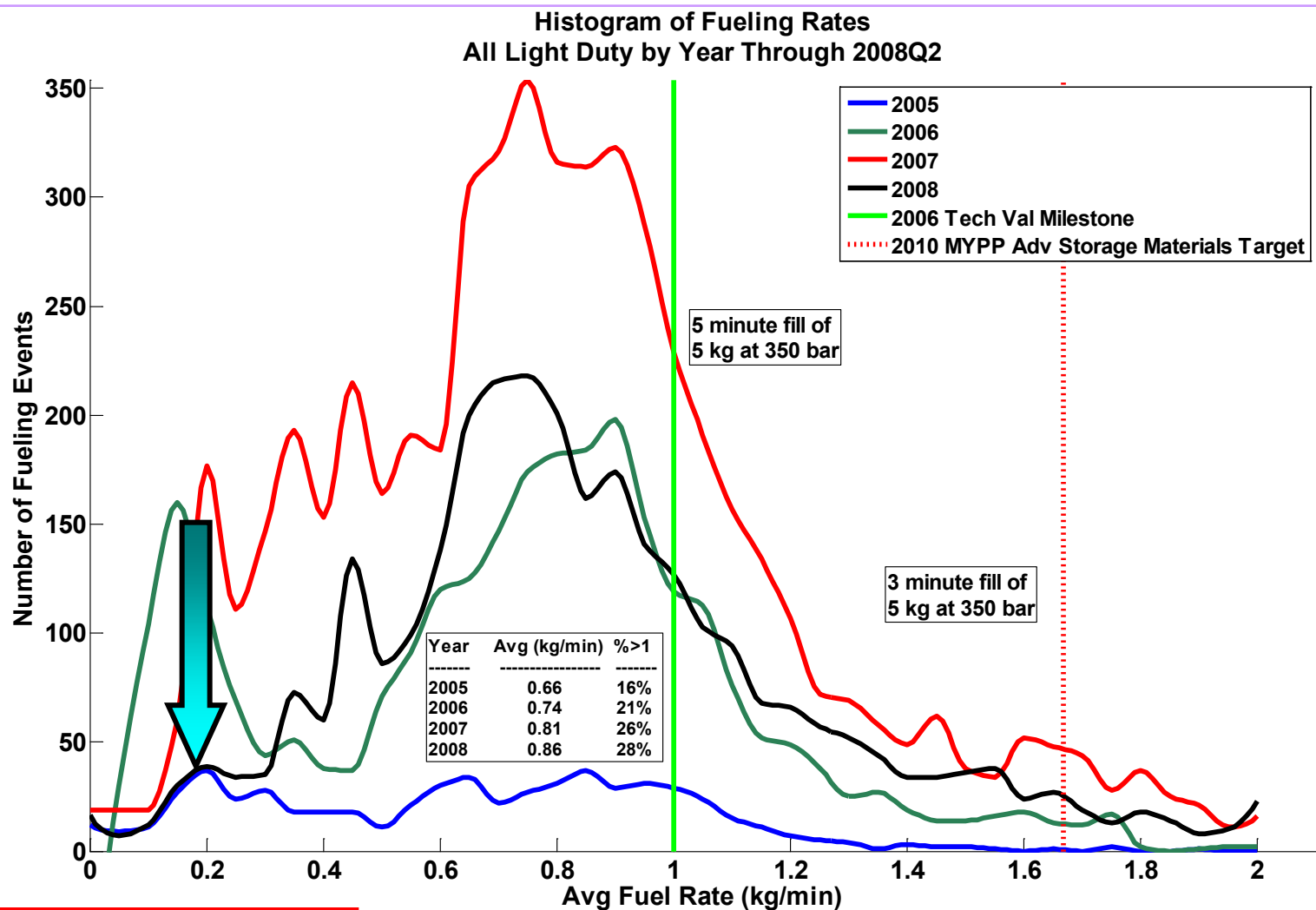
Communication H2 Fills Achieving Higher Fill Rate than Non-Communication

Histogram of Fueling Rates
Comm vs Non-Comm Fills - All Light Duty Through 2008Q2



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Examining Refueling Data by Year Shows 0.2 kg/min Rate Phased Out

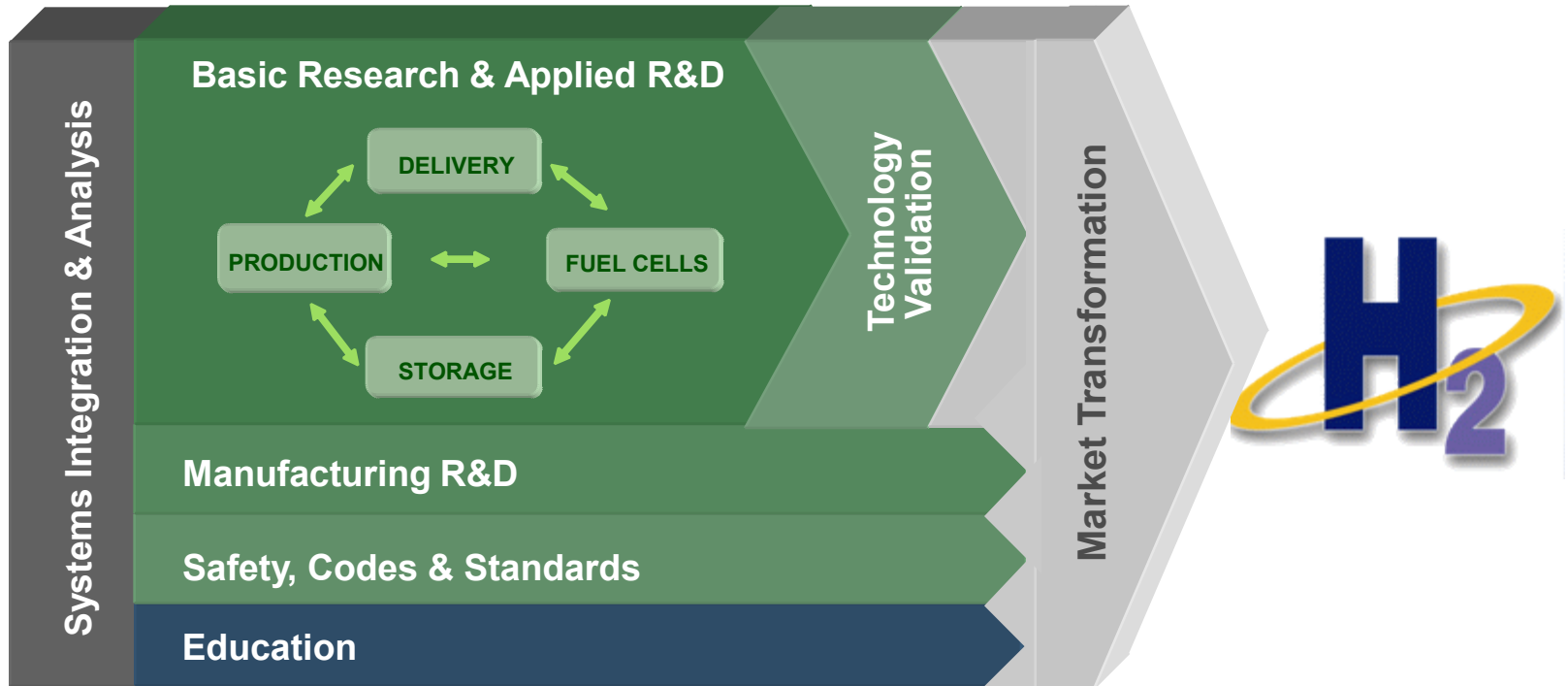


Includes Communication and Non-Communication Fills

Summary

- Learning Demo project is ~60% complete
 - 122 vehicles and 16 stations deployed
 - 1.5 million miles traveled, 60,000 kg H₂ produced or dispensed
 - 270,000 individual vehicle trips analyzed
 - Project to continue through 2010 with additional vehicles & stations
- Many new results in the Fall 2008 composite data products
 - 50 new/updated results, 3 unchanged, for a total of 53
 - Several Gen 1 vs. Gen 2 vehicle comparisons
 - Hydrogen production efficiency related results
 - Vehicle greenhouse gas estimates using actual production efficiencies
 - Fuel cell system W/kg and W/L
 - Hydrogen impurity breakdown by year and production technology
- All results available on web site
- Roll-out of 2nd generation vehicles continues
 - Most of remaining vehicles to be deployed this year
 - Additional 700 bar stations coming online soon

Questions and Discussion



Project Contact: Keith Wipke, National Renewable Energy Lab
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All public Learning Demo papers and presentations are available
online at http://www.nrel.gov/hydrogen/proj_tech_validation.html