National Renewable Energy Laboratory
*Innovation for Our Energy Future*

# Fuel Cell Vehicle and Infrastructure Learning Demonstration Status and Results

**214th Electrochemical Society Meeting**

**Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden, John Garbak**

**October 13, 2008**
**Honolulu, HI**

NREL/PR-560-44266

# Outline

- Objectives and Partners
- NREL's Role in the Project and Methodology
- How to Access Complete Results
- Analysis Results
- Summary

# Fuel Cell Vehicle Learning Demonstration Project Objectives and Targets

## Objectives

- Validate $H_2$ FC Vehicles and Infrastructure in Parallel
- Identify Current Status and Evolution of the Technology
  - Assess Progress Toward Technology Readiness
  - Provide Feedback to $H_2$ 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

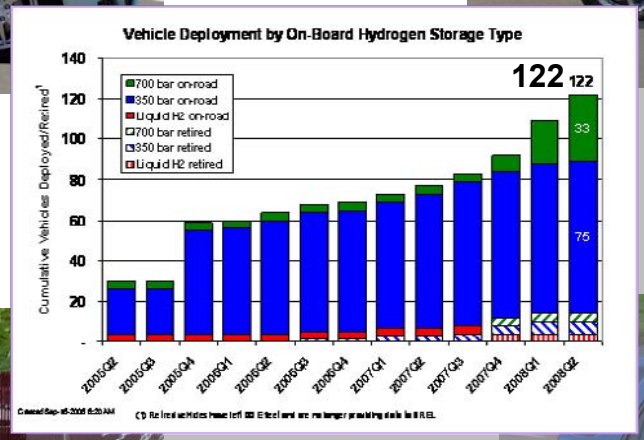


CHRYSLER

bp


Ford

bp






GM

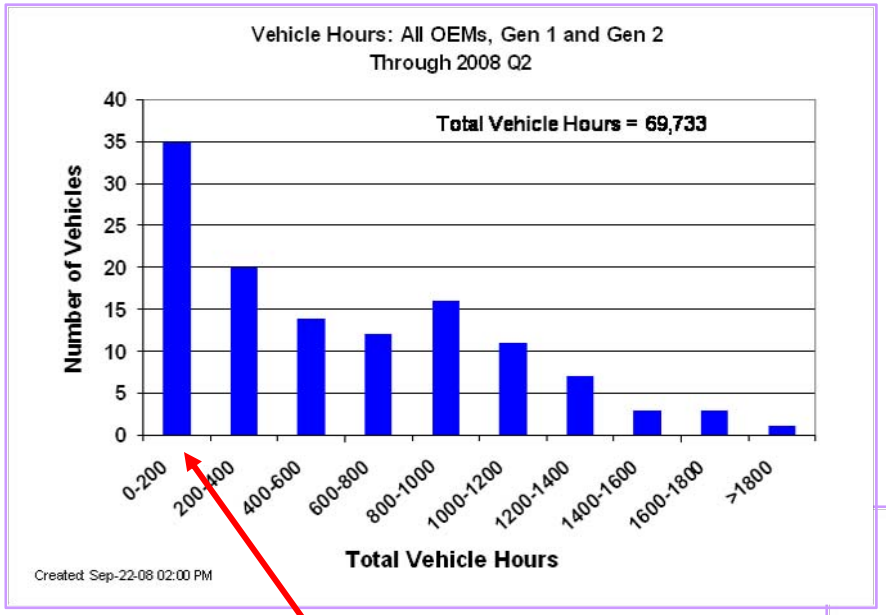

Chevron

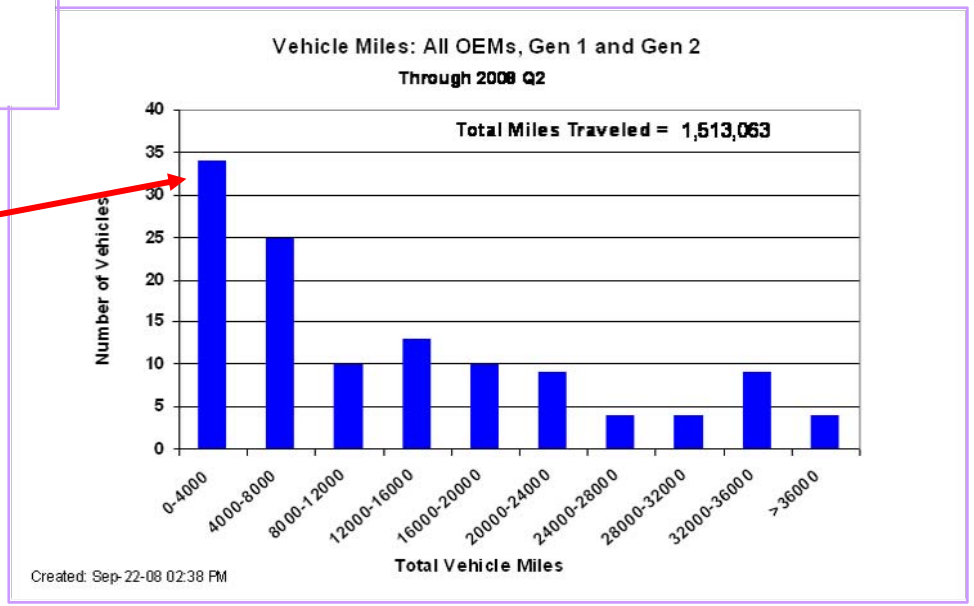
HYUNDAI

KIA

UTC Power
A United Technologies Company

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

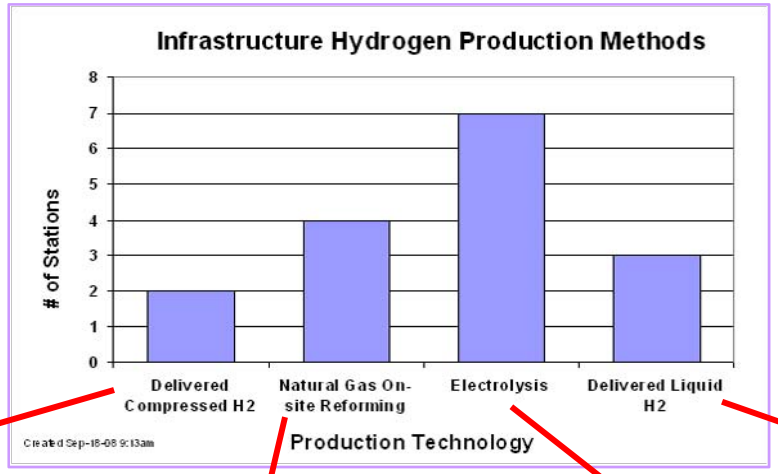



Gen 2 vehicle introduction now appears as the 2nd bulge at low hours/miles

# 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

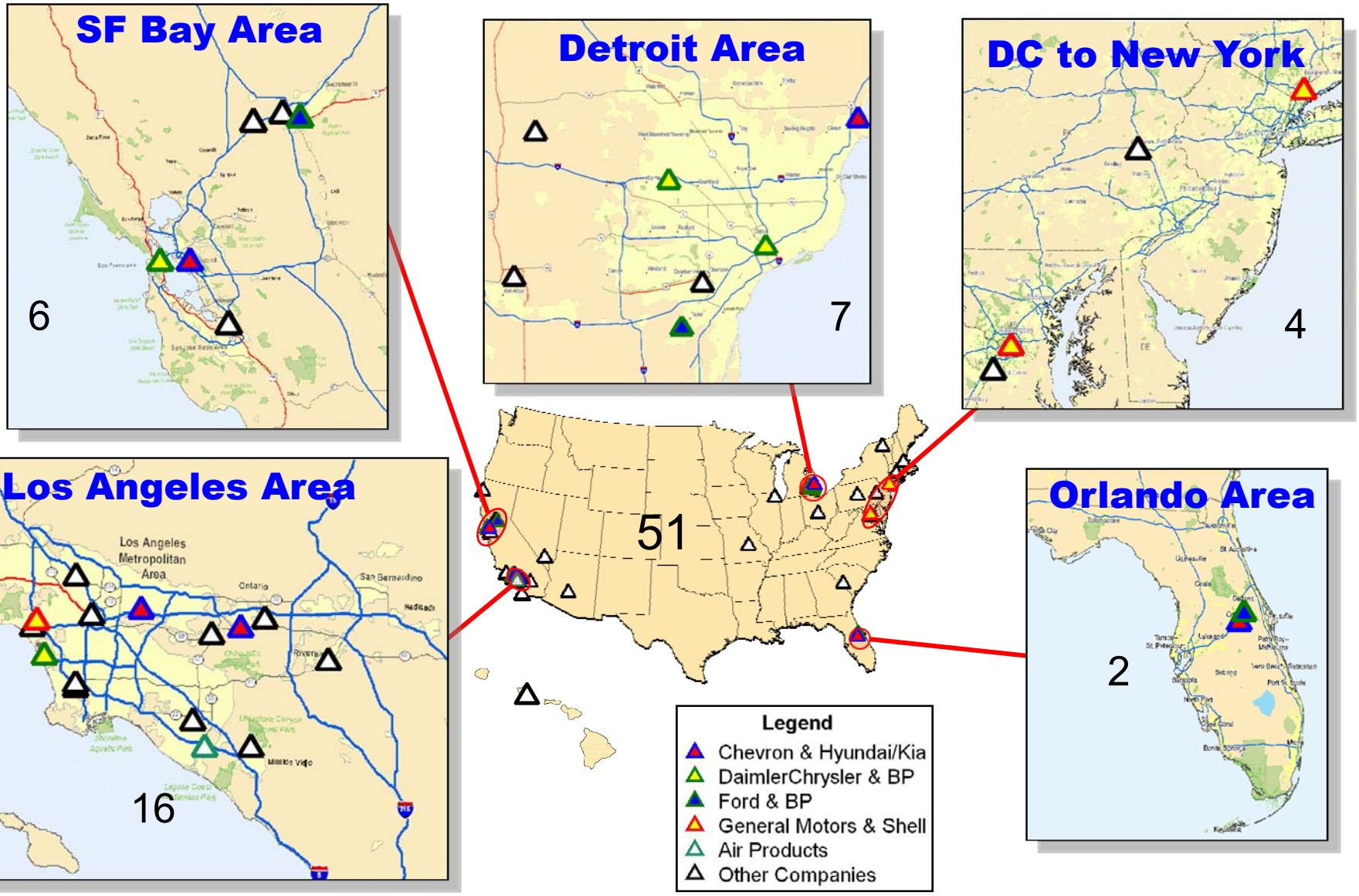
Total of >60,000 kg H2 produced or dispensed

Steam Methane Reforming
Oakland, CA

Water Electrolysis
Santa Monica, CA

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

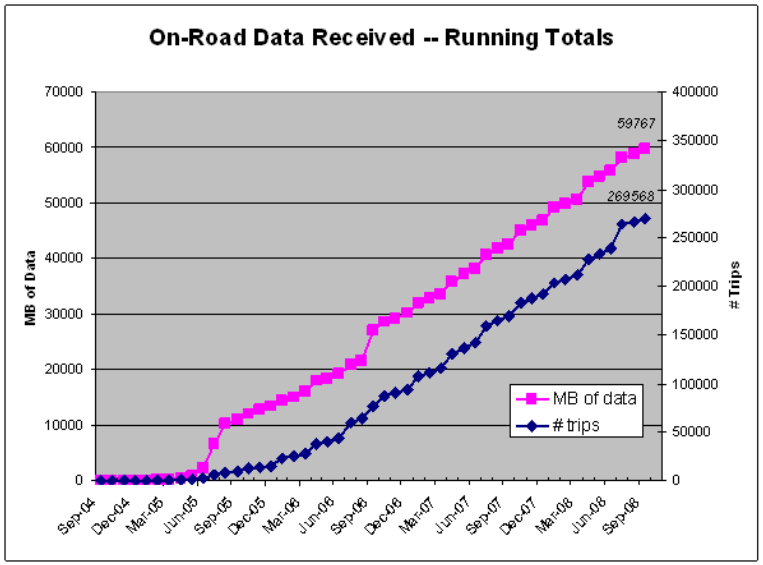
# Refueling Stations Test Performance in Various Climates; Learning Demo Comprises ~1/4 of all US Stations

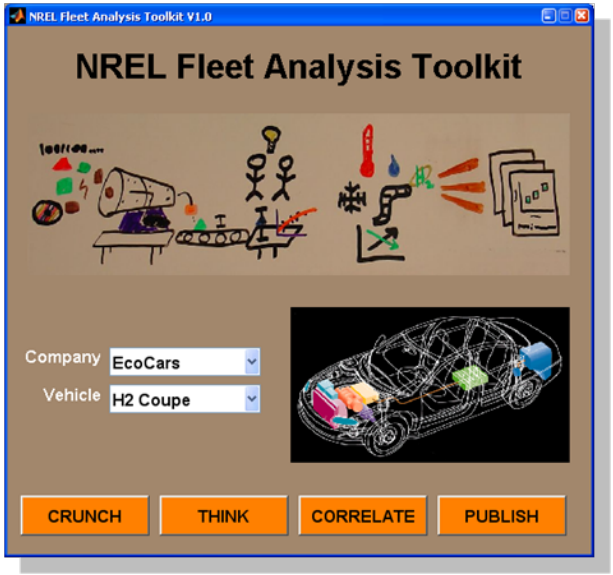



Oct-09-2008

# Extremely Large Data Sets Have Resulted in Sophisticated NREL-Developed Data Processing Tools

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



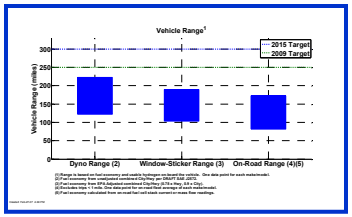

**NREL HSDC**

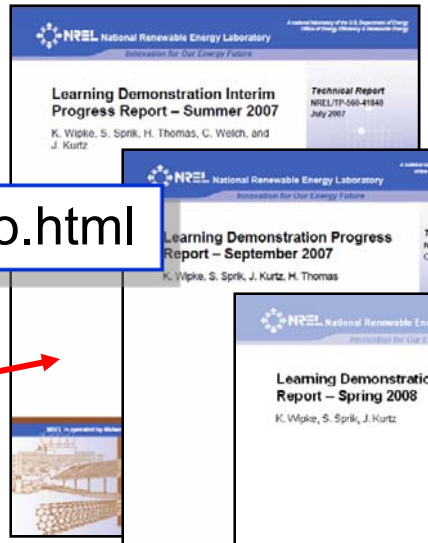
Composite Data Products → http://www.nrel.gov/hydrogen/cdp_topic.html

Detailed Data Products → Individual Team Discussions

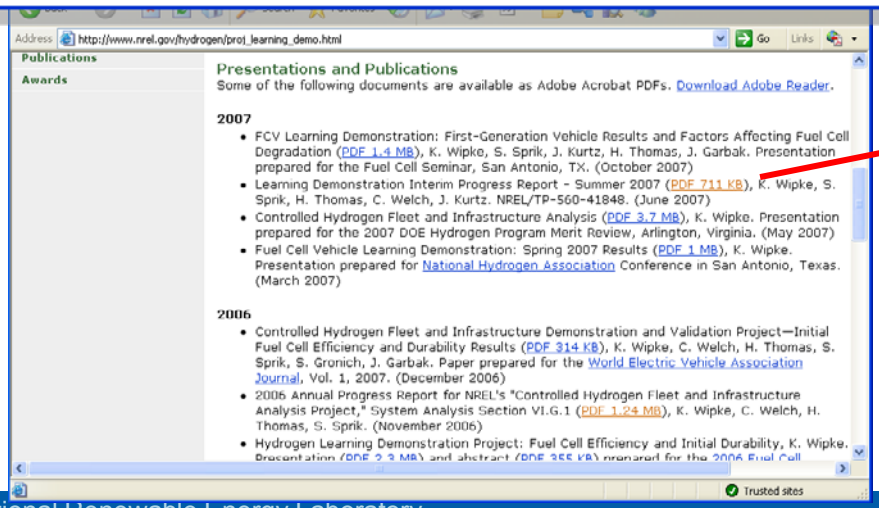
Data Flow

# NREL Web Site Provides Direct Access to All Composite Data Products (53), Reports, and Presentations

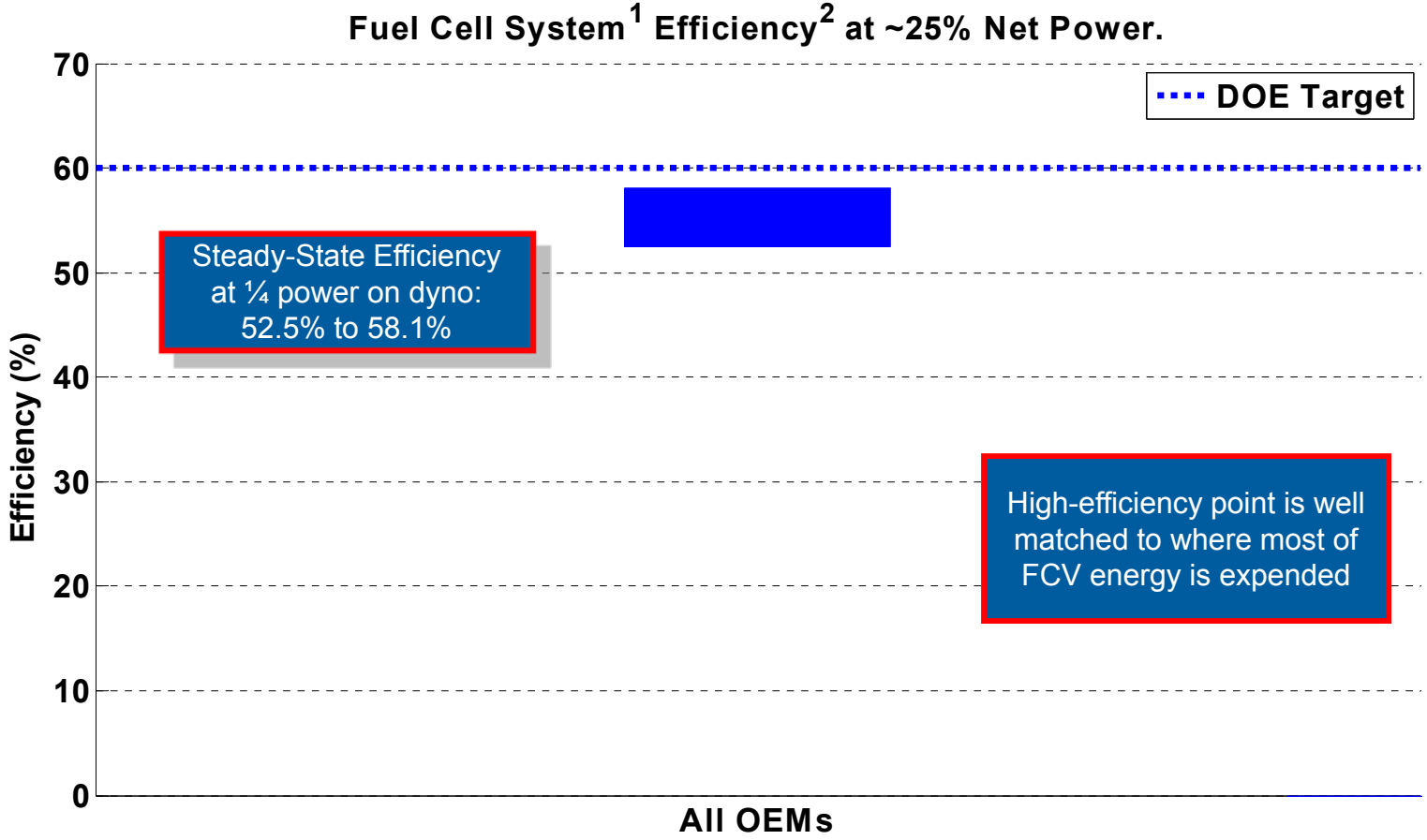




http://www.nrel.gov/hydrogen/proj_learning_demo.html




A subset of the 53 latest results will be presented now

# Gen 1 Baseline Dyno Tests Validated High Efficiency at ¼ Power Point – *Gen 2 Efficiency Results Public in 2009*

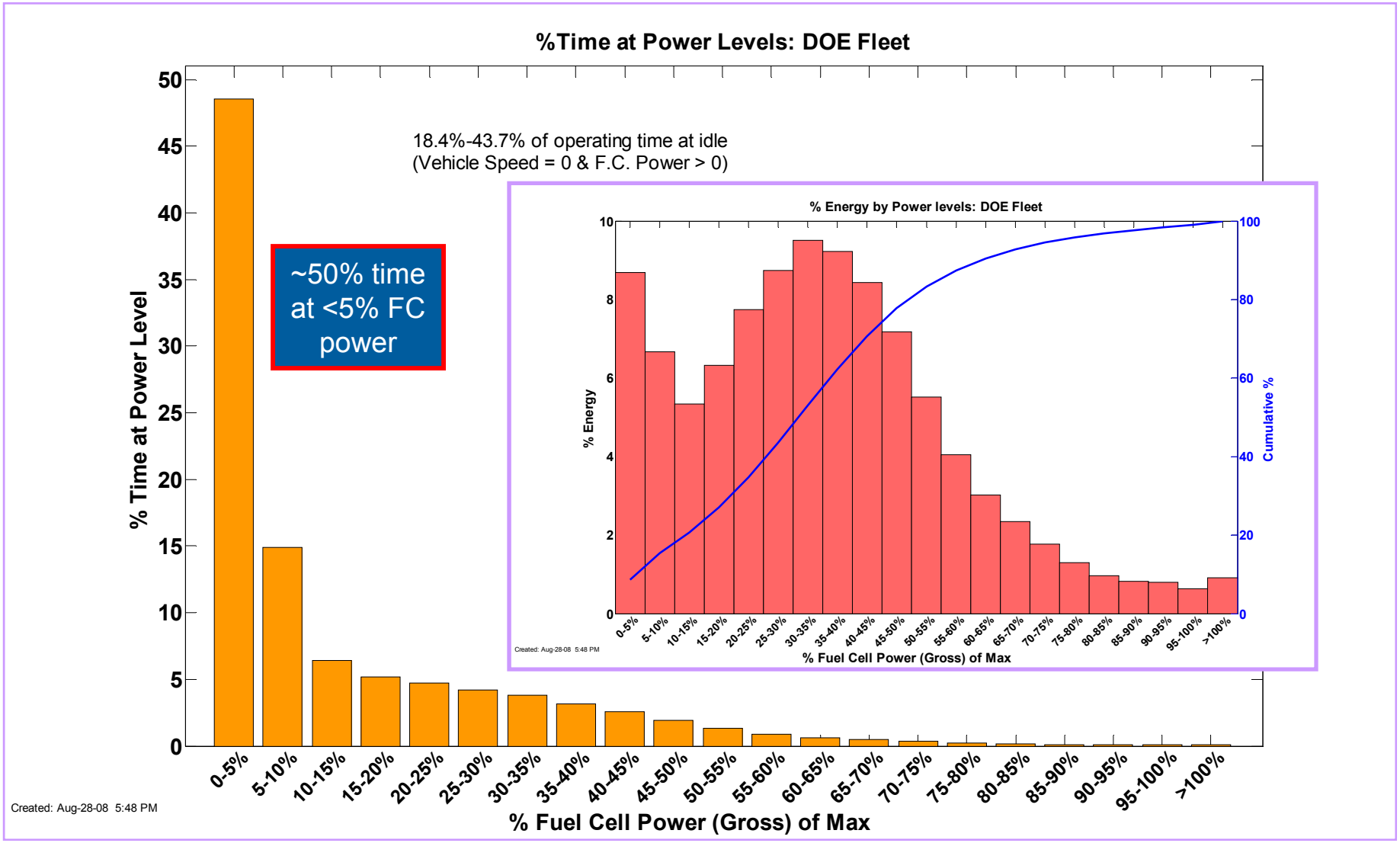



[1] Gross stack power minus fuel cell system auxiliaries, per DRAFT SAEJ2615.

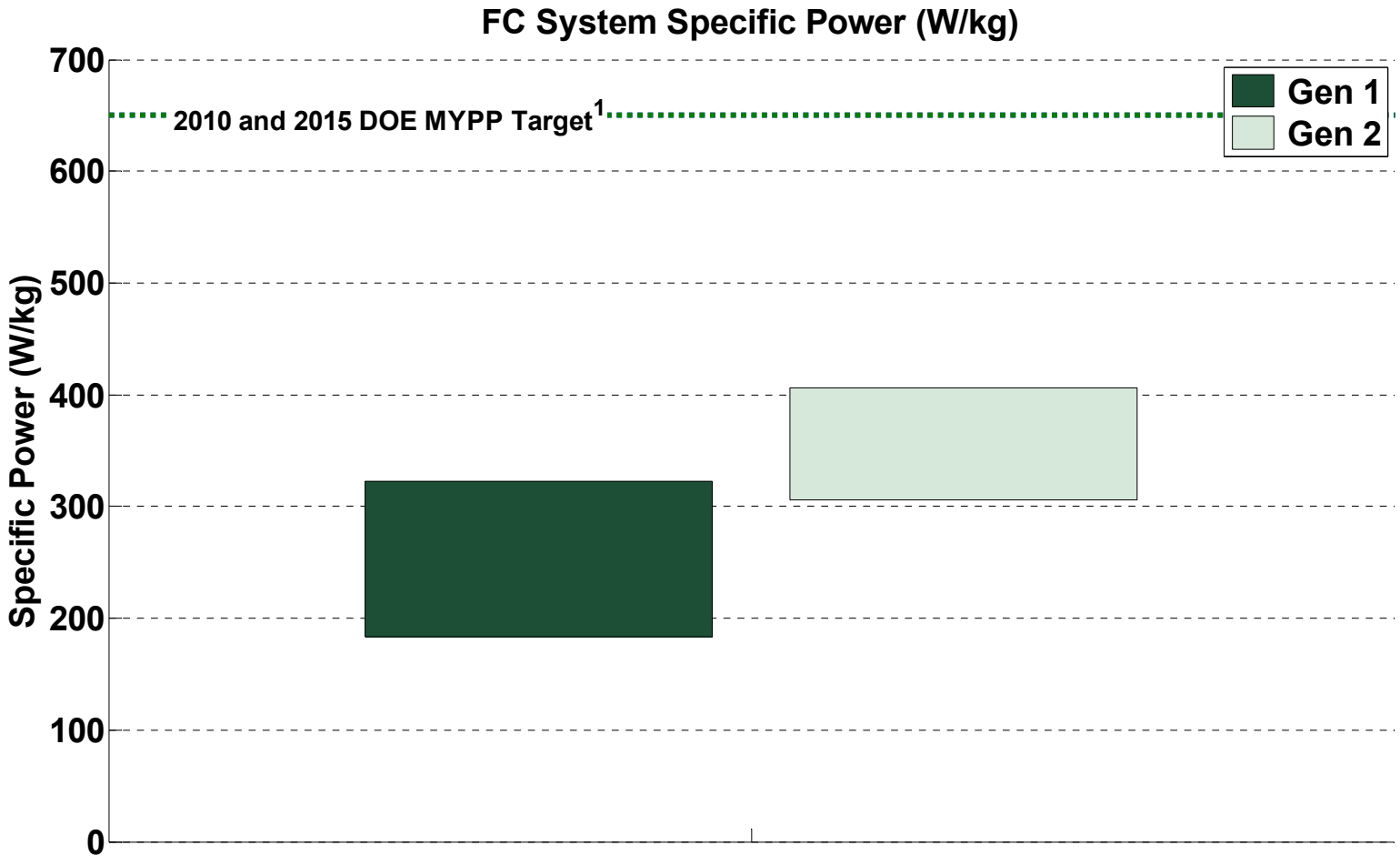
[2] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Excludes power electronics and electric drive.

Created: Aug-29-06 4:09 PM

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



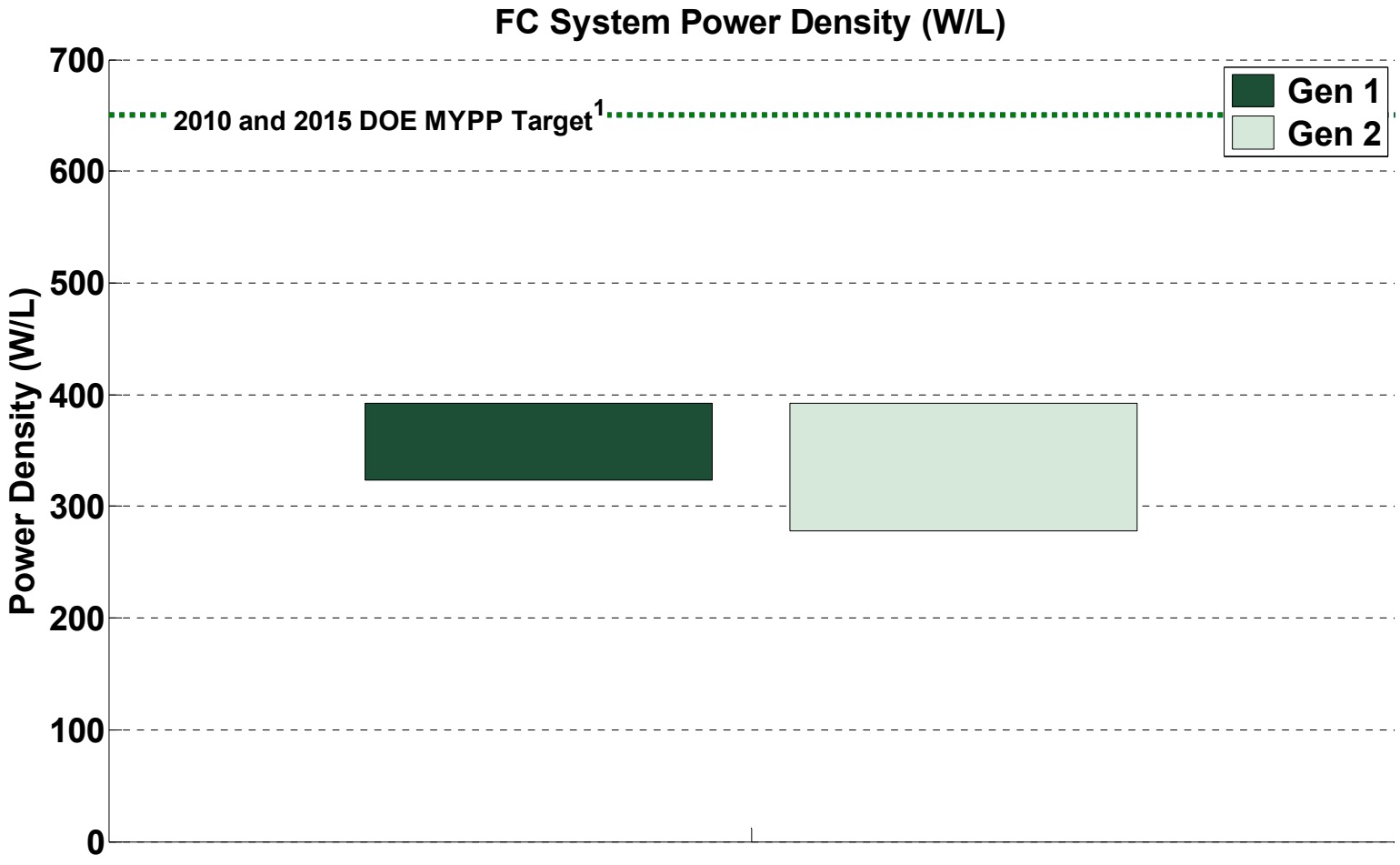
# Fuel Cell System Specific Power Shows Dramatic Improvement from Gen 1 to Gen 2




Created: Sep-17-08 10:30 AM

(1) Fuel cell system includes fuel cell stack and BOP but excludes H2 storage, power electronics, and electric drive.

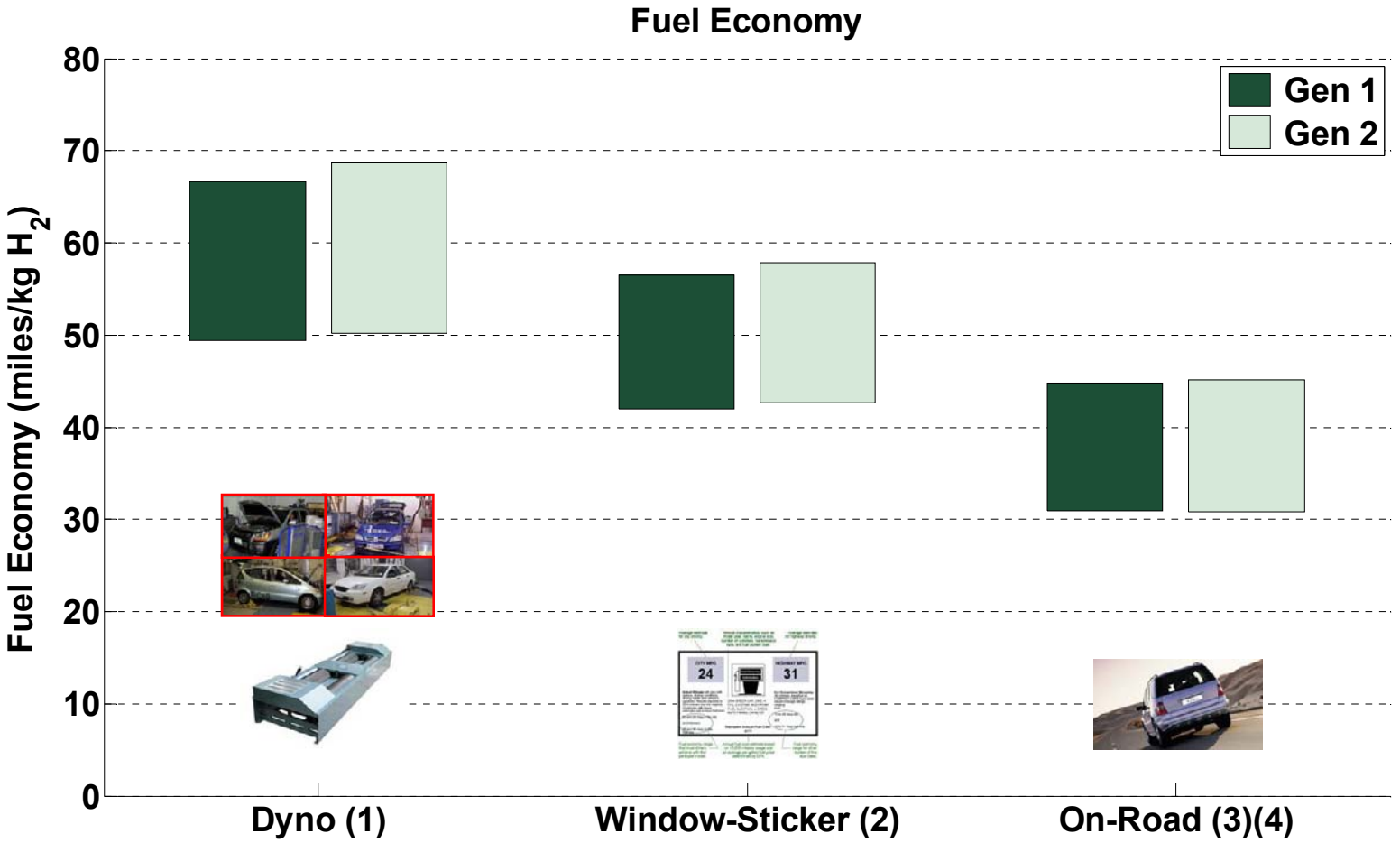
# Fuel Cell System Power Density Remained ~Same Between Gen 1 and 2




Created: Sep-17-08 10:29 AM

(1) Fuel cell system includes fuel cell stack and BOP but excludes H2 storage, power electronics, and electric drive.

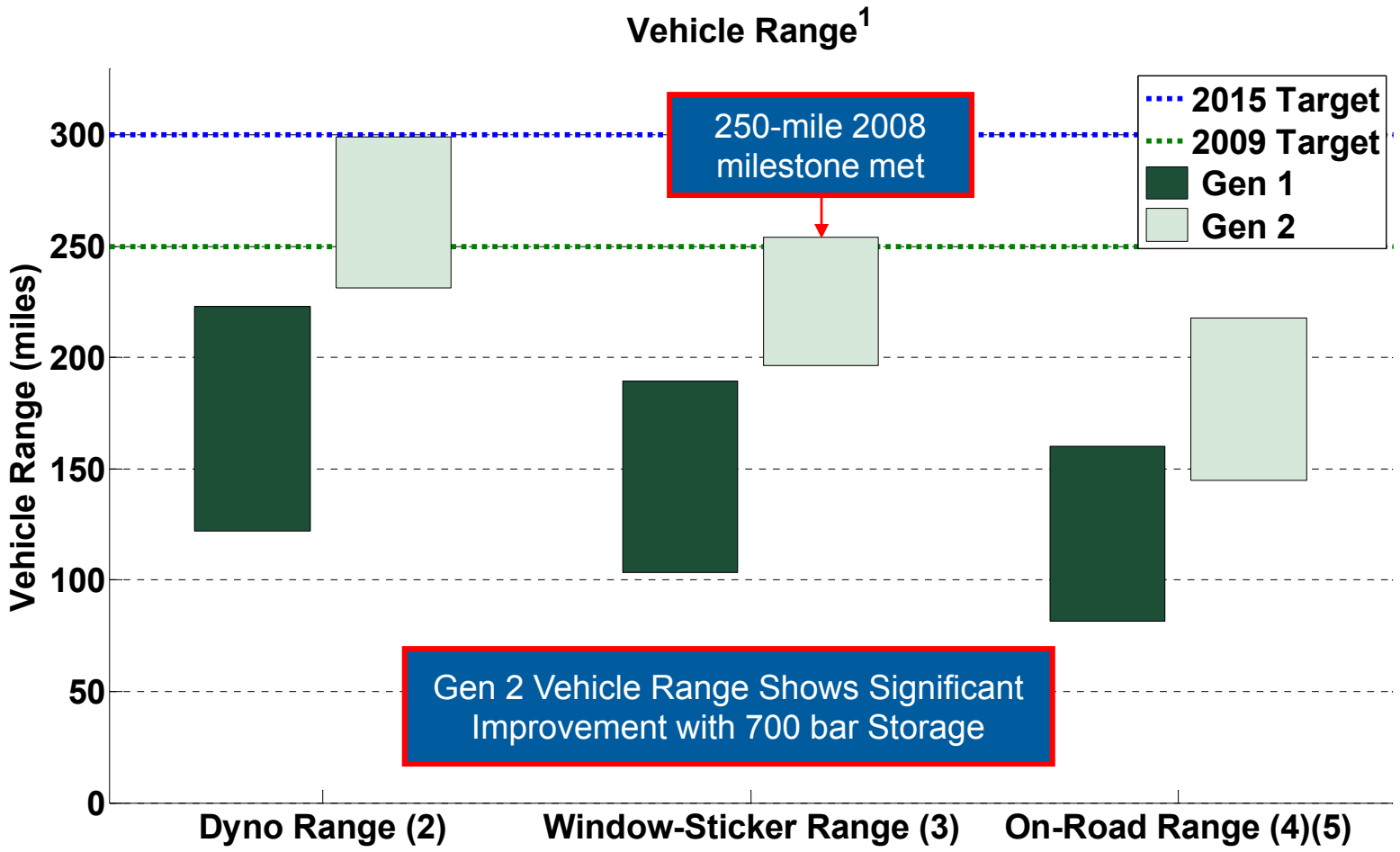
# Ranges of Fuel Economy from Dynamometer and On-Road Data Similar for Gen 1 & 2




(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.

Created: Sep-22-08 11:51 AM

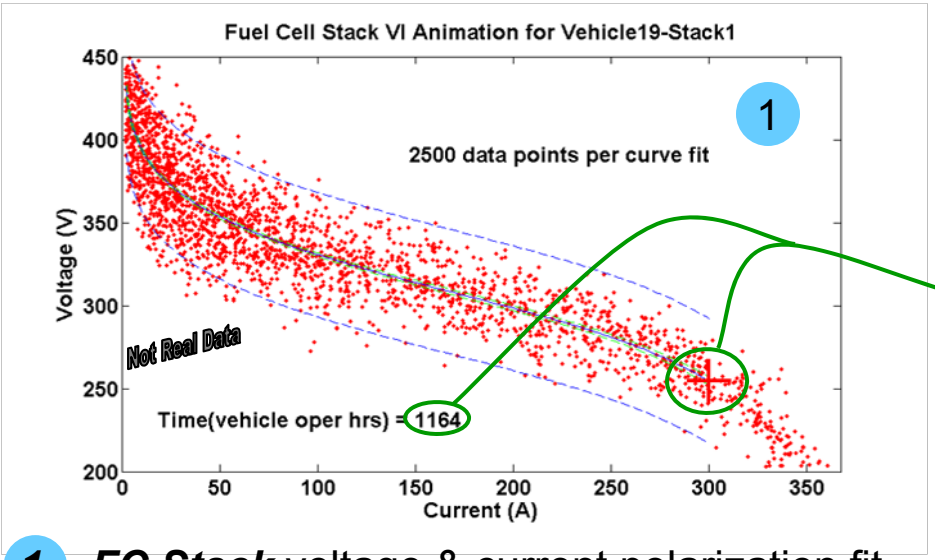
# Vehicle Range Based on Dyno Results and Usable H2 Fuel Stored On-Board

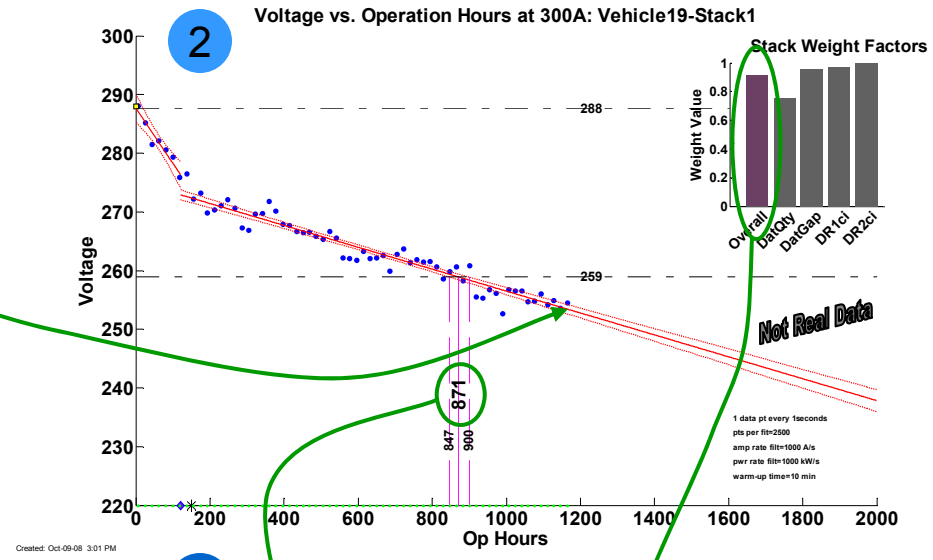


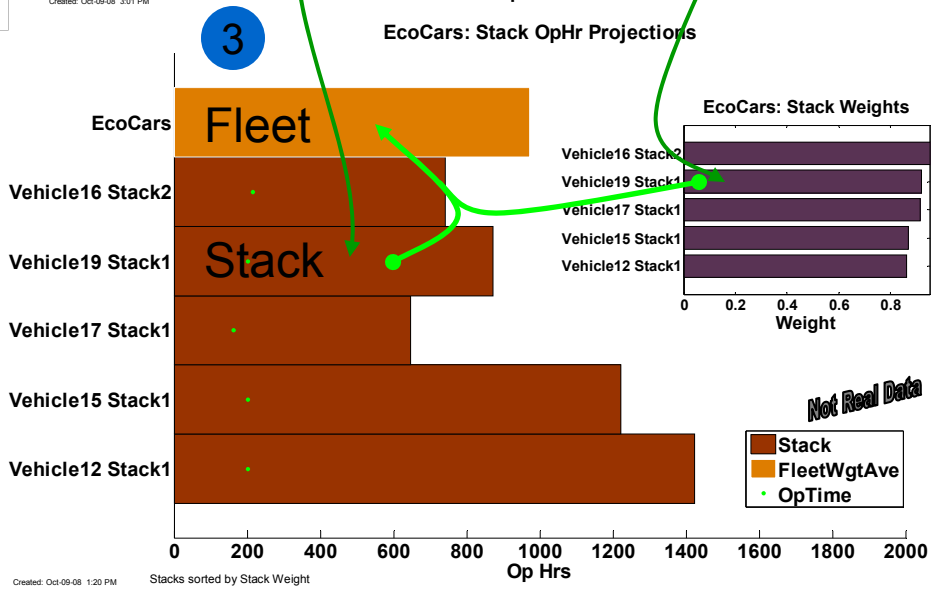

(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data 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.

Created: Sep-22-08 11:51 AM

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



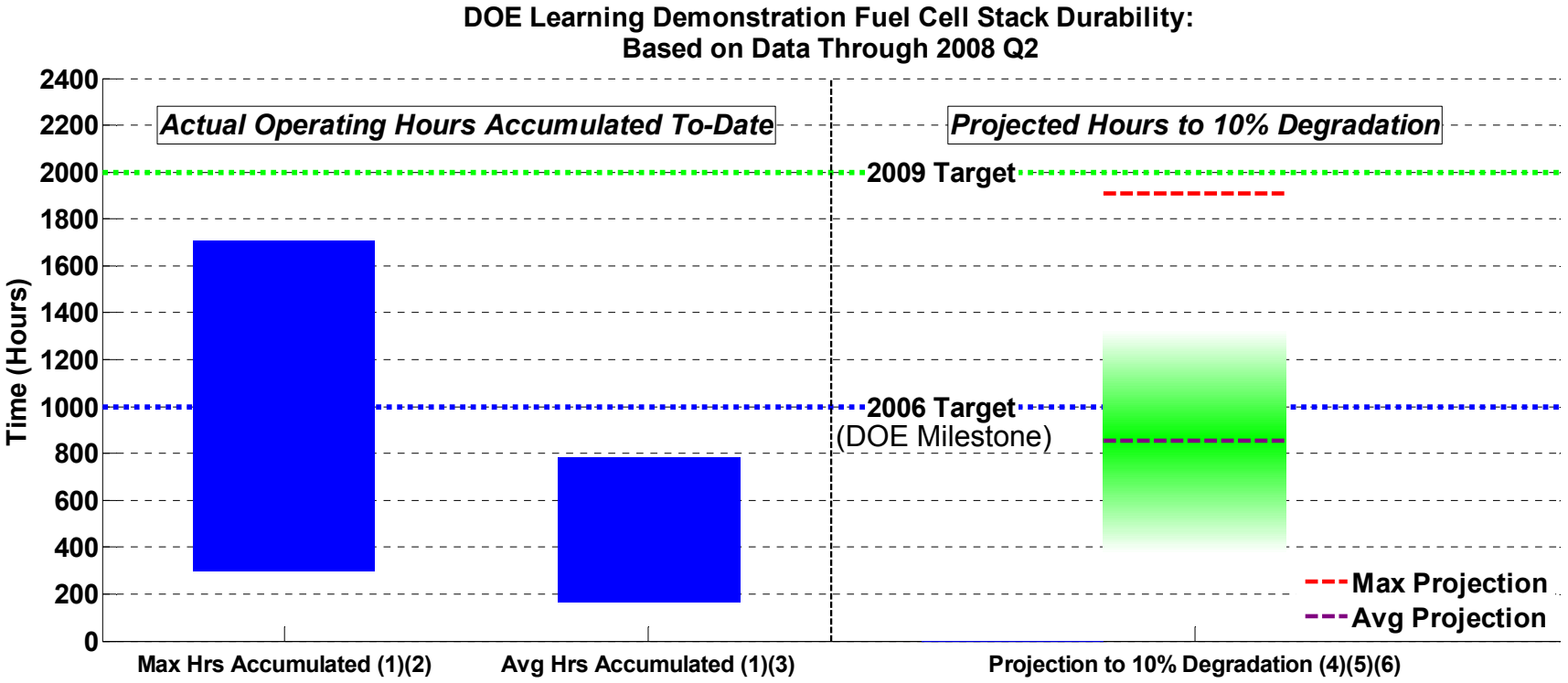




1. ***FC Stack*** voltage & current polarization fit
2. ***FC Stack*** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)
3. ***Fleet*** weighted average using FC Stack operating hour projections and weights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

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

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

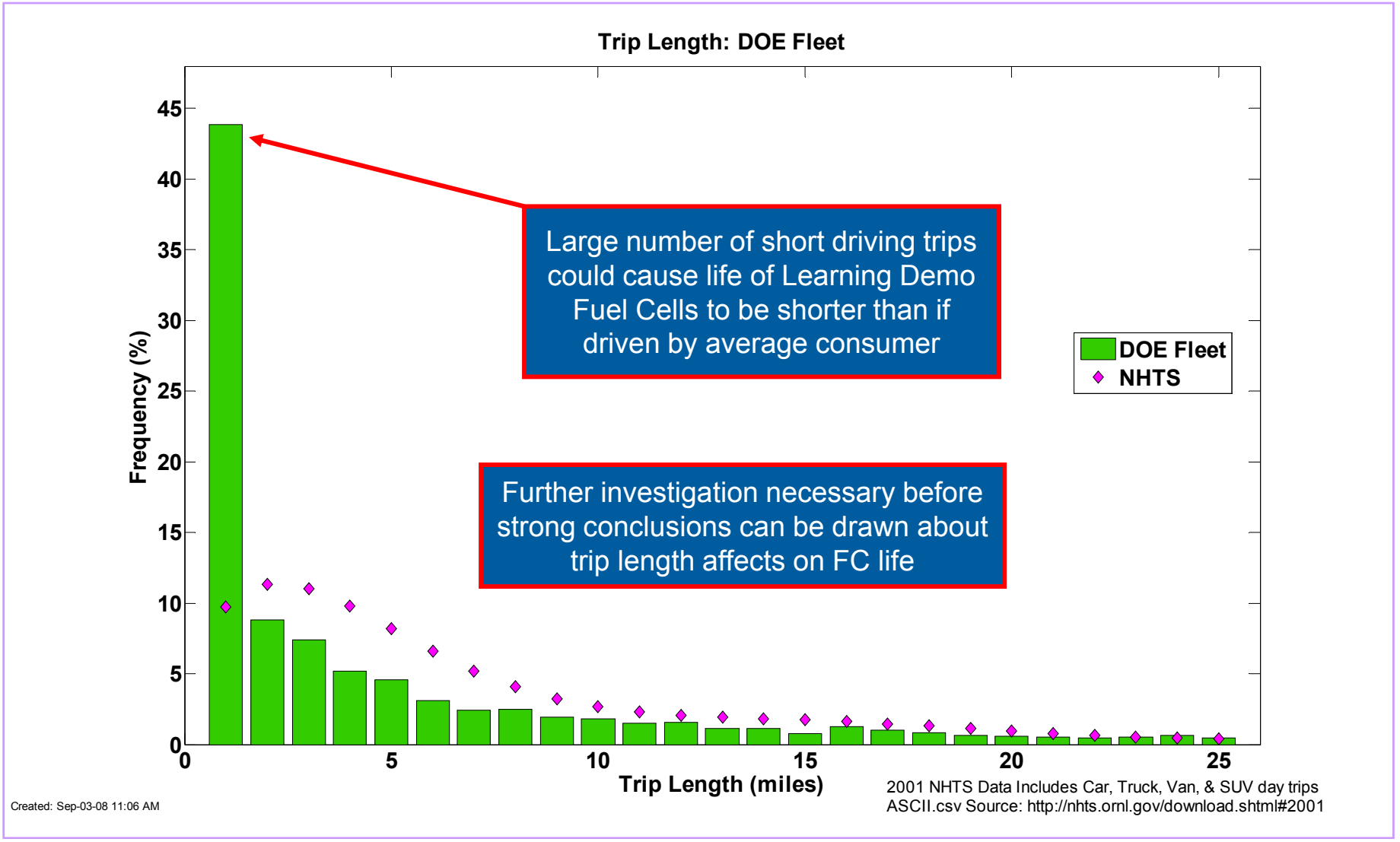



(1) Range bars created using one data point for each OEM. Some stacks have accumulated hours beyond 10% voltage degradation.
(2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
(3) Range (highest and lowest) of the 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.

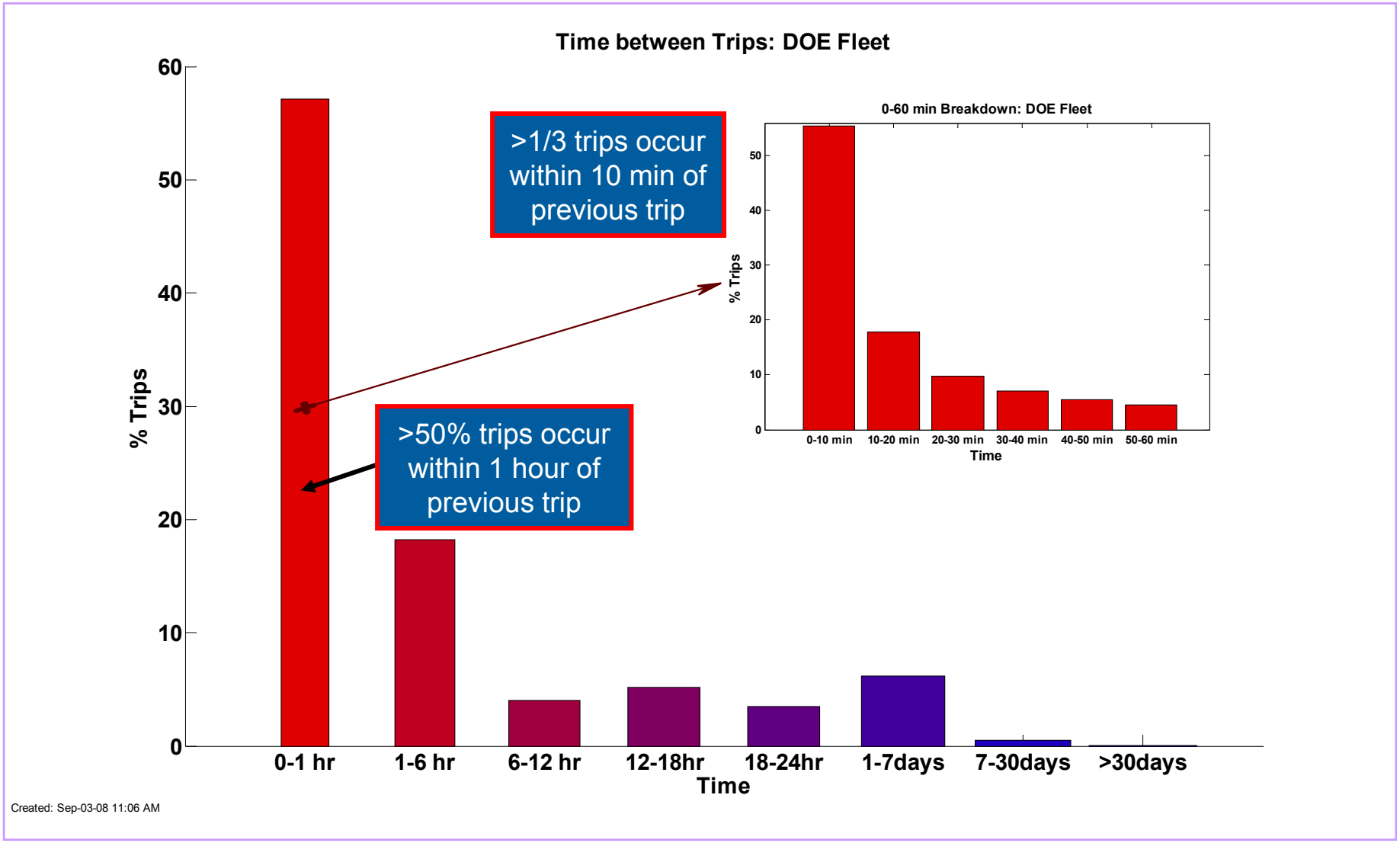
Created: Sep-03-08 10:36 AM

More data required to make Gen 2 projections (2009)

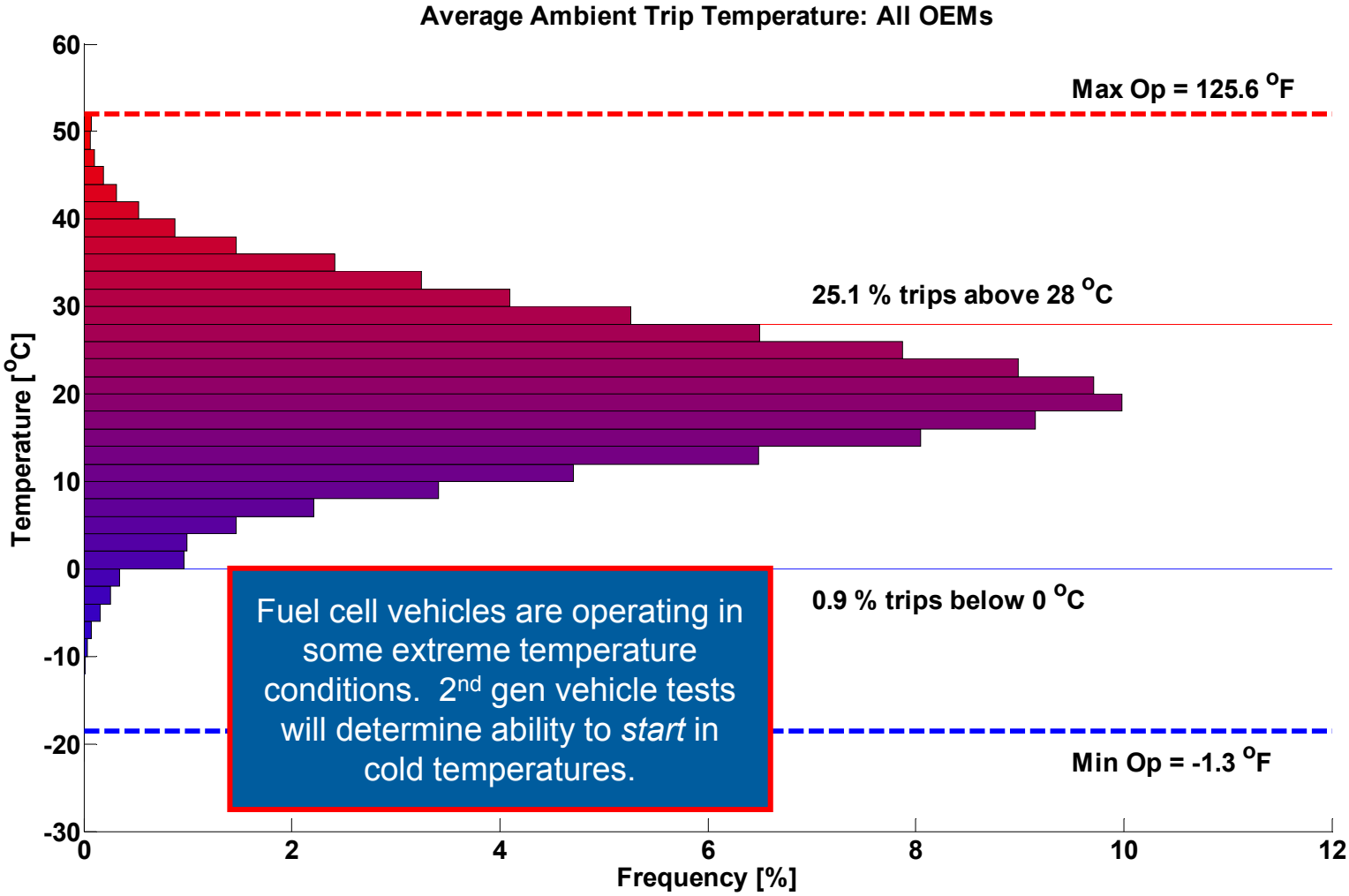
# Learning Demo FCVs Tend to Take Many More Trips <1 Mile Than Compared to National Average



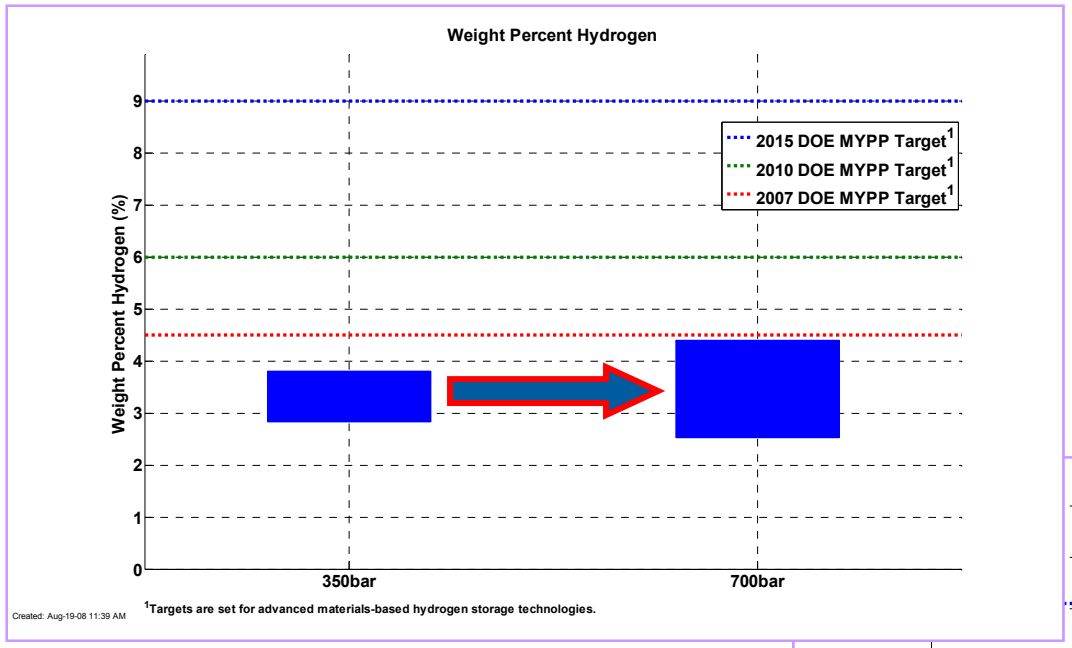
# Examining Time Between Trips Shows Fuel Cells Experiencing Large Number of Hot Starts

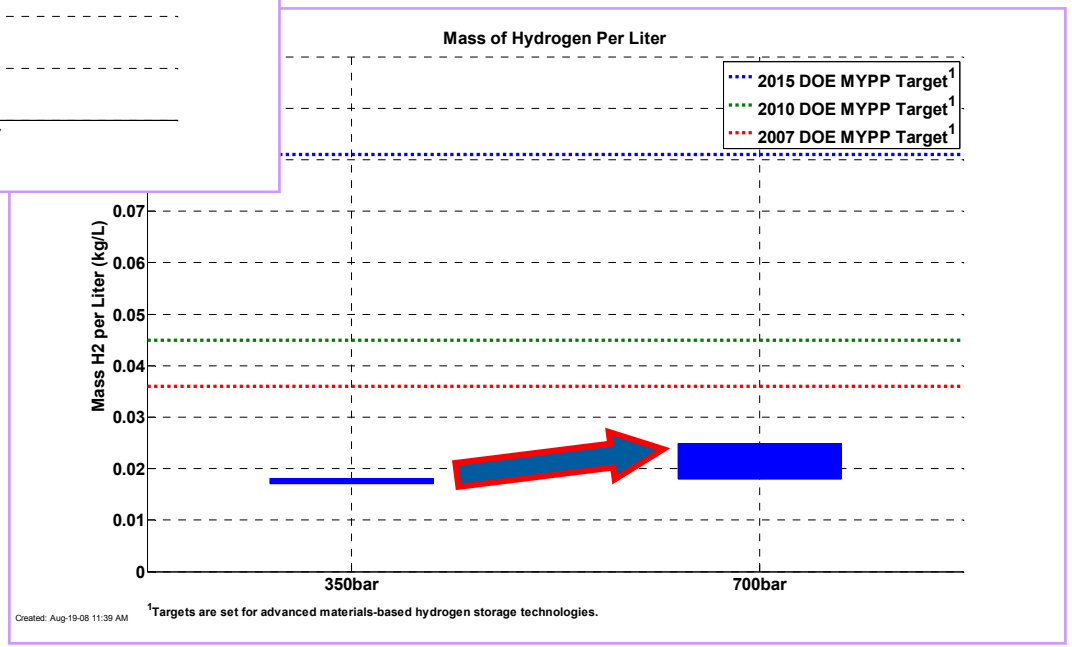


# Range of Average Ambient Temperatures During Vehicle Operation



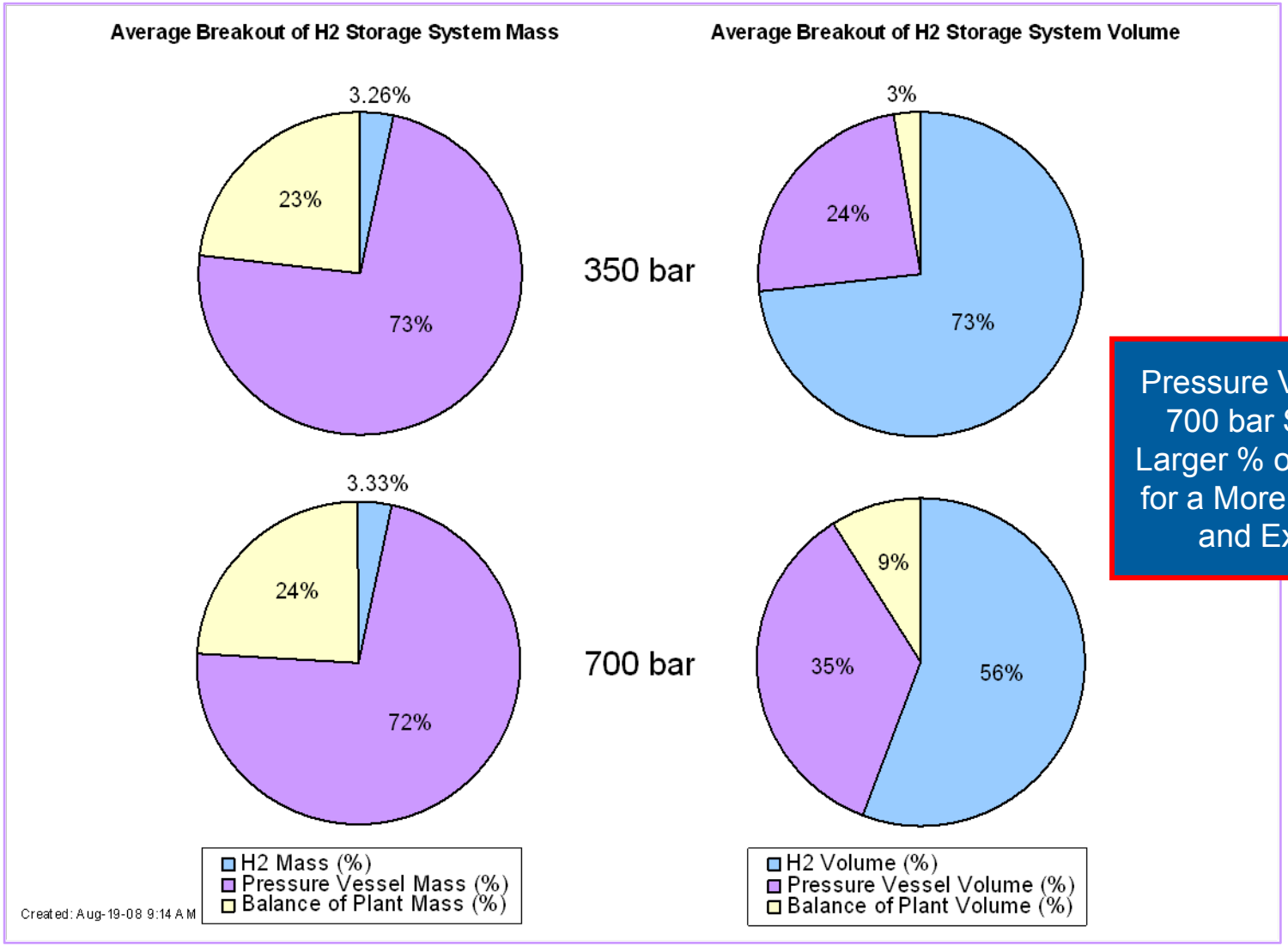
# 700 bar On-Board H2 Storage Systems Demonstrate Potential for Improved Performance Over 350 bar



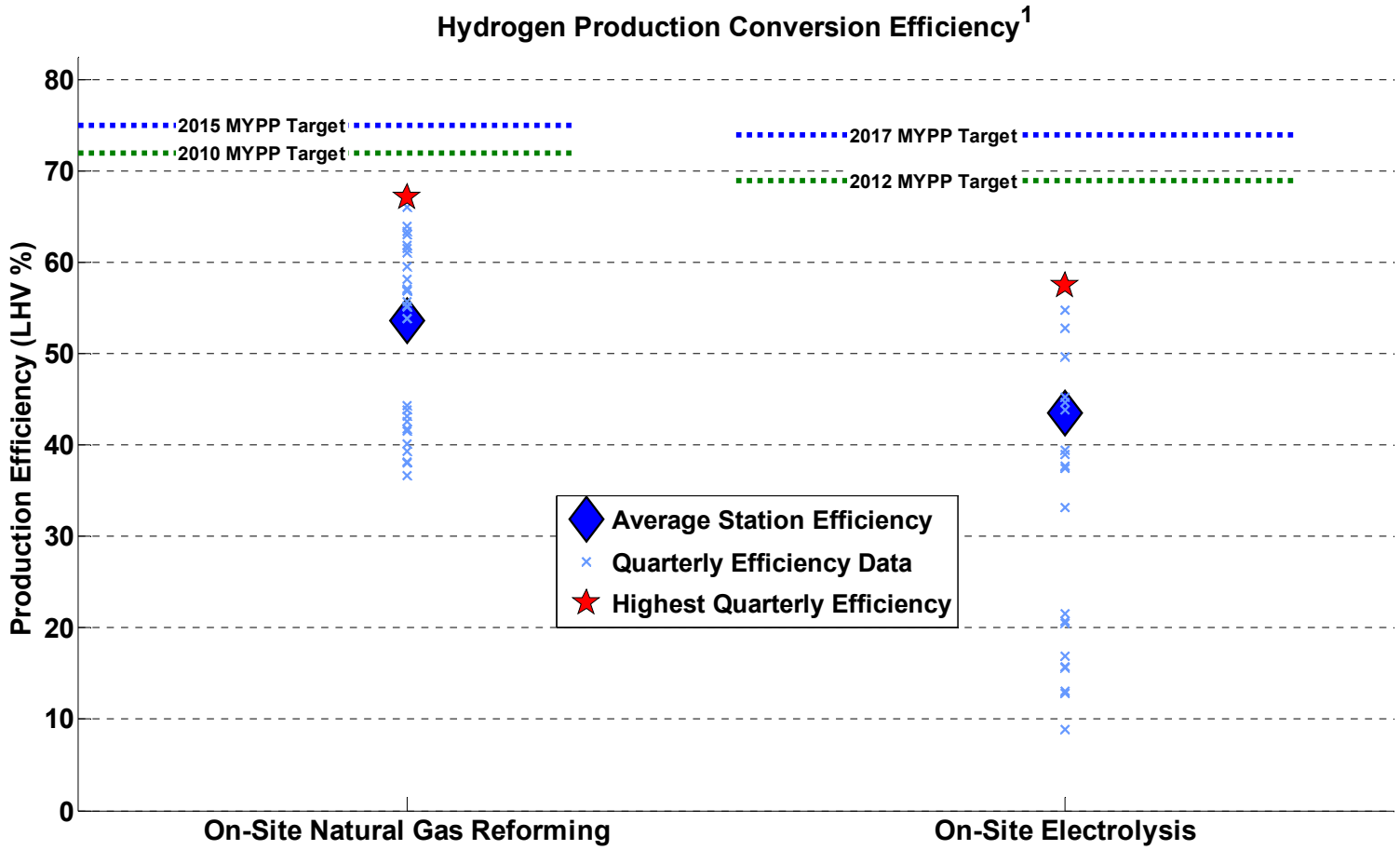

2nd Gen Vehicle Storage Data Collected; Allows a Comparison of 350 bar vs. 700 bar

# More Detailed Data Reporting Allows a Comparison of Mass and Volume of H2, Pressure Vessel, and BOP




Pressure Vessel and BOP for 700 bar Systems Take Up Larger % of Volume, but Allow for a More Compact Package and Extended Range

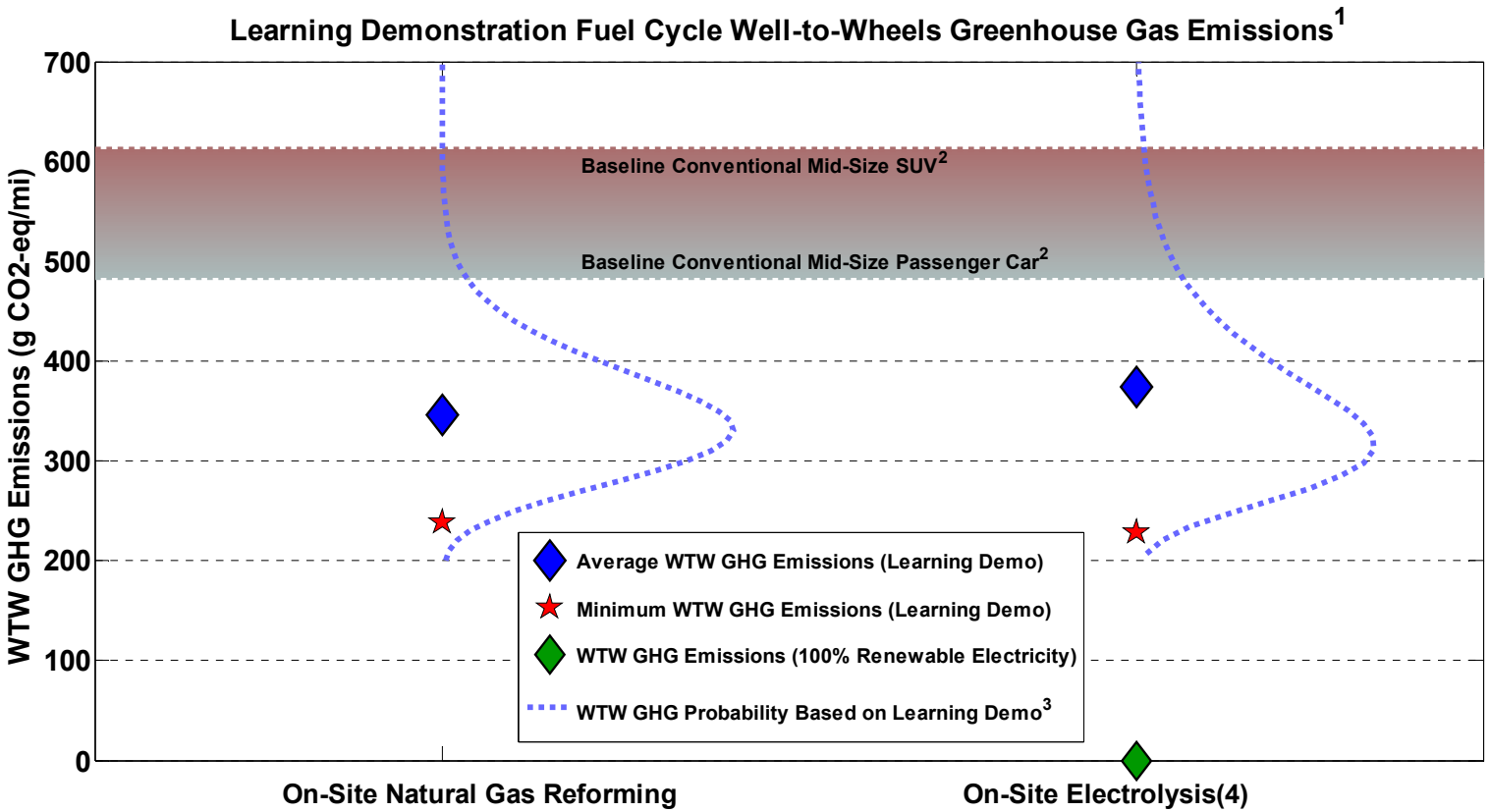
# On-Site Production Efficiency from Natural Gas Reformation and Electrolysis Compared to Targets




[1]Production 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.

Created: Sep-24-08 4:17 PM

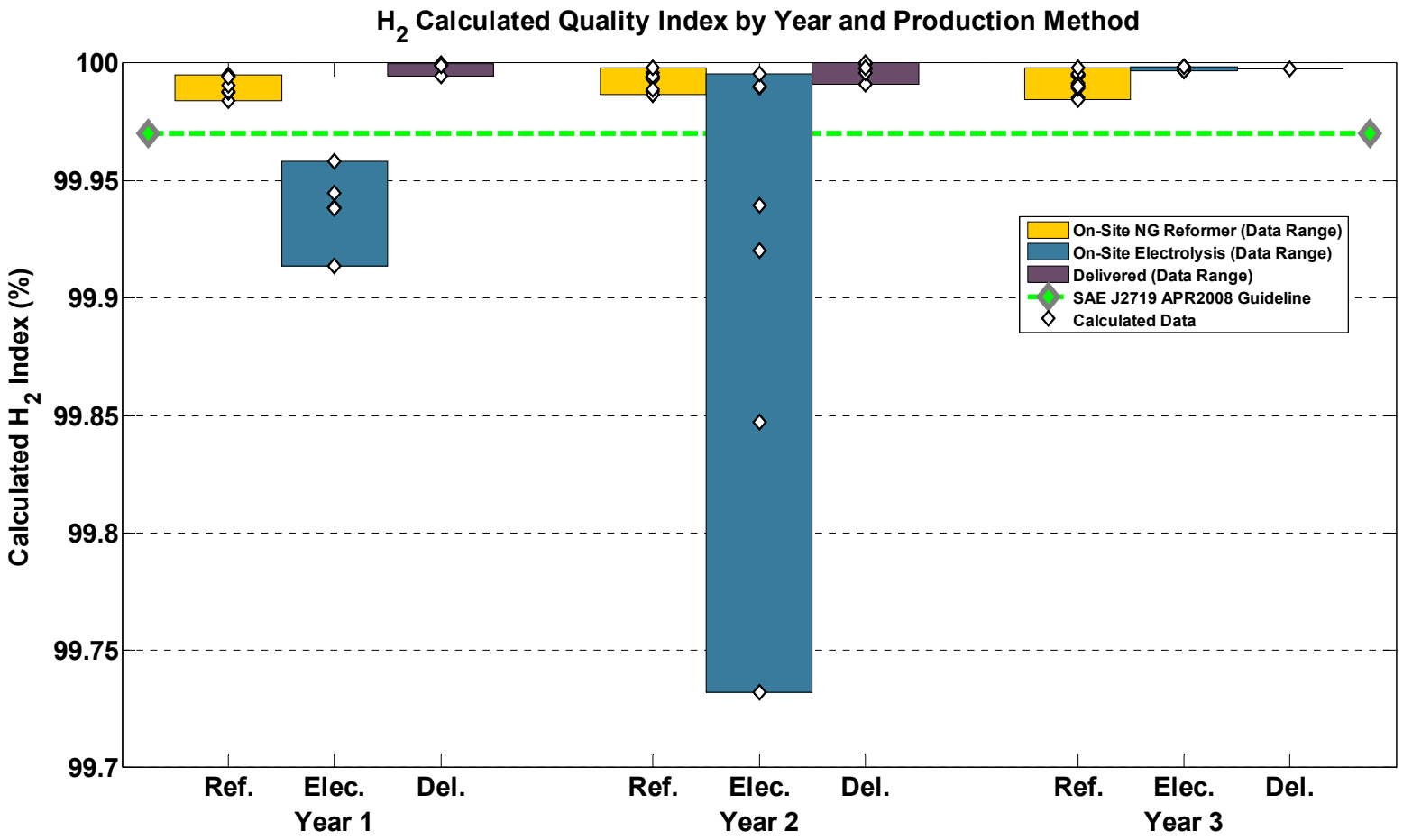
# Learning Demonstration Vehicle Greenhouse Gas Emissions Using Actual Production Efficiencies and Fuel Economies



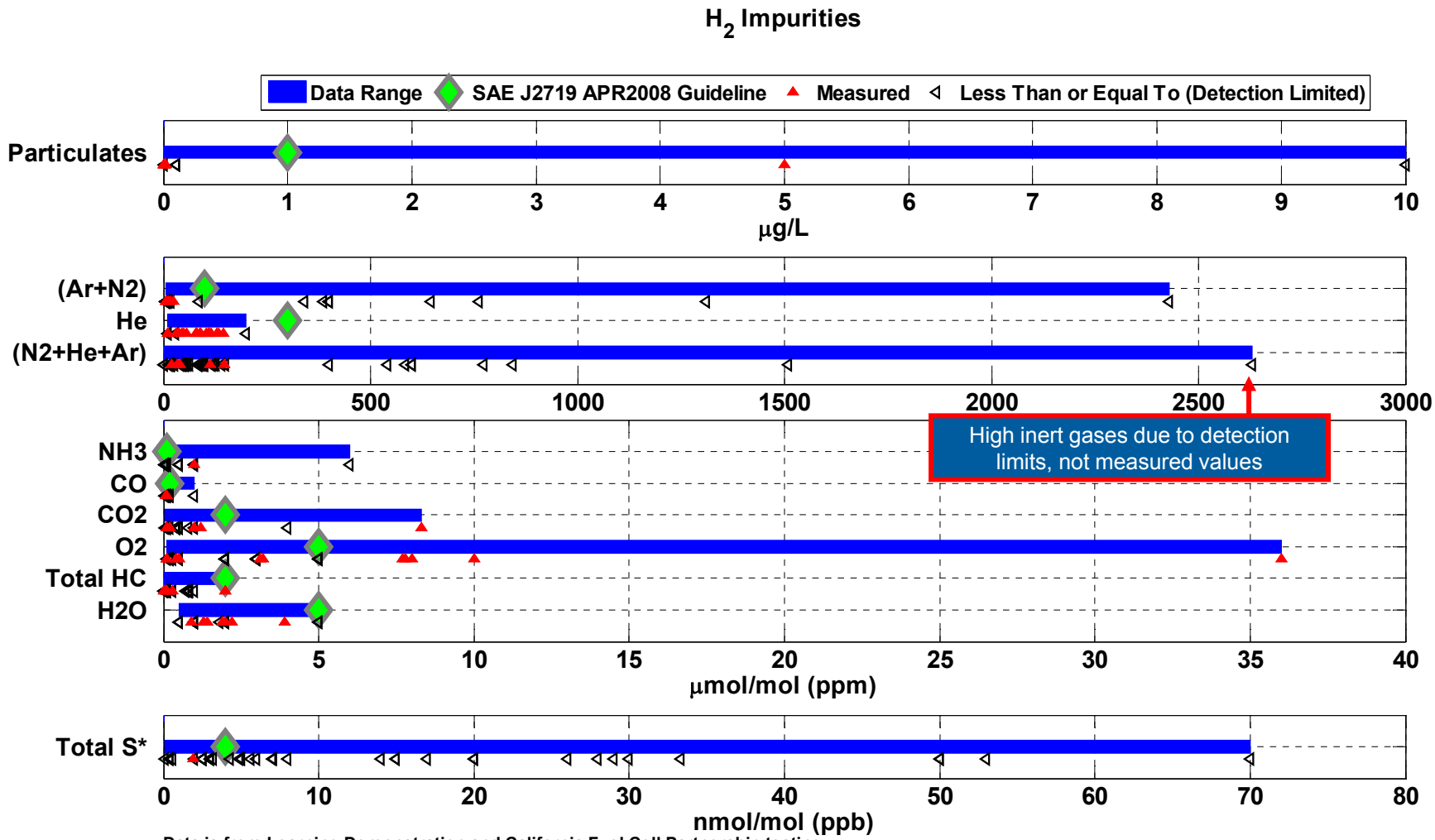

1. Well-to-Wheels greenhouse gas emissions based on DOE's GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all 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.

Created: Sep-24-08 4:19 PM

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



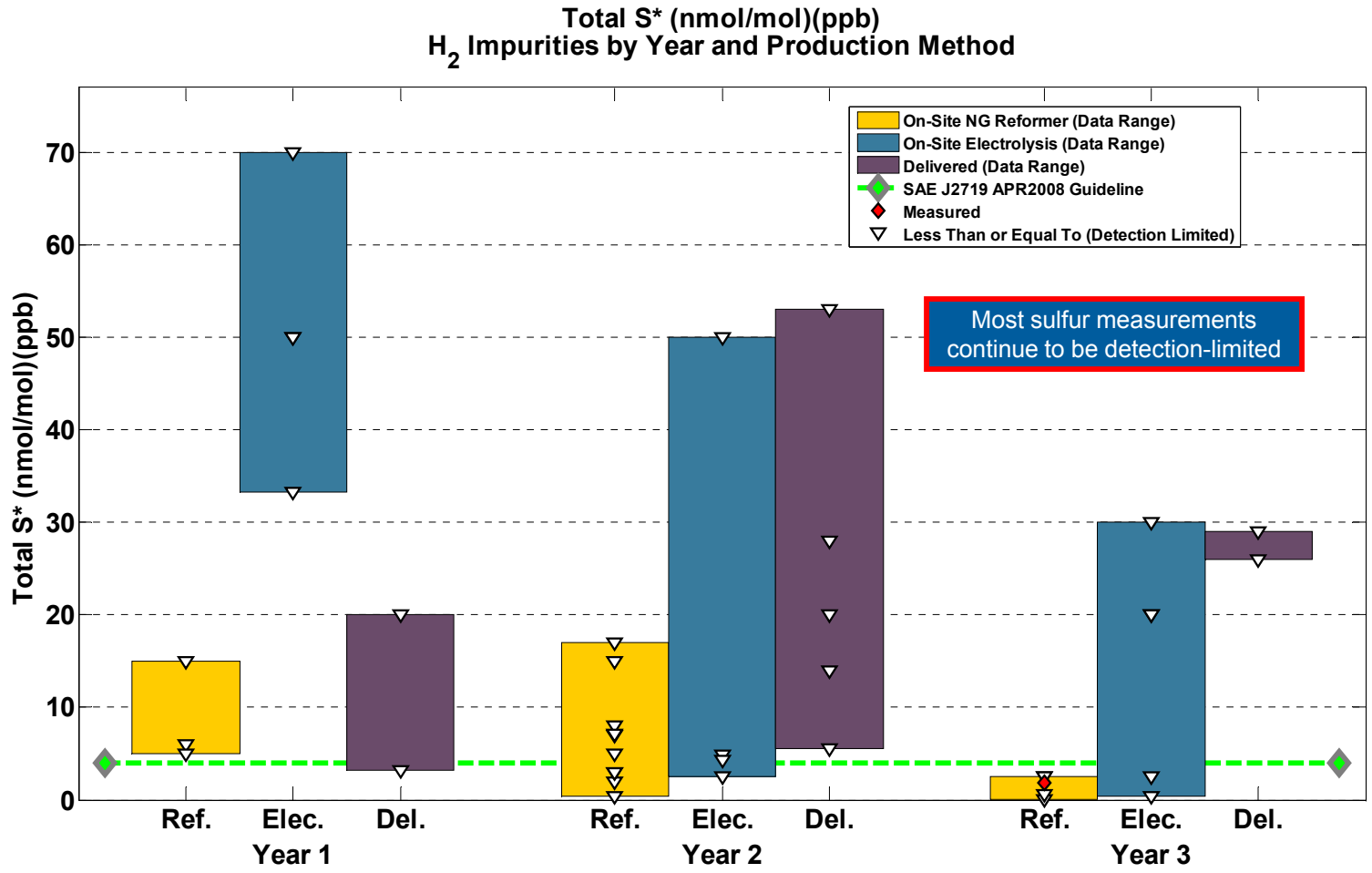
# Hydrogen Impurities Sampled from All Stations to Date




Created: Sep-22-08 1:41 PM

**Data is from Learning Demonstration and California Fuel Cell Partnership testing**
***Total S calculated from SO2, COS, H2S, CS2, and Methyl Mercaptan (CH3SH).**

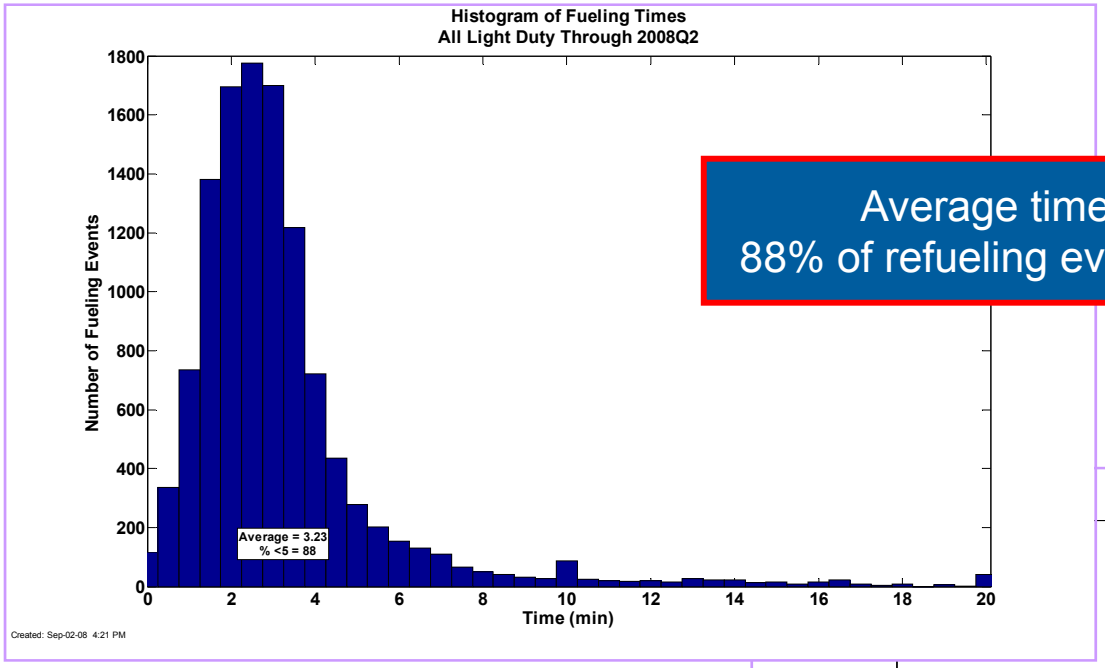
# Hydrogen Impurities by Year and Production Method – Total Sulfur



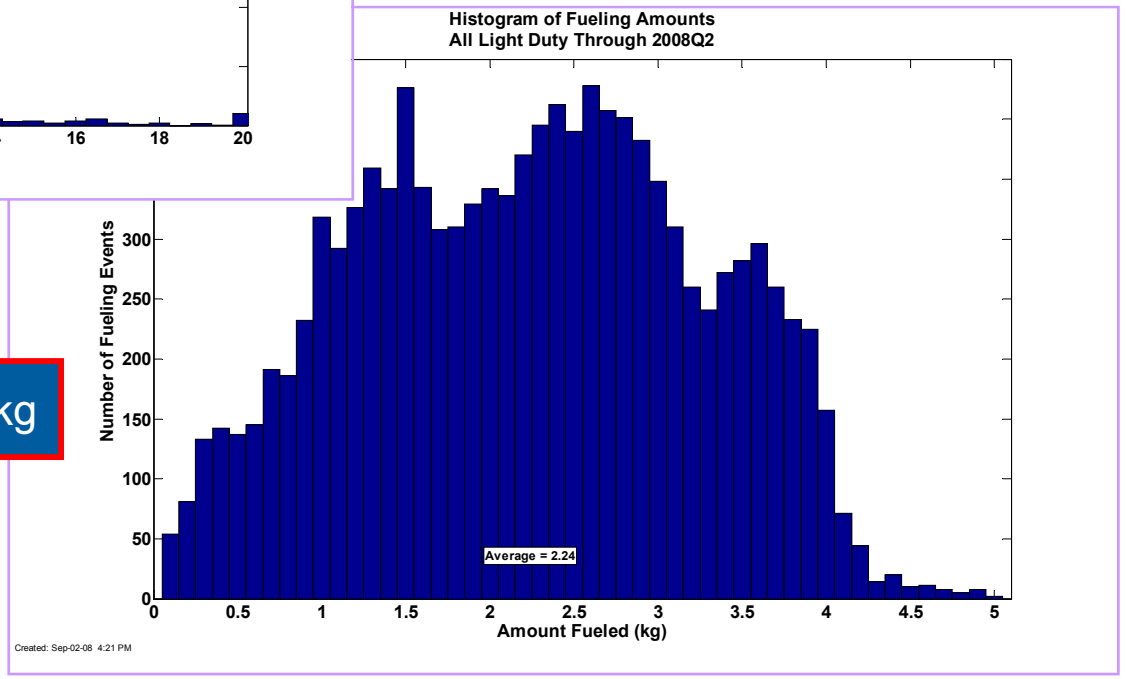

Data is from Learning Demonstration and California Fuel Cell Partnership testing
Year 1 is 2005Q3-2006Q2, Year 2 is 2006Q3-2007Q2, and Year 3 is 2007Q3-2008Q2
*Total S calculated from SO2, COS, H2S, CS2, and Methyl Mercaptan (CH3SH).

Created: Sep-22-08 1:42 PM

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



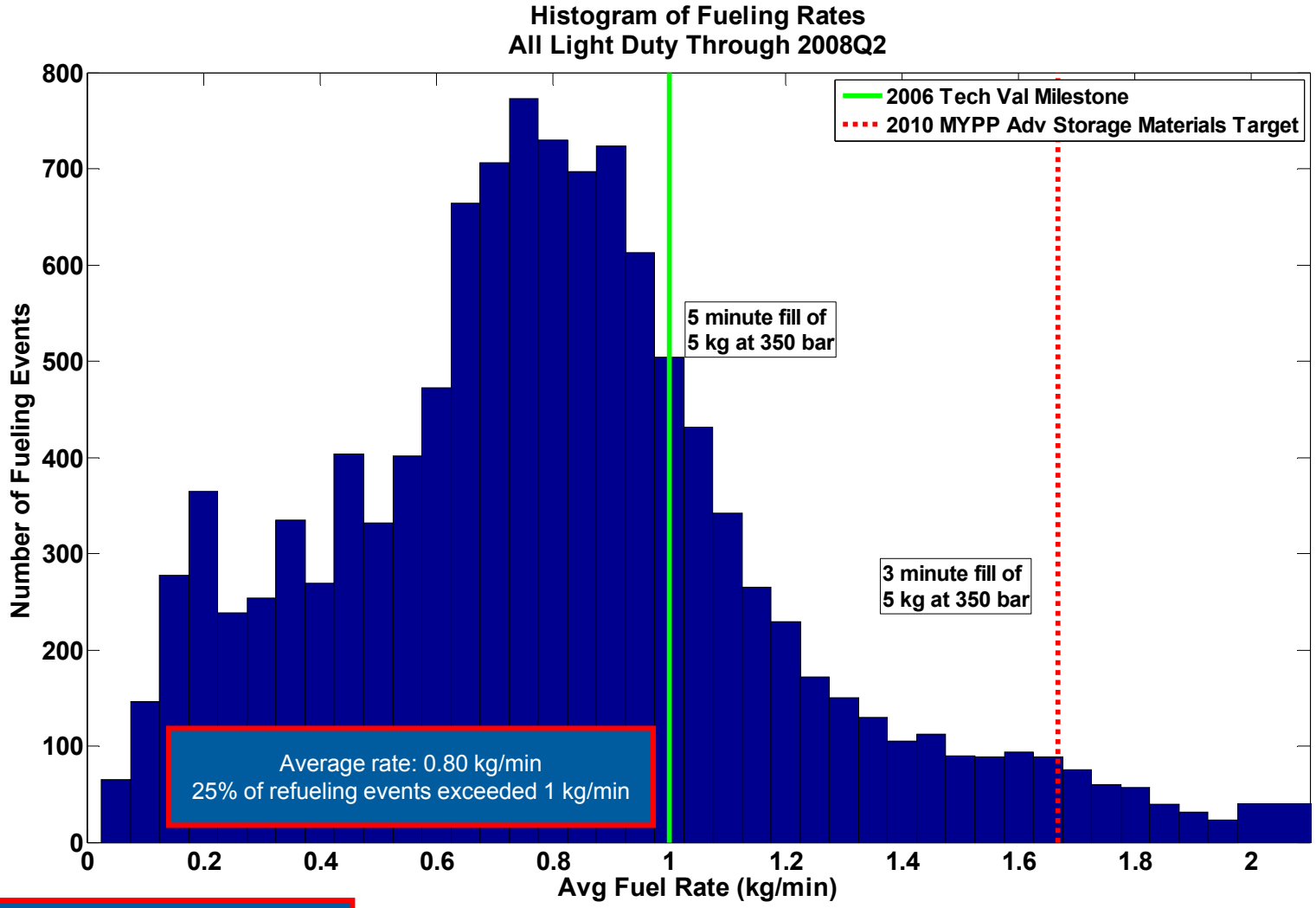

Average time: 3.23 min
88% of refueling events took <5 min




Average fill amount: 2.24 kg

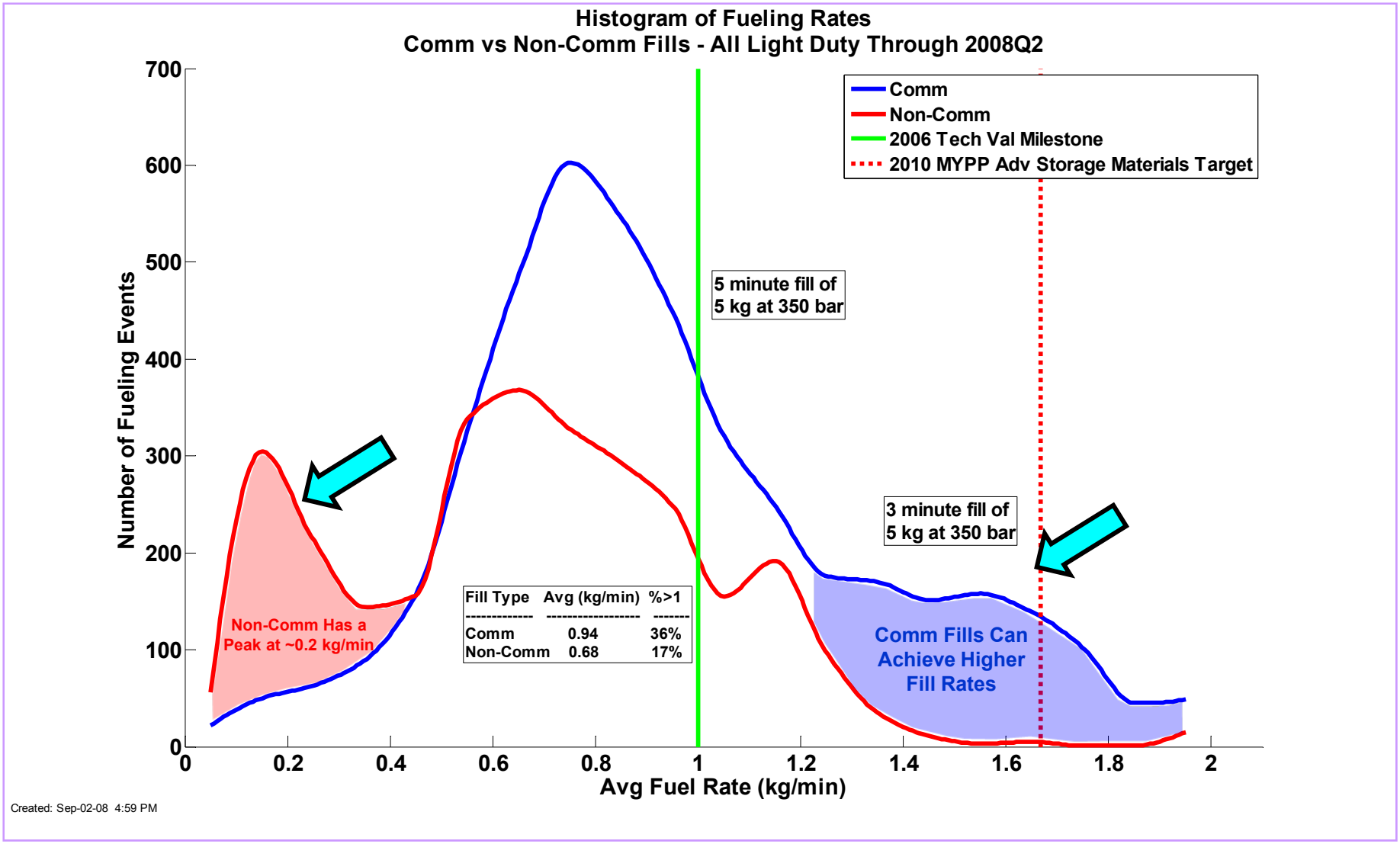
Includes Communication and Non-Communication Fills

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

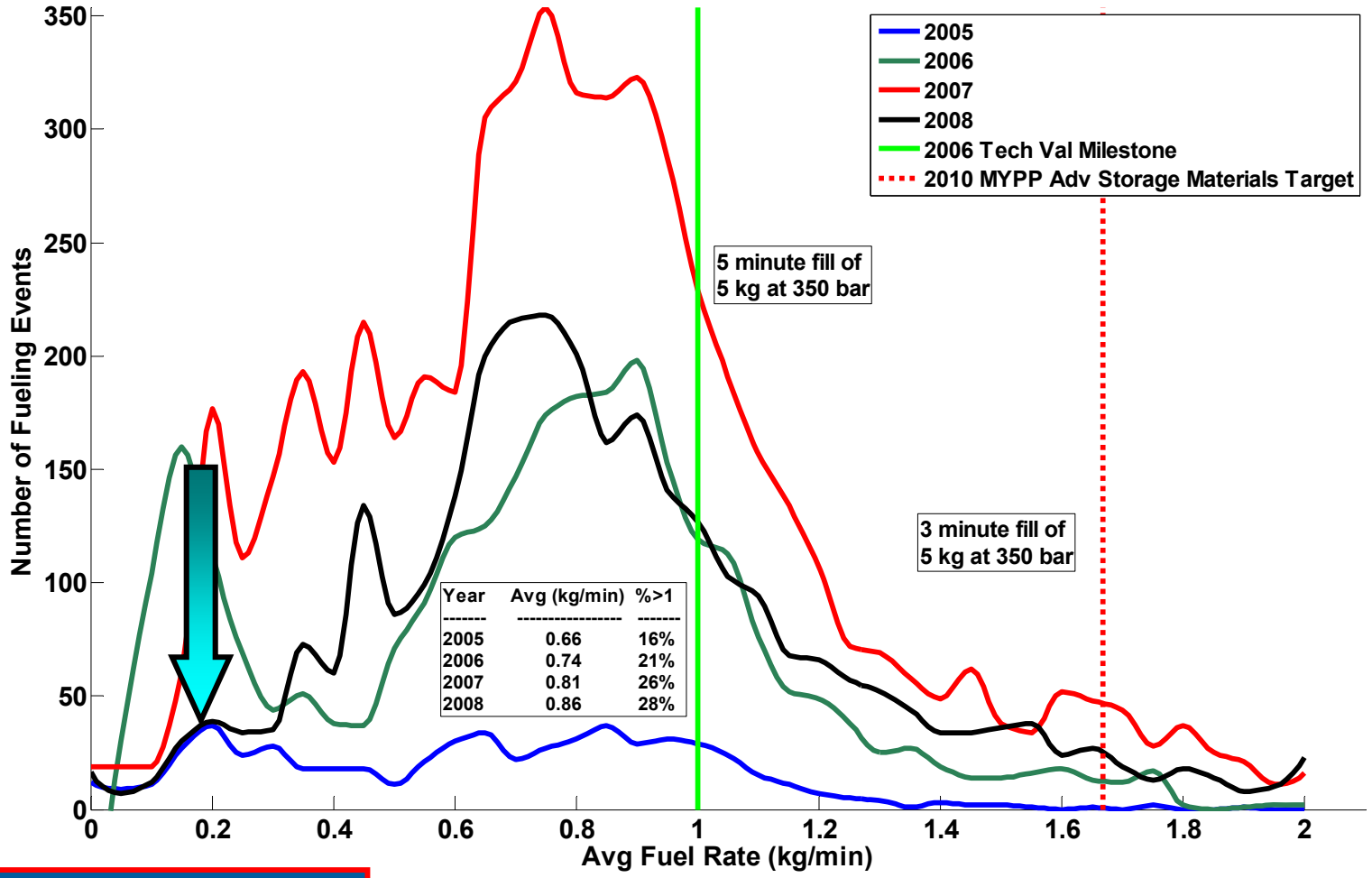



Includes Communication and Non-Communication Fills

# Communication H2 Fills Achieving Higher Fill Rate than Non-Communication



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

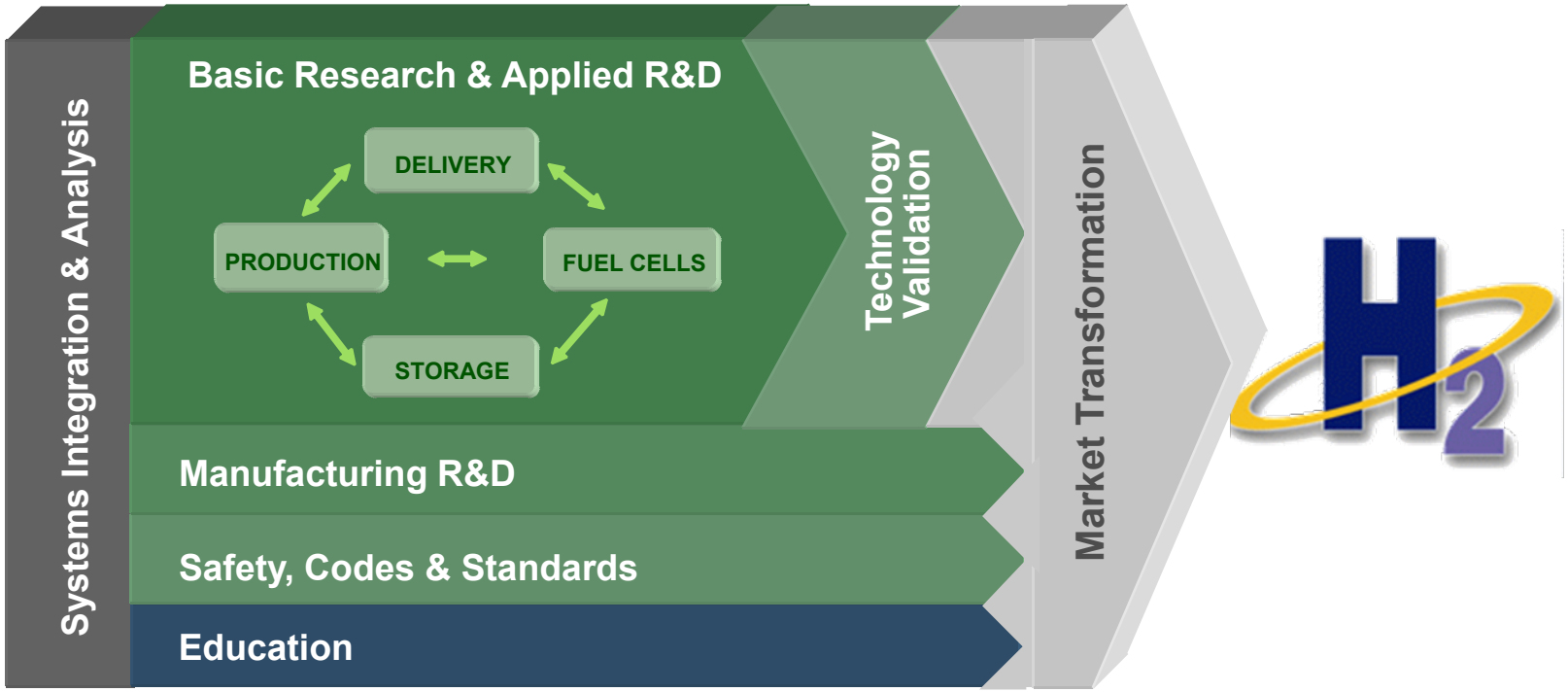



Includes Communication and Non-Communication Fills

# Summary

- Learning Demo project is ~60% complete
  - 122 vehicles and 16 stations deployed
  - 1.5 million miles traveled, 60,000 kg $H_2$ 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
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