NREL National Renewable Energy Laboratory
*Innovation for Our Energy Future*

SAE 2009 World Congress

Session: PFL101, Part 2/3

# National Fuel Cell Vehicle Learning Demonstration: Status and Results

**Society of Automotive Engineers World Congress 2009**

**Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden[1], John Garbak[2]**

**April 22, 2009**
**Detroit, MI**

**NREL/PR-560-45641**

[1]NREL, [2]US Dept. of Energy

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# Outline

- Project Objectives and Partners
- Overall Project Status: Vehicles & Stations
- NREL's Role in the Project and Methodology
- Vehicle Analysis Results
- Infrastructure 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
  - Objectively 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: Four Automaker/Energy-Supplier Teams



CHRYSLER
bp

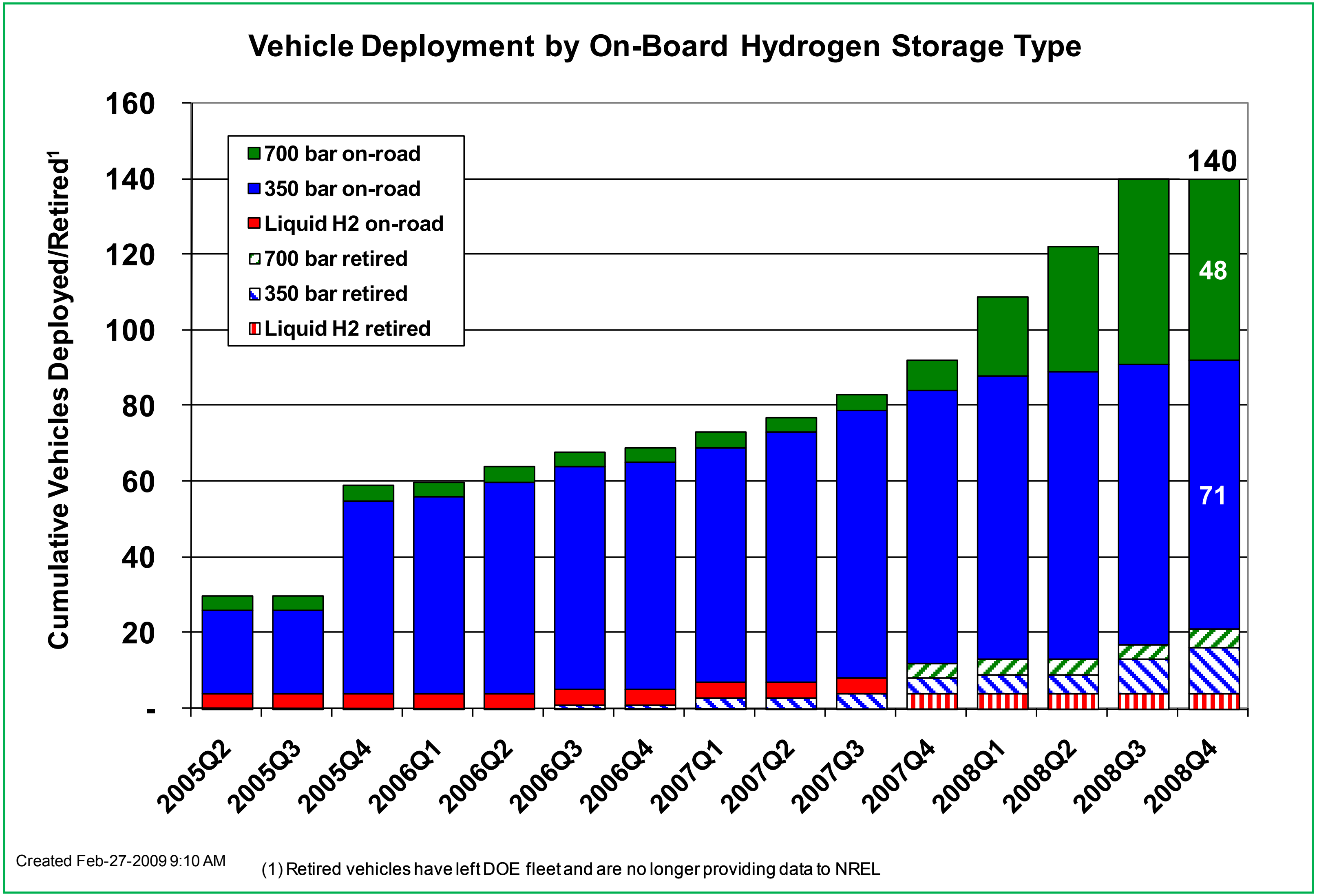

Ford
bp



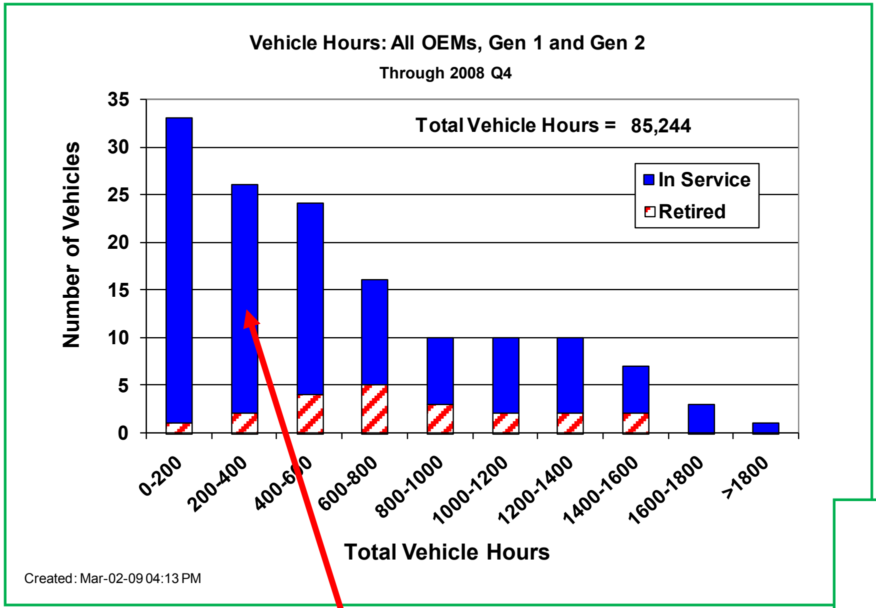
GM


Chevron
HYUNDAI
KIA
UTC Power

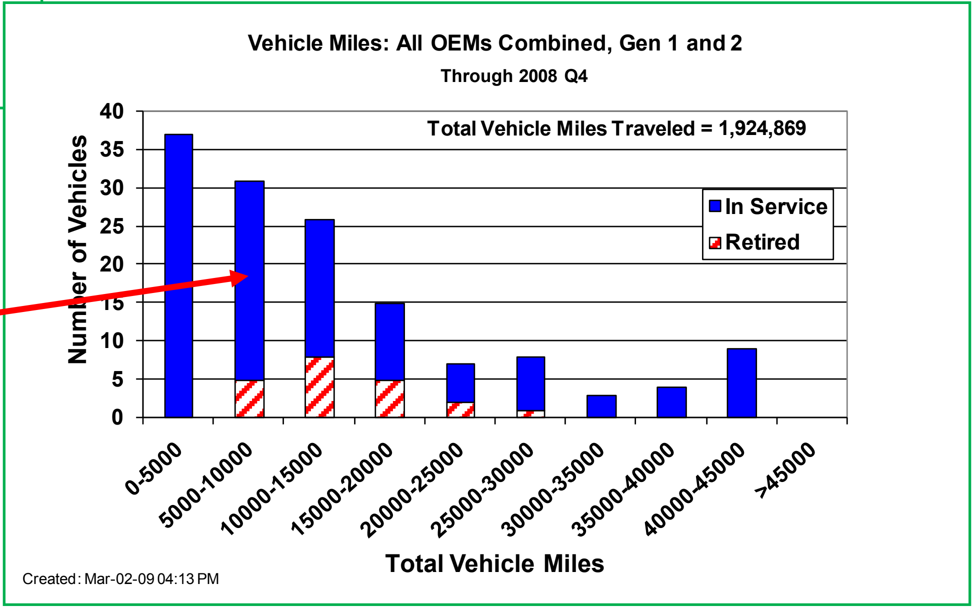
# All Gen 2 Vehicles Now Deployed, Some Early Vehicles Have Been Retired



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

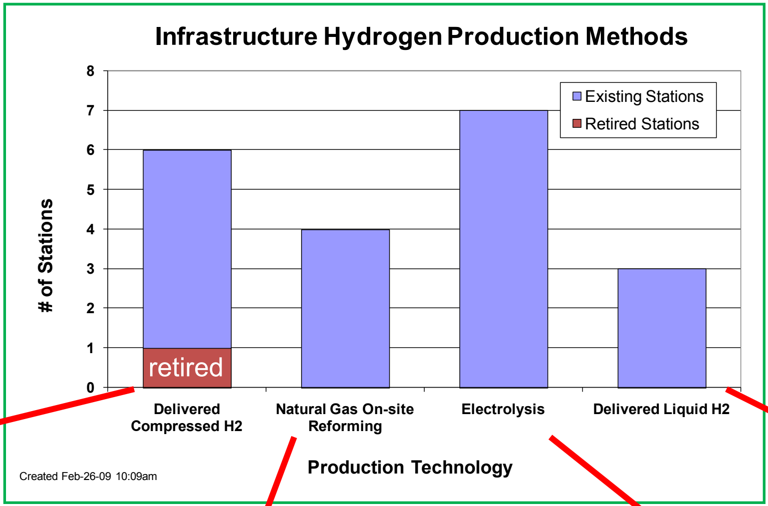



Some Gen 1 vehicles have now been retired (red bars)



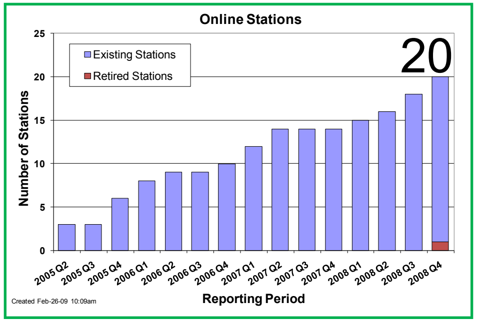

Gen 2 vehicles make up most of 2nd bulge at low hours/miles

# 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**



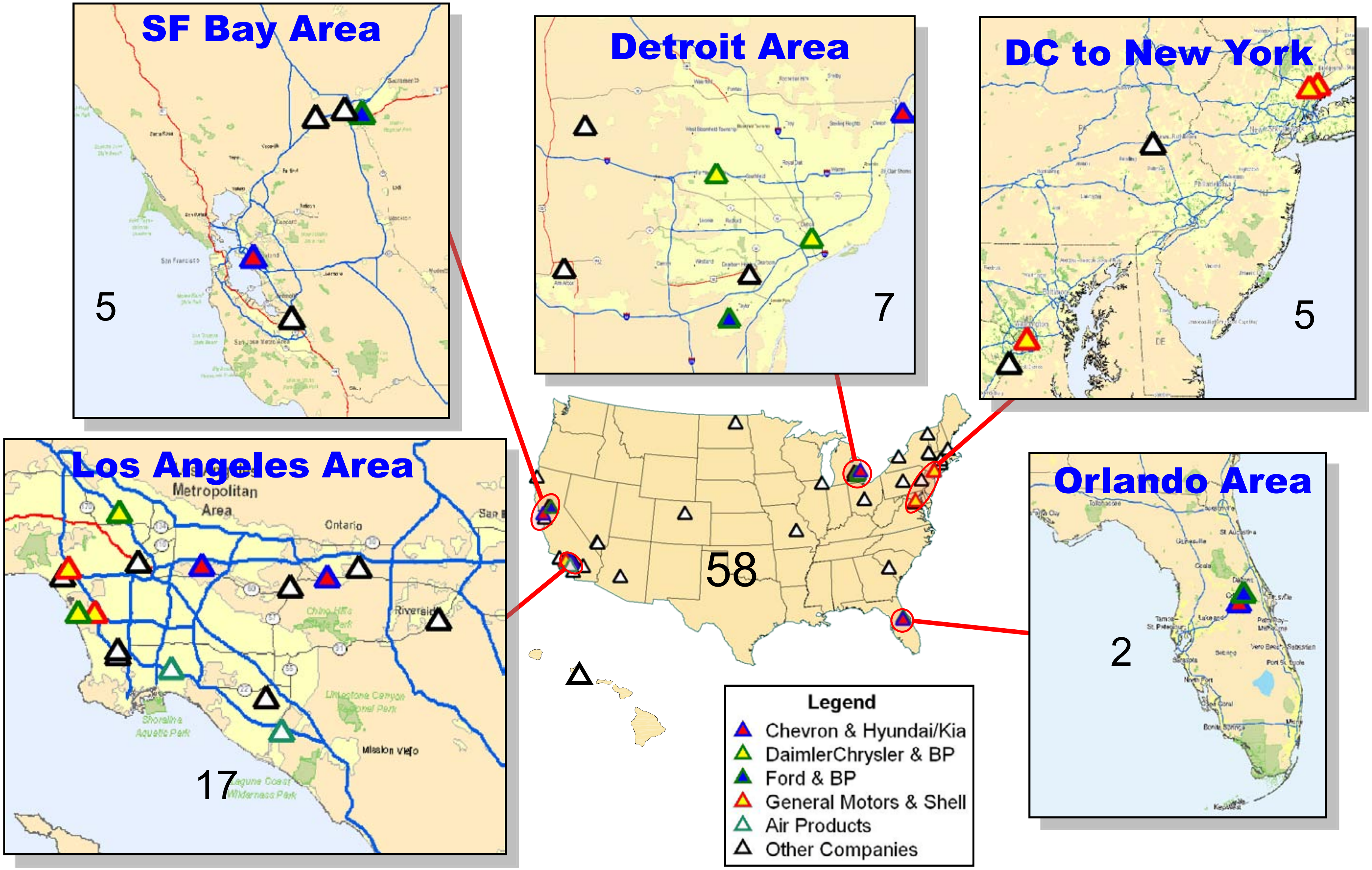

**Steam Methane Reforming**
**Oakland, CA**


**Water Electrolysis**
**Santa Monica, CA**

Total of 90,000 kg $H_2$ 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

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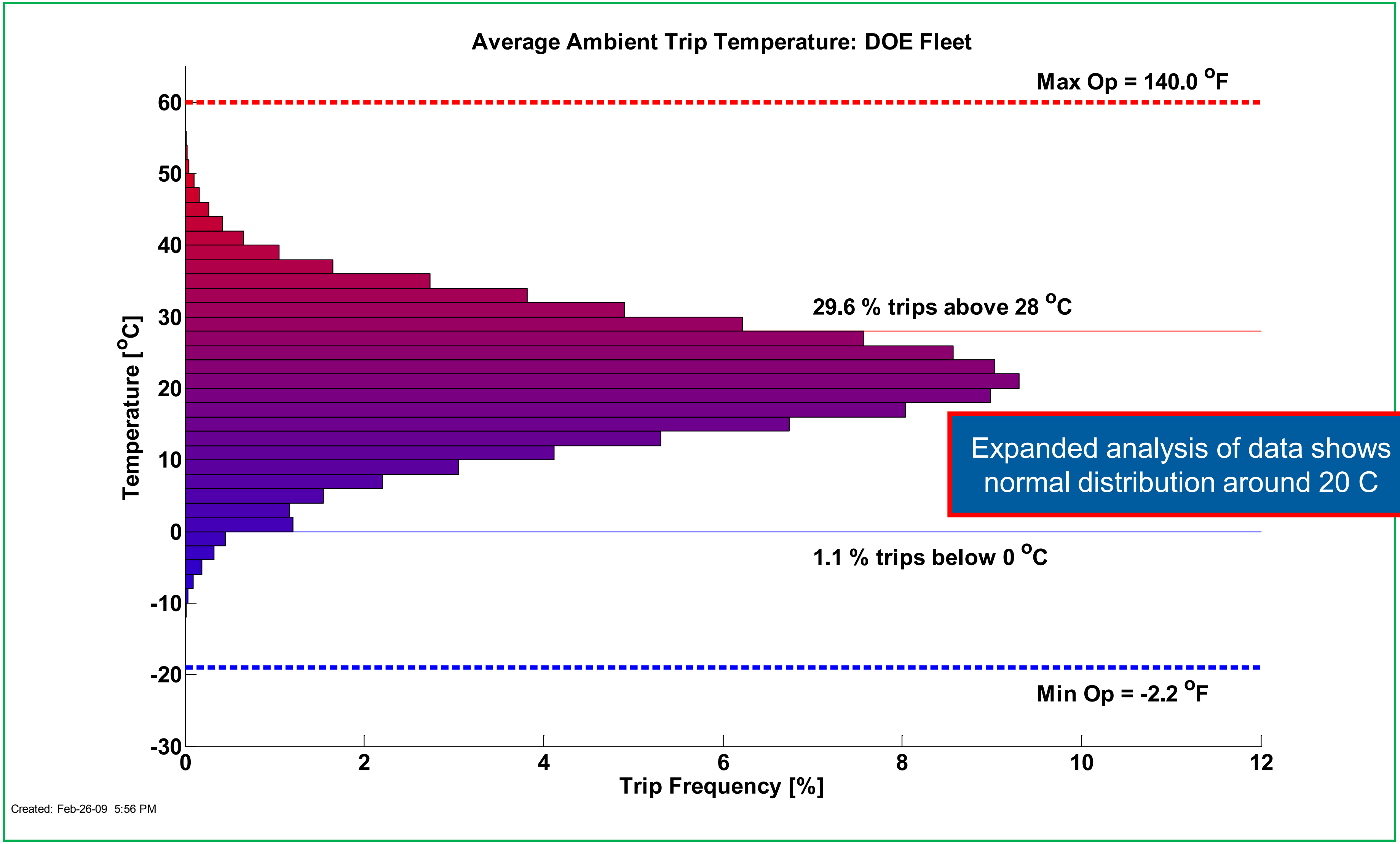
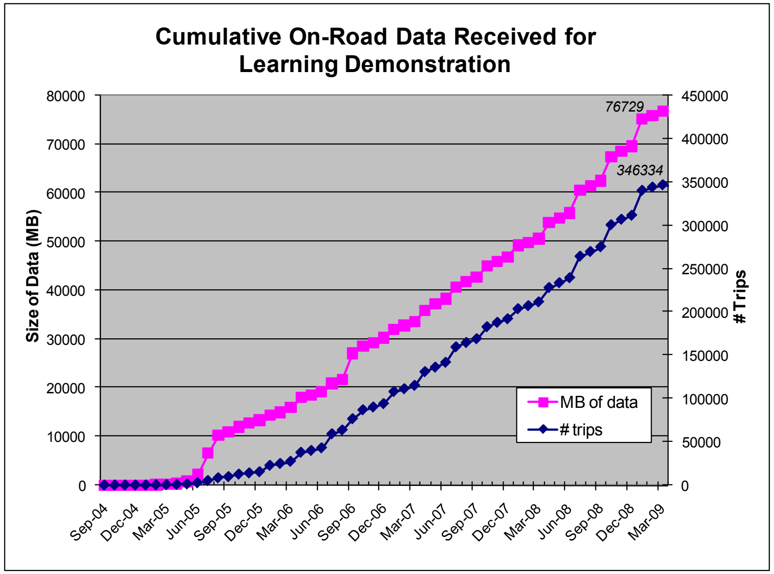
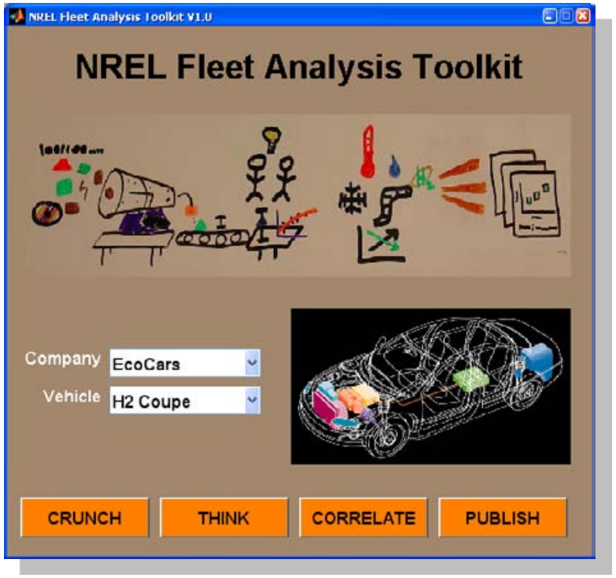
# Distribution of Average Ambient Temperature During Vehicle Operation from All Trips

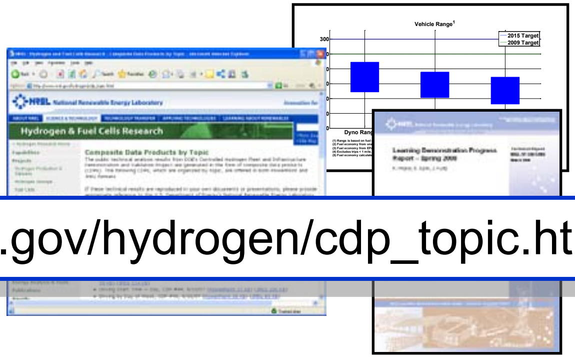


# Large Data Sets Processed with NREL Tools; Two Types of Results Serve a Diverse Audience




Through March 2009:
346,000 individual vehicle trips
76 GB of on-road data



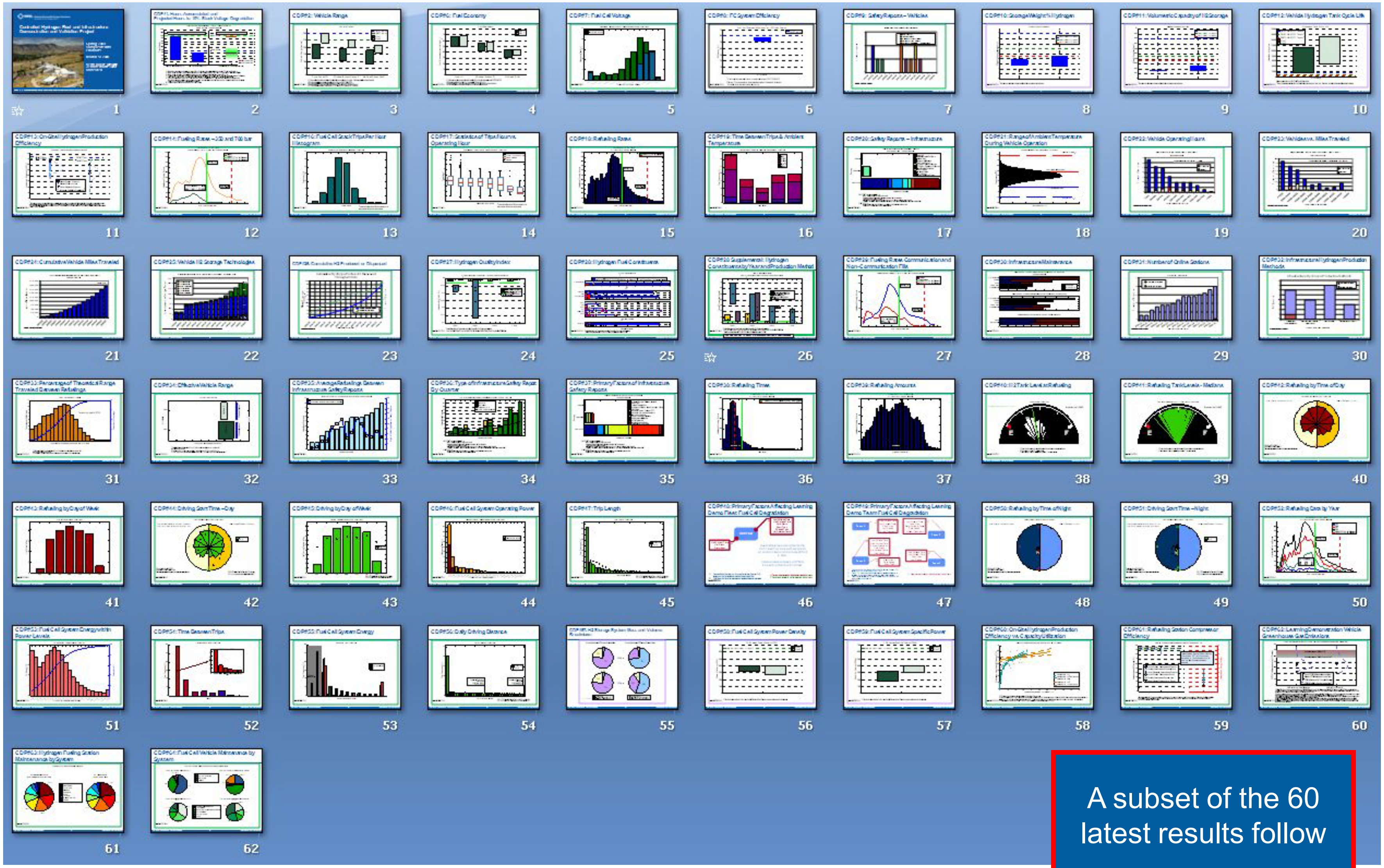
**NREL HSDC**

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

Detailed Data Products → Individual Team Discussions

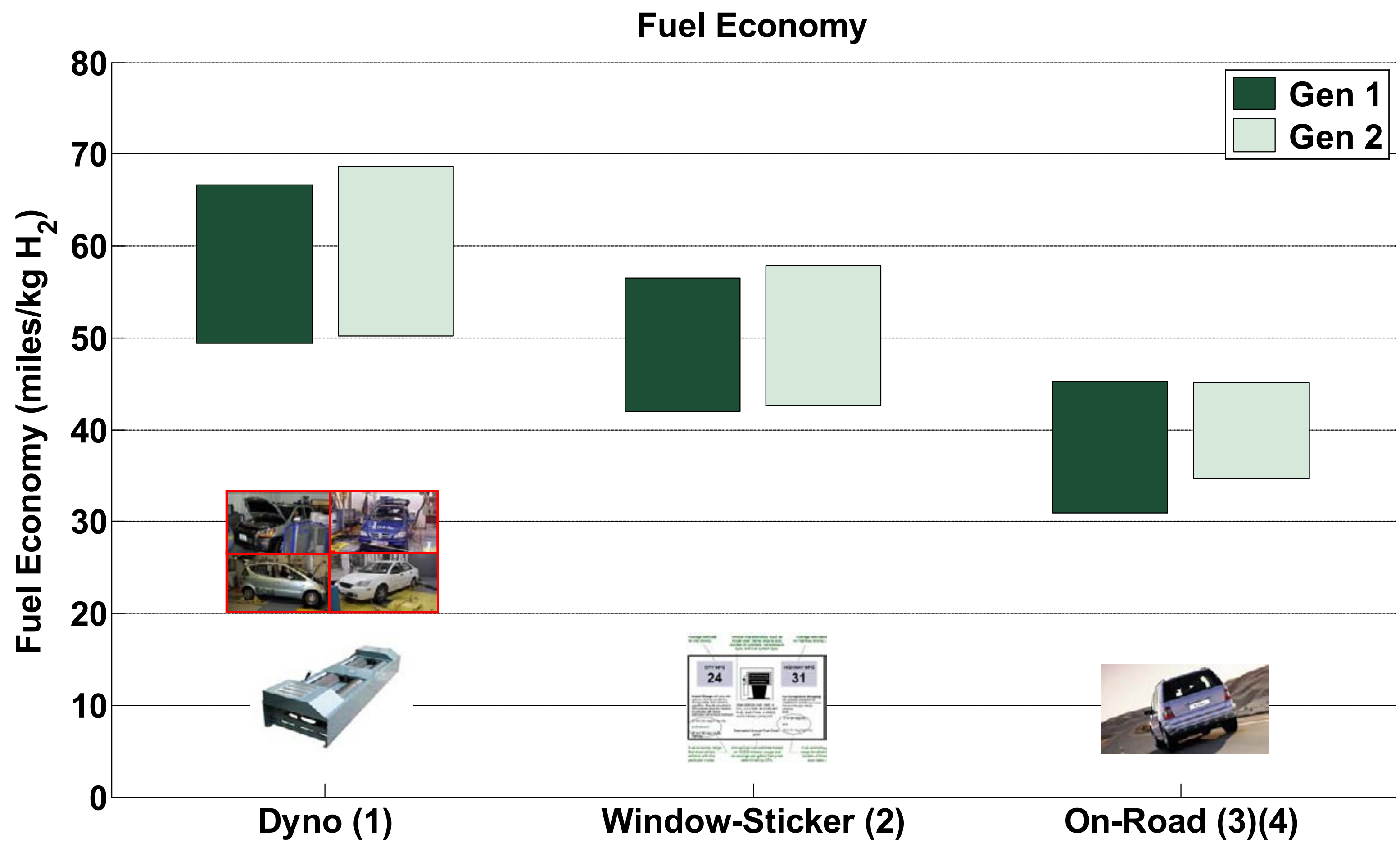
Data Flow

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



A subset of the 60 latest results follow

# 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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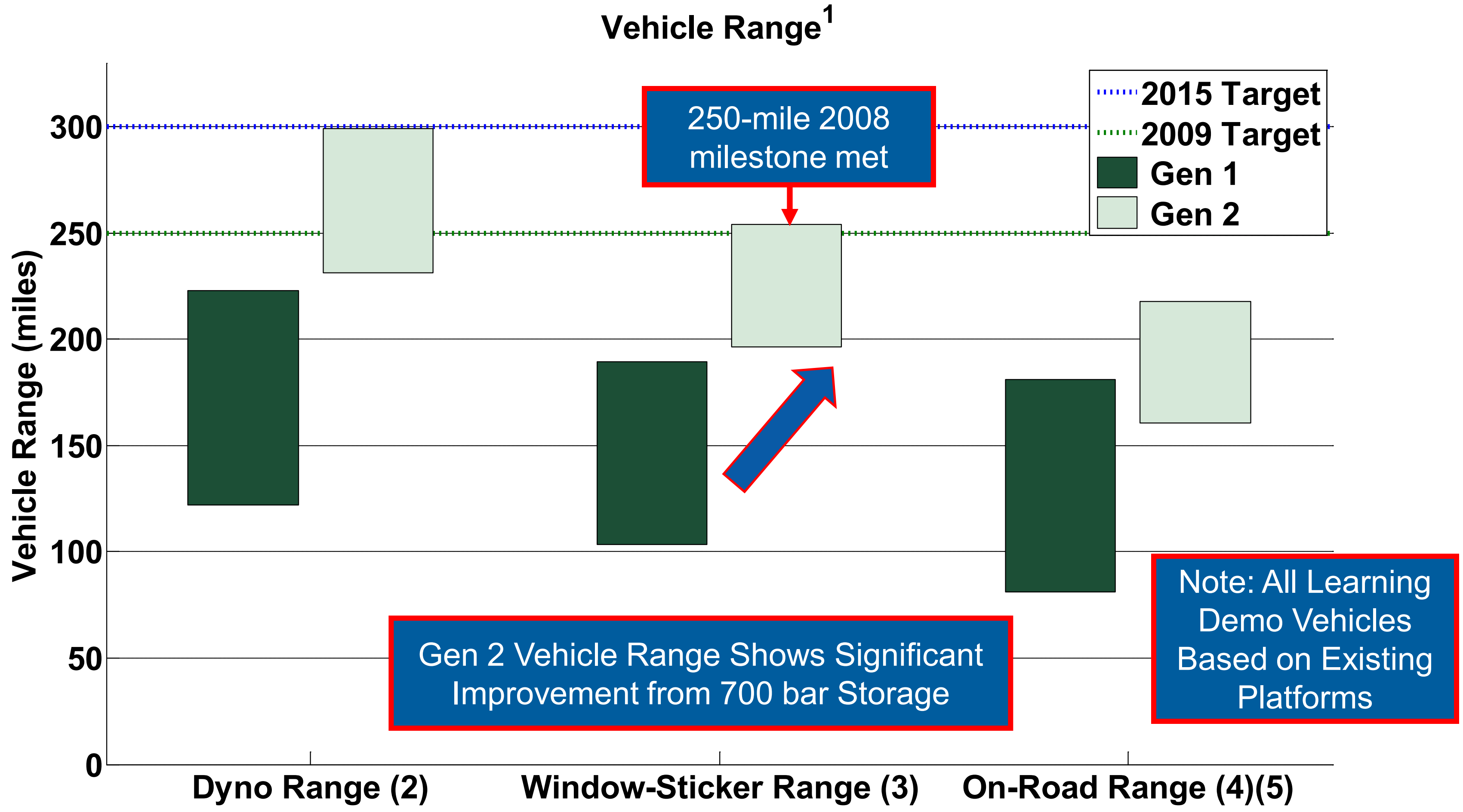
# Driving Range for Gen 1 and Gen 2 Vehicles: Based on Fuel Economy and Usable $H_2$

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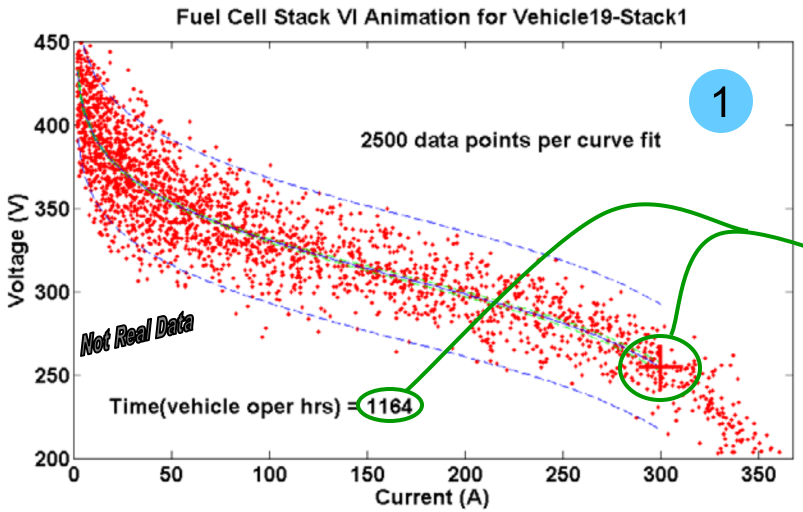
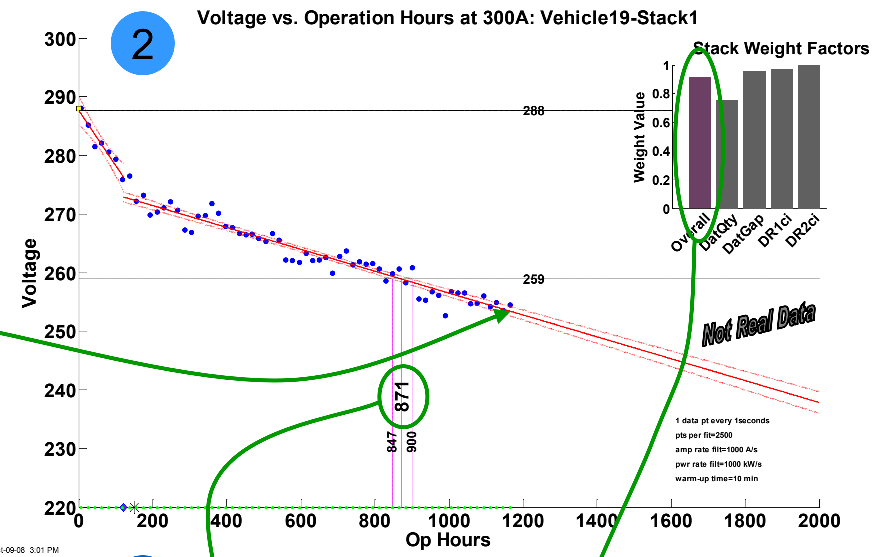
(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data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

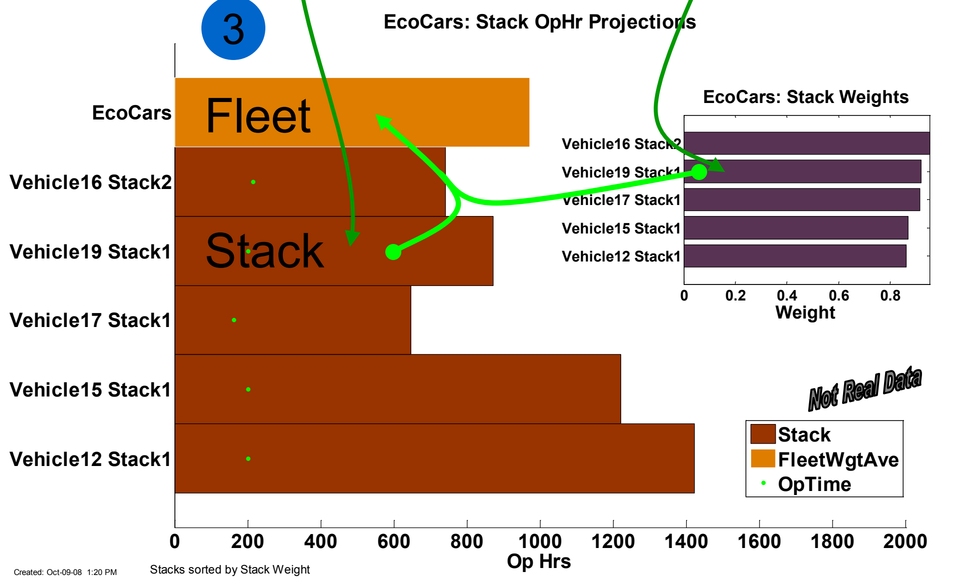
# Improved Approach for Calculating Projected Time to 10% Voltage Drop for Stack and Fleet



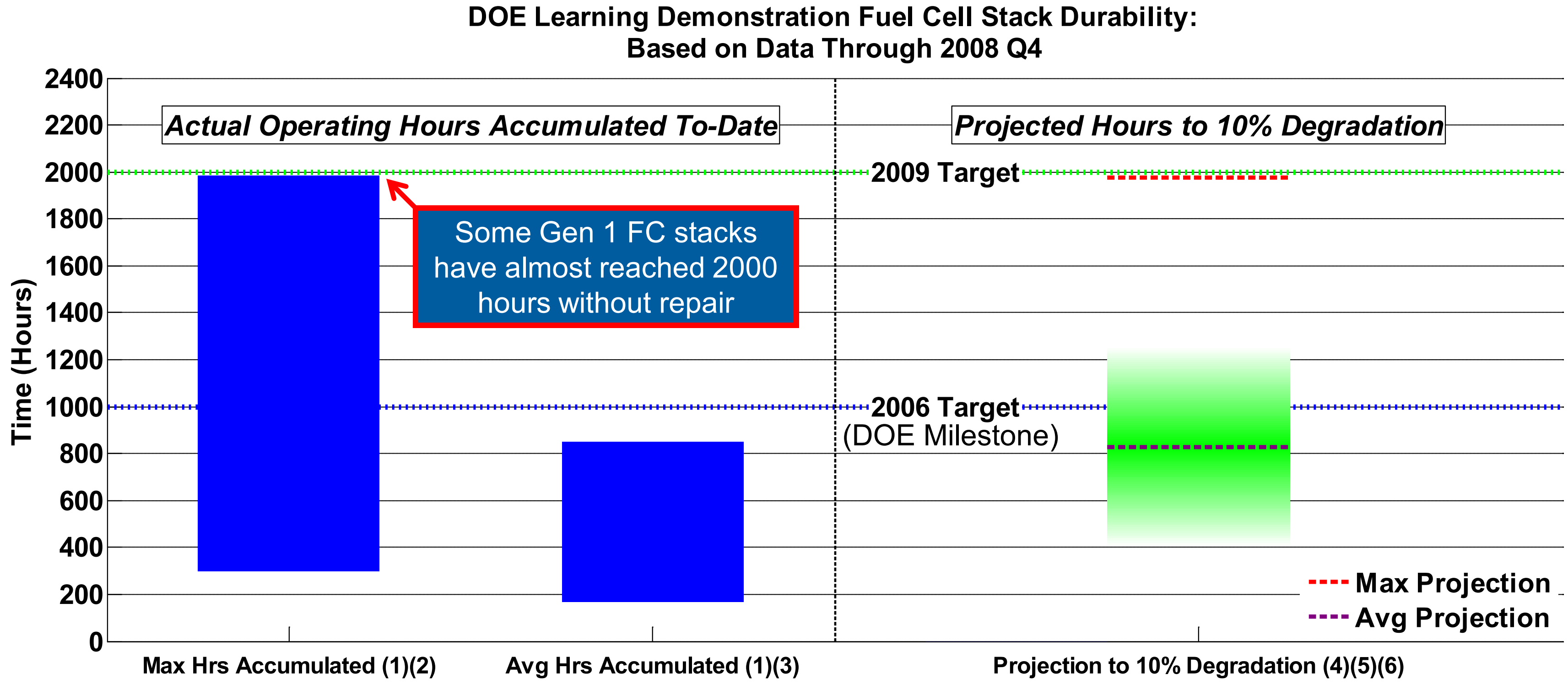




1. ***FC Stack*** voltage & current polarization fit
2. ***FC Stack*** voltage decay estimate using robust, improved **segmented linear fit** instead of linear fit (follows non-linear decay trends & early voltage decay)
3. ***Fleet*** weighted average using FC Stack operating hour projections and weights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




(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.

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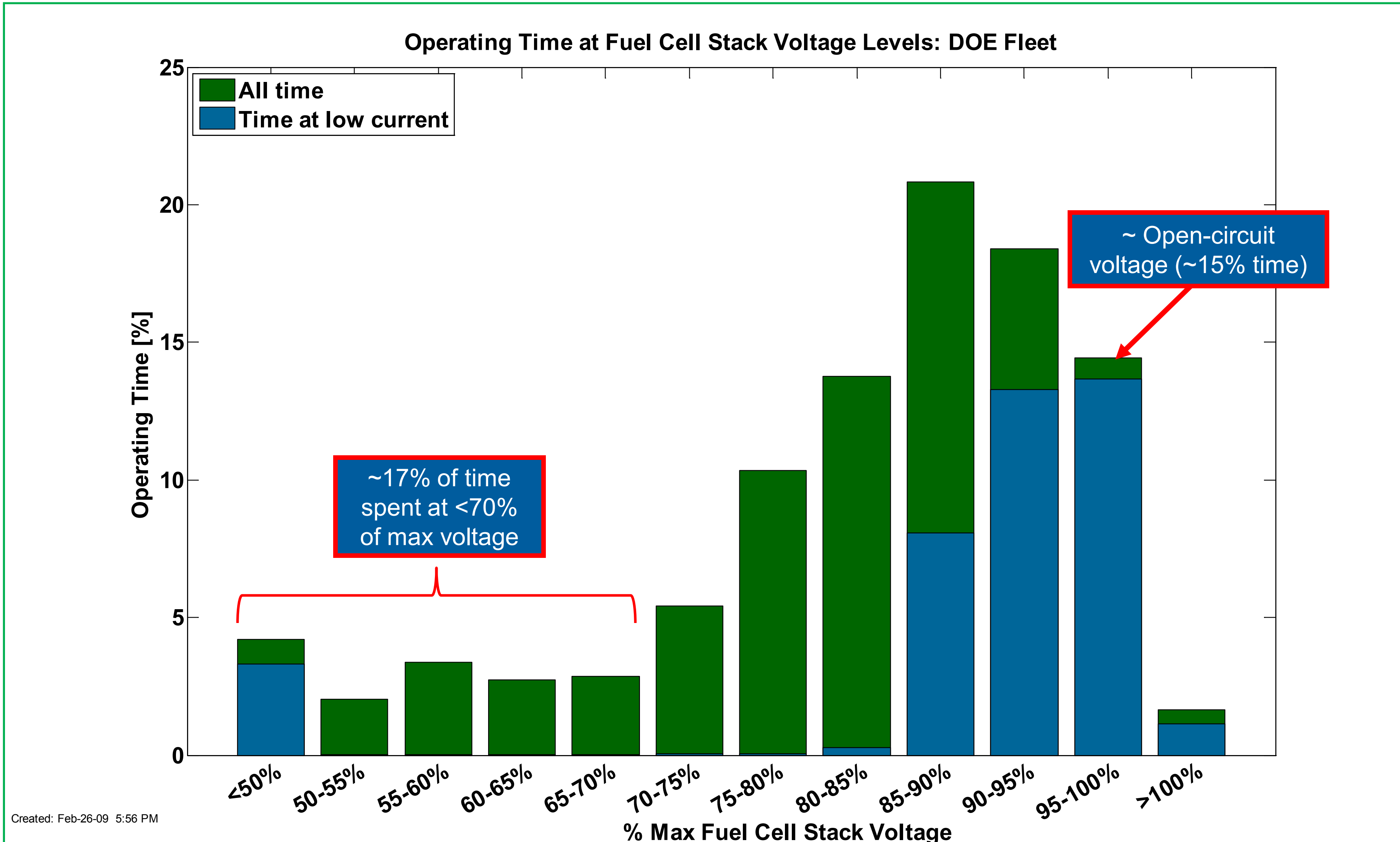
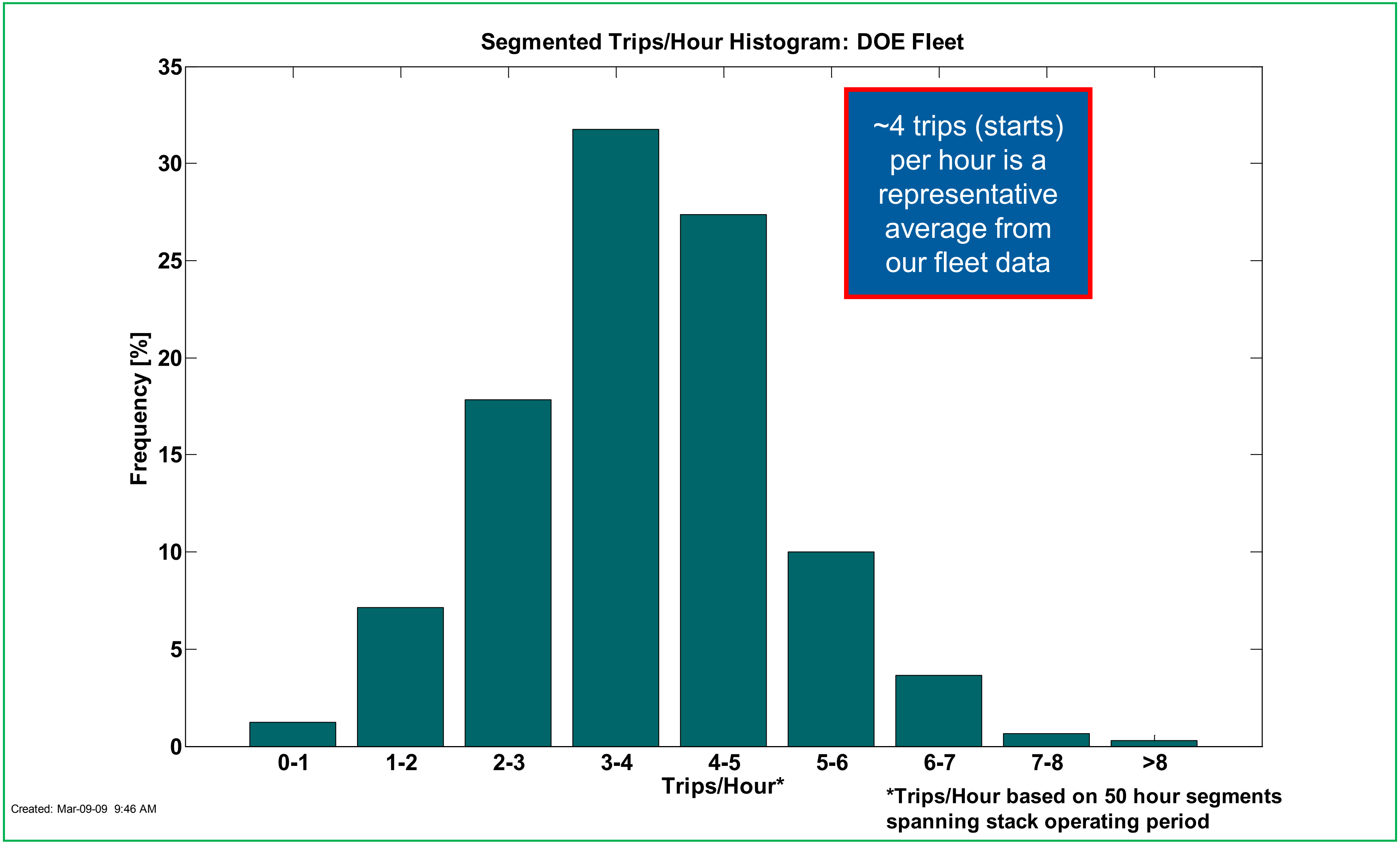
More data required to make Gen 2 projections (late 2009)

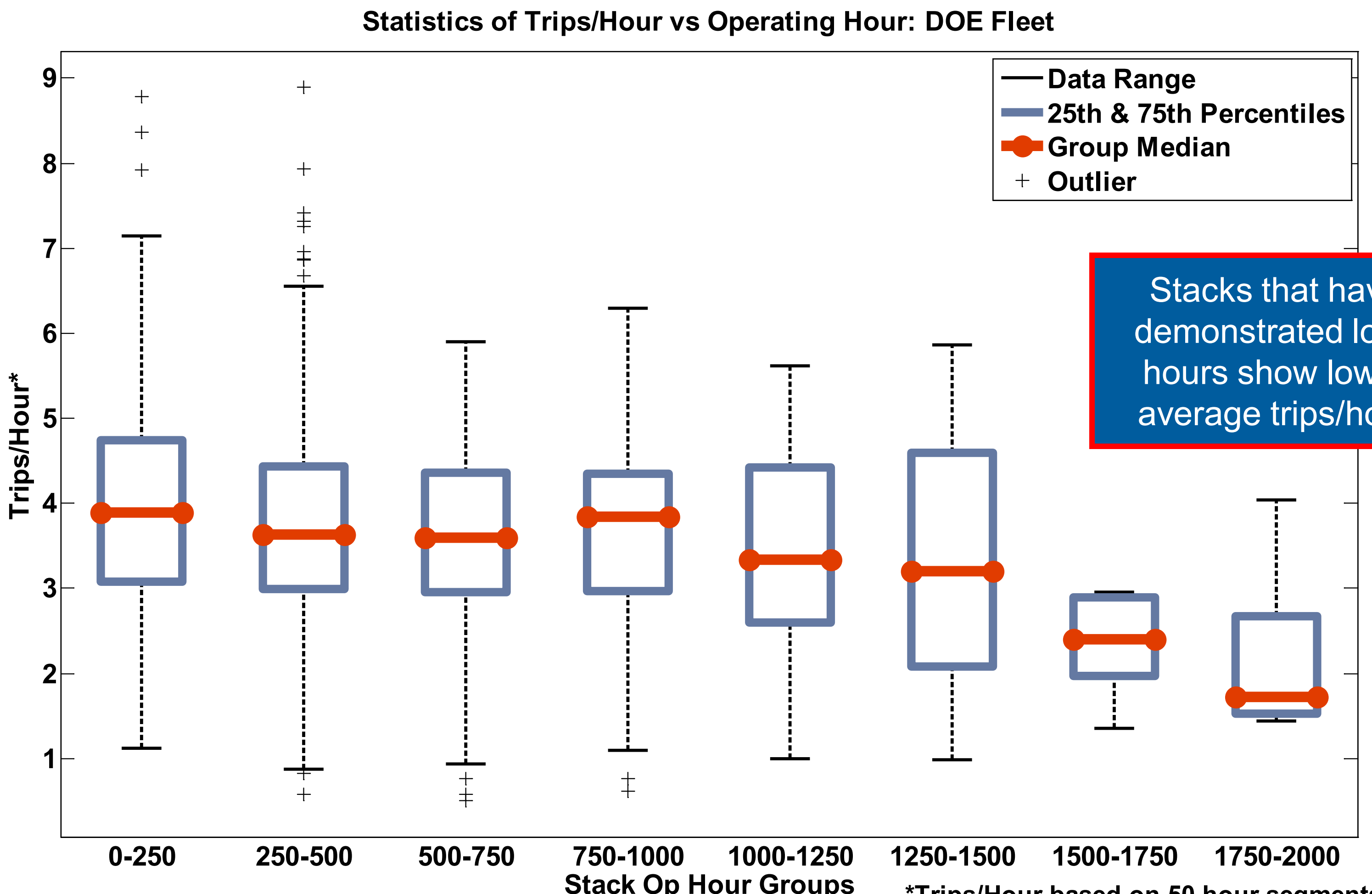
# Stack Duty Cycle: Time Fuel Cell Spends at Various Voltage Levels Was Requested by FC Developers



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



# Average Trips/Hour as a Function of Stack Operating Hour




Stacks that have demonstrated long hours show lower average trips/hour

*Trips/Hour based on 50 hour segments spanning stack operating period

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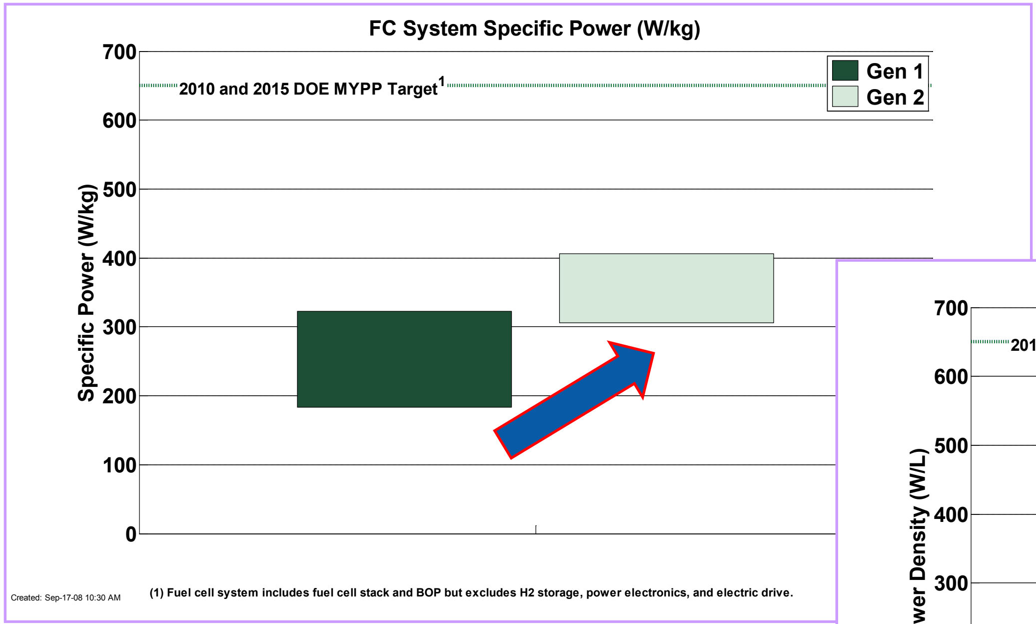
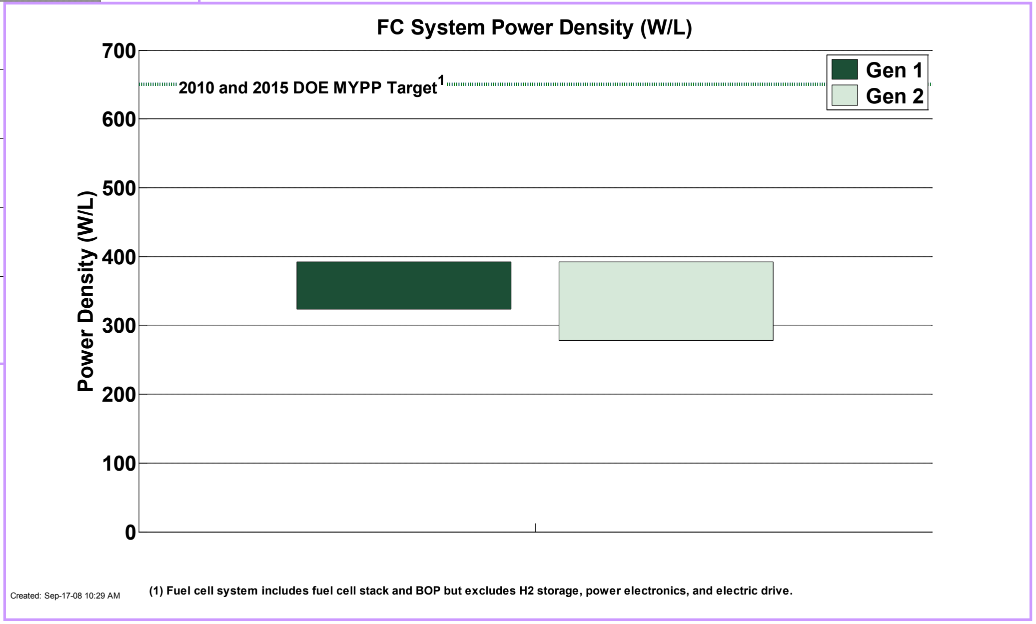
# Comparison of FC System Specific Power and Power Density Between Gen 1 to Gen 2




Freeze Capability of Gen 2 Systems May Have Increased Volume

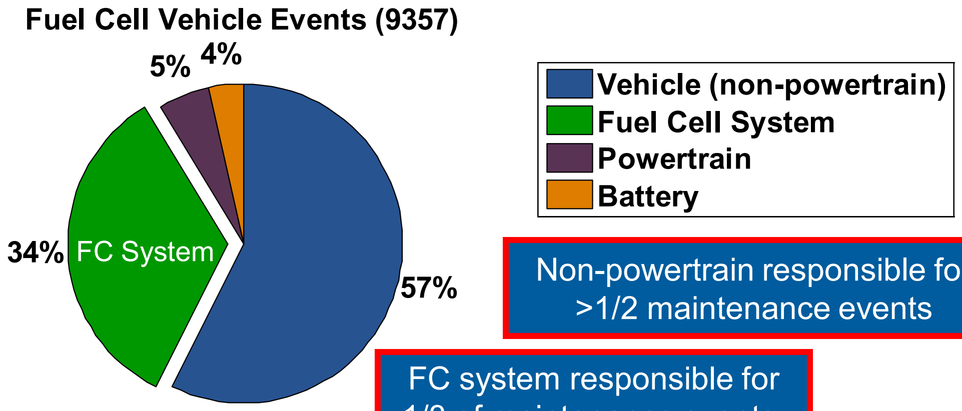
Significant Improvements Seen in Specific Power (…systems getting lighter)

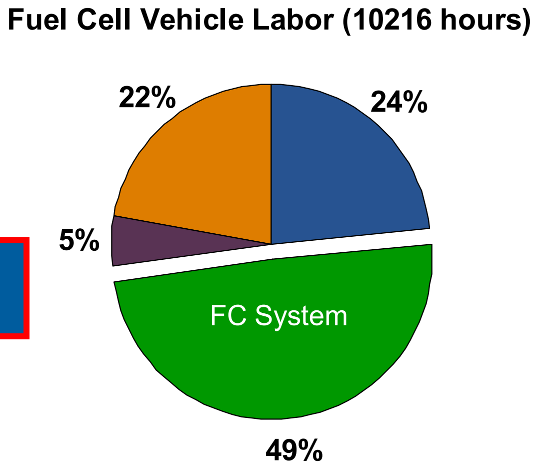



Power Density Did Not Improve Between Gen 1 and Gen 2 (…same size or larger)

# New Analysis of Vehicle Maintenance Data Highlights Areas for Improvement

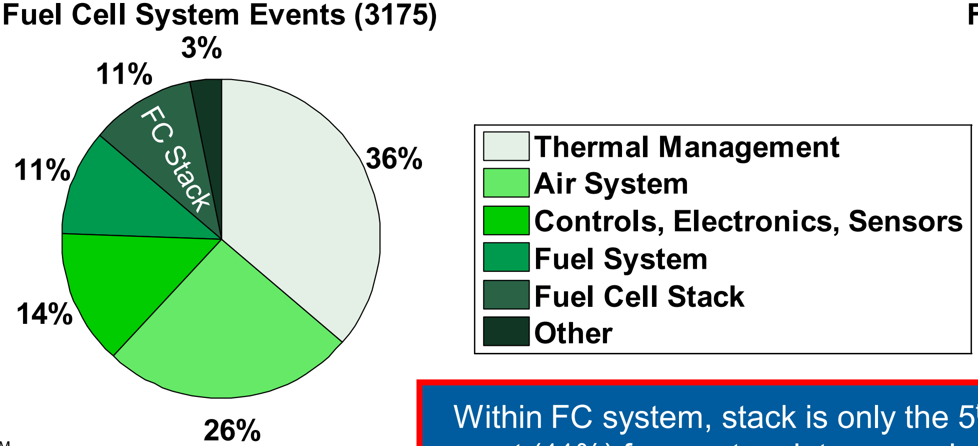
**Fuel Cell Vehicle Maintenance Events and Labor Hours**

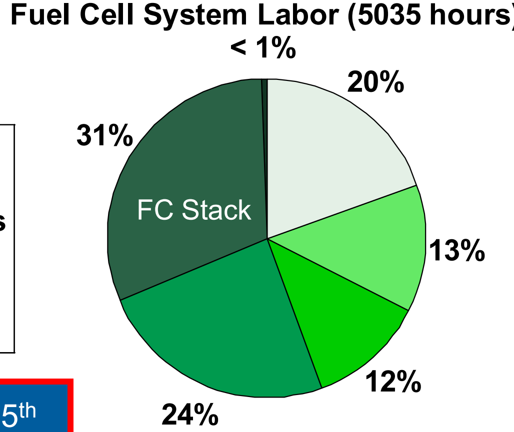



Non-powertrain responsible for >1/2 maintenance events

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

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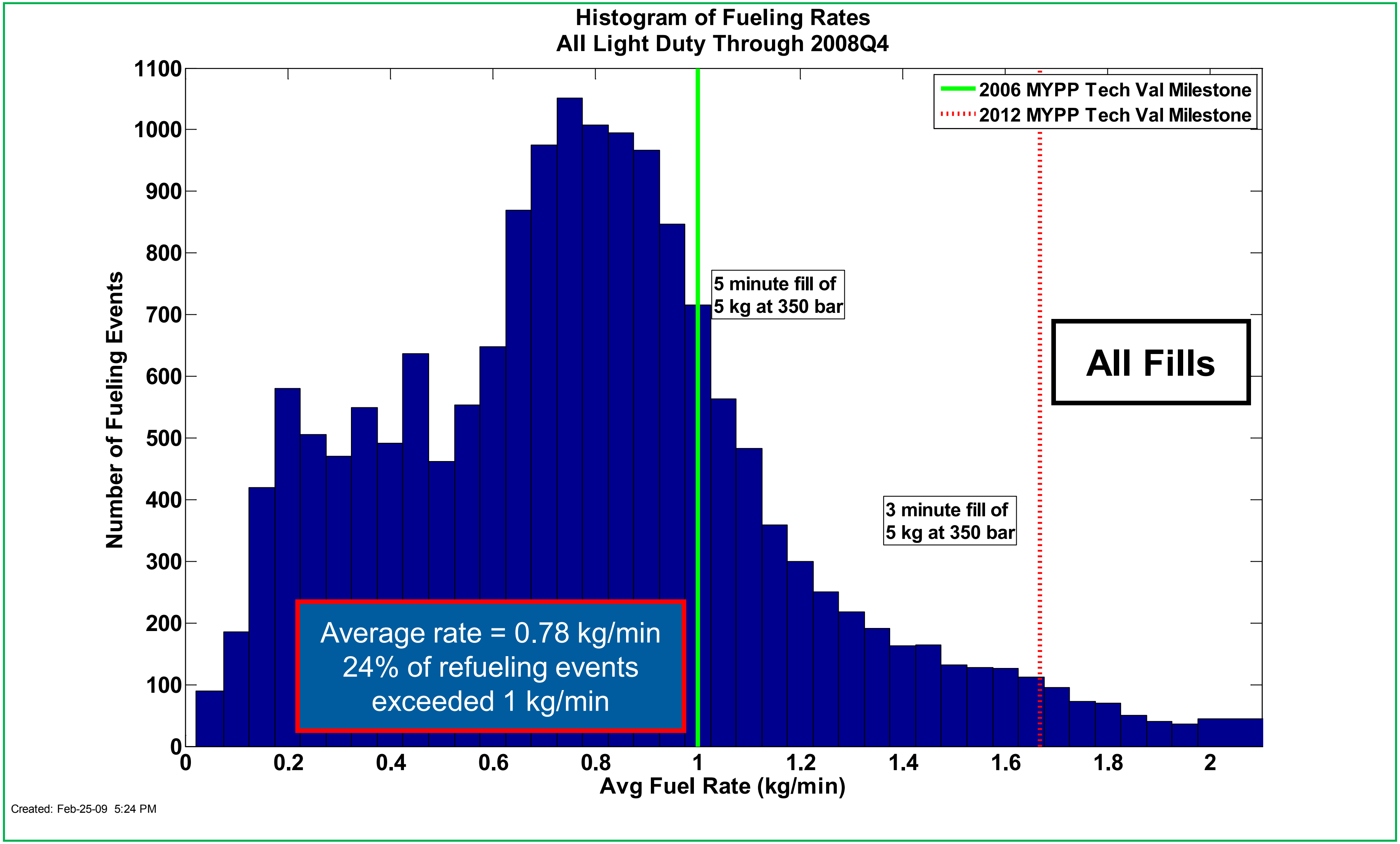
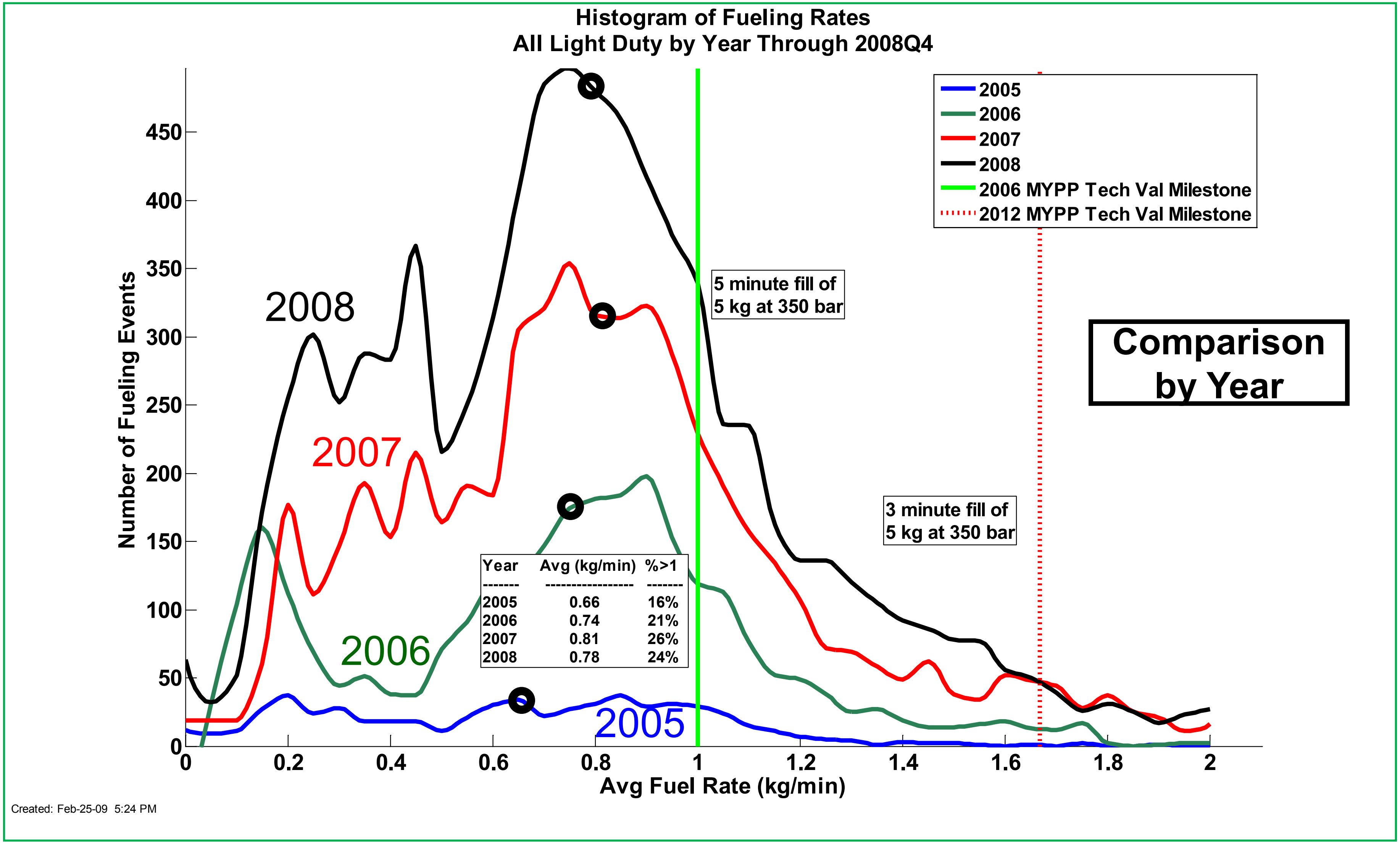
Within FC system, stack is only the 5th most (11%) frequent maintenance, but responsible for 1/3 of repair time

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

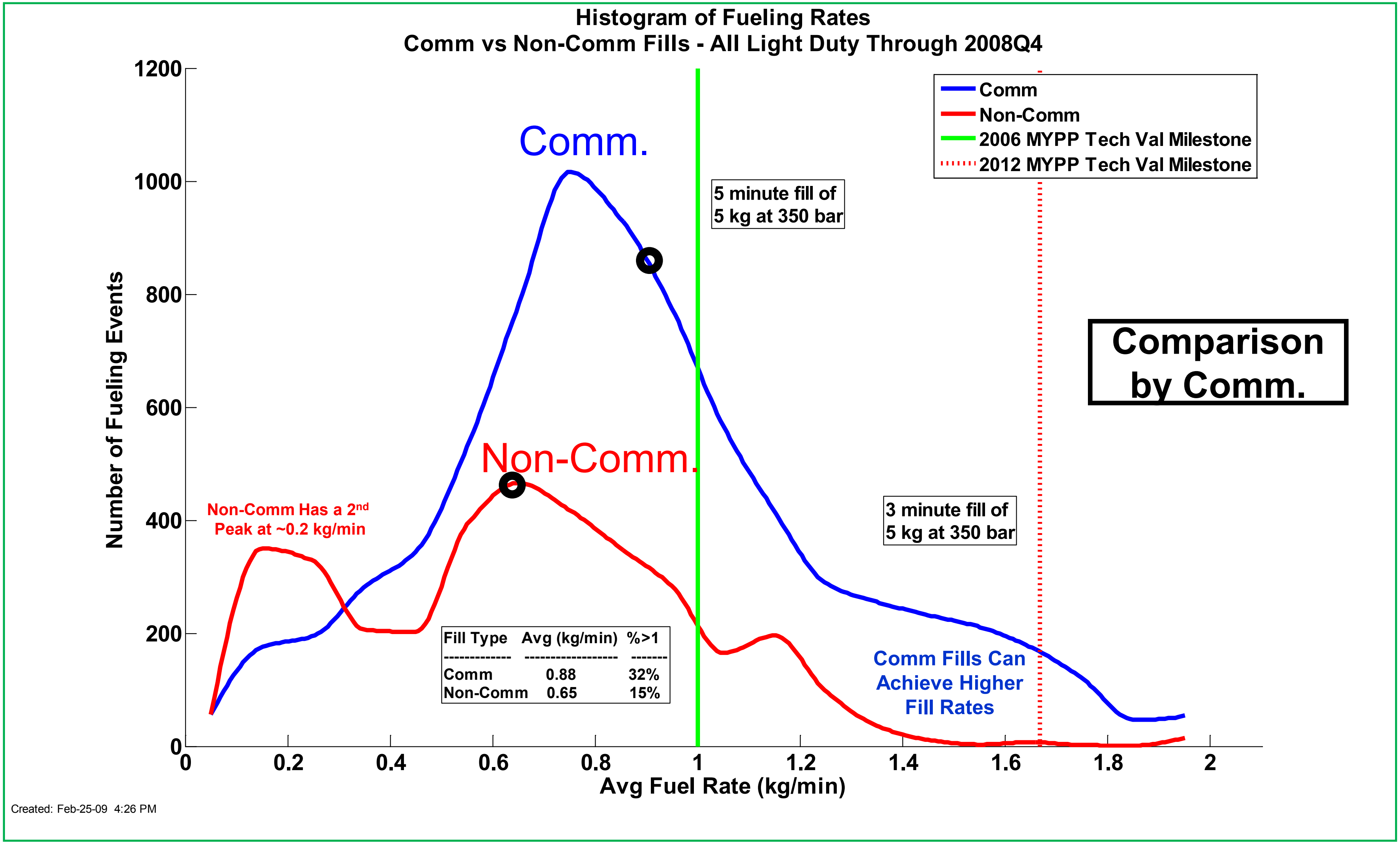


# Refueling Rates by Year: Highest Number of Fills in 2008; ~1/4 Now Exceed 1 kg/min

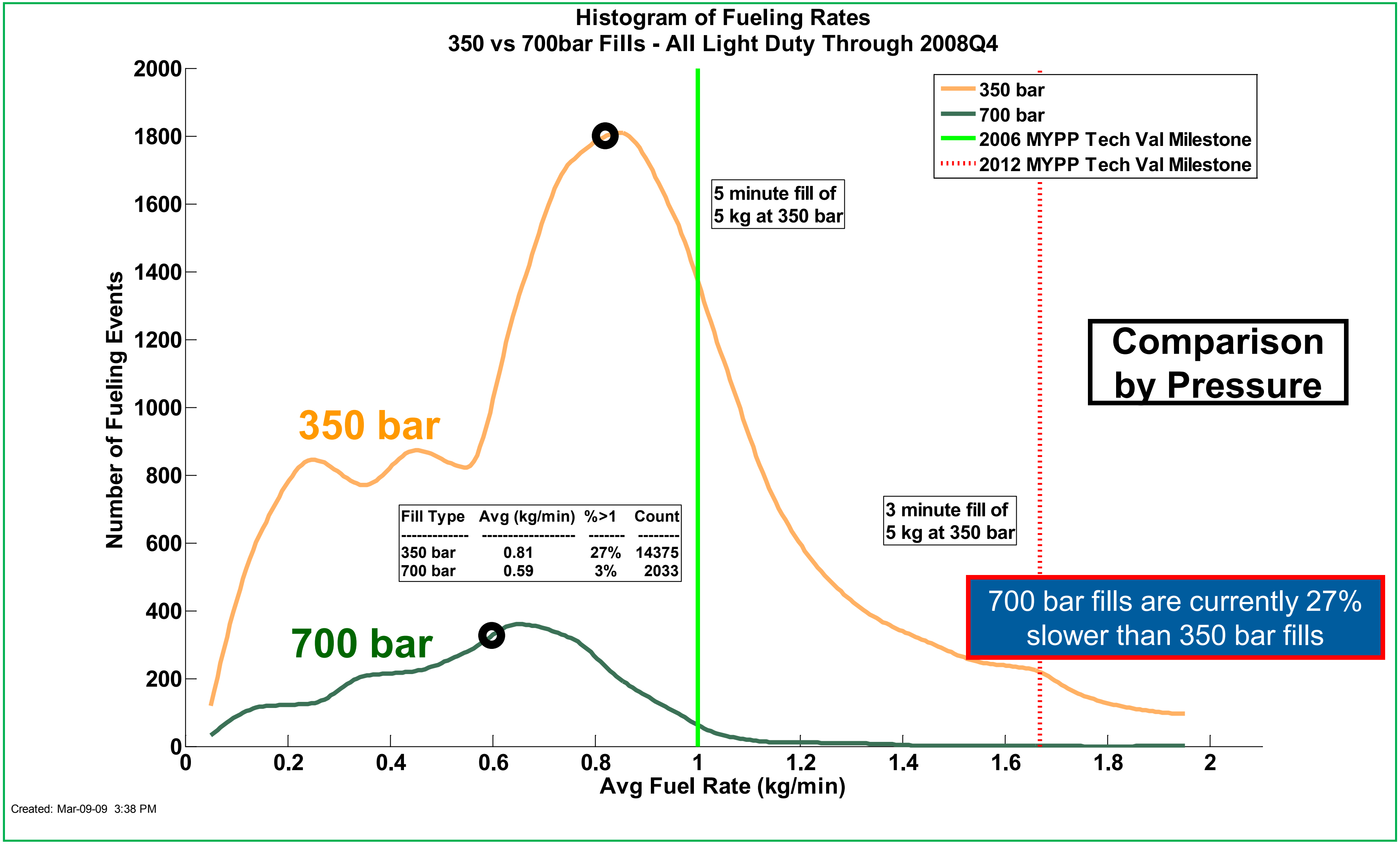



| Year | Avg (kg/min) | %>1 |
|---|---|---|
| 2005 | 0.66 | 16% |
| 2006 | 0.74 | 21% |
| 2007 | 0.81 | 26% |
| 2008 | 0.78 | 24% |

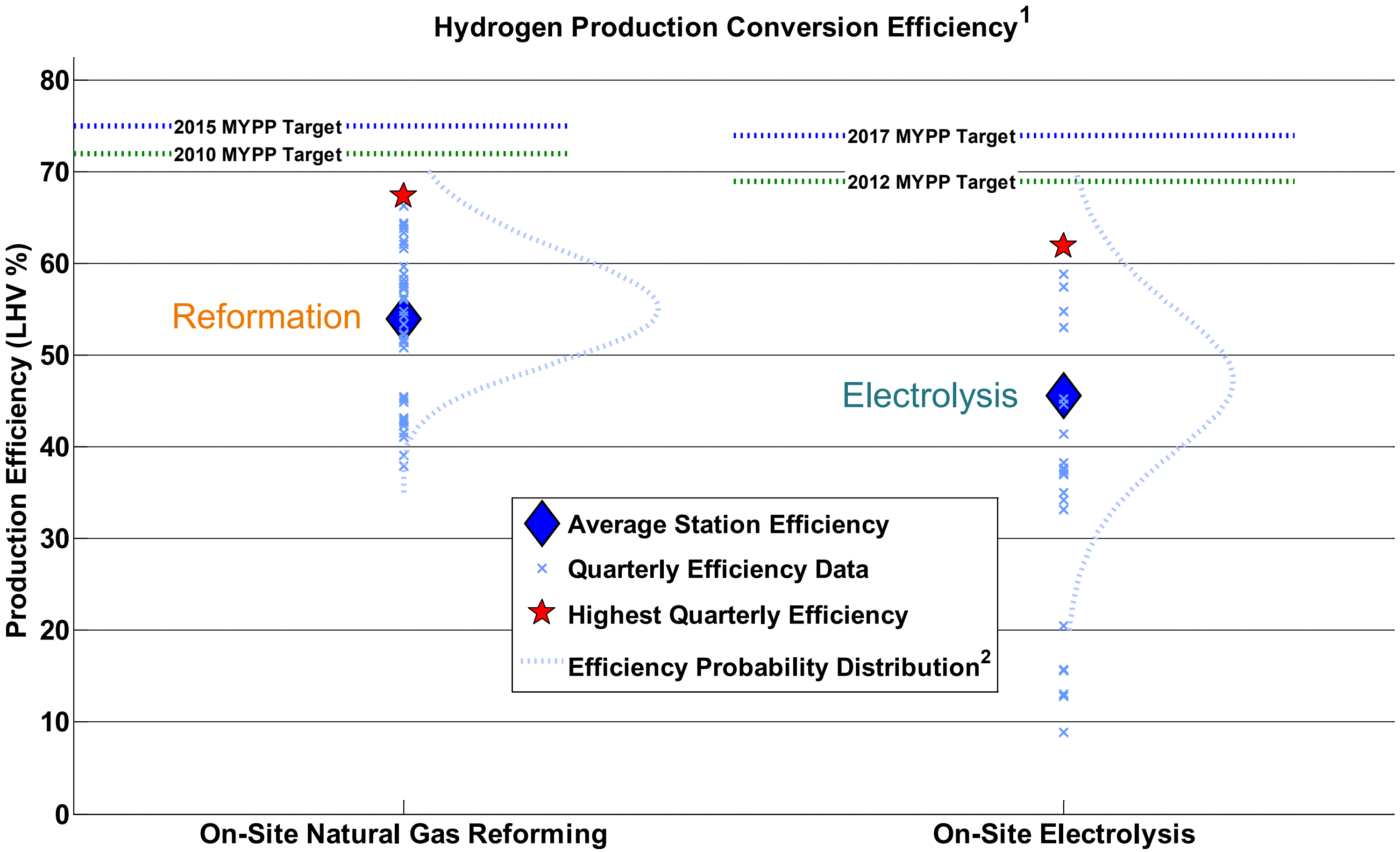
# Communication $H_2$ Fills Achieving 35% Higher Average Fill Rate than Non-Communication



# 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




[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.
[2]The 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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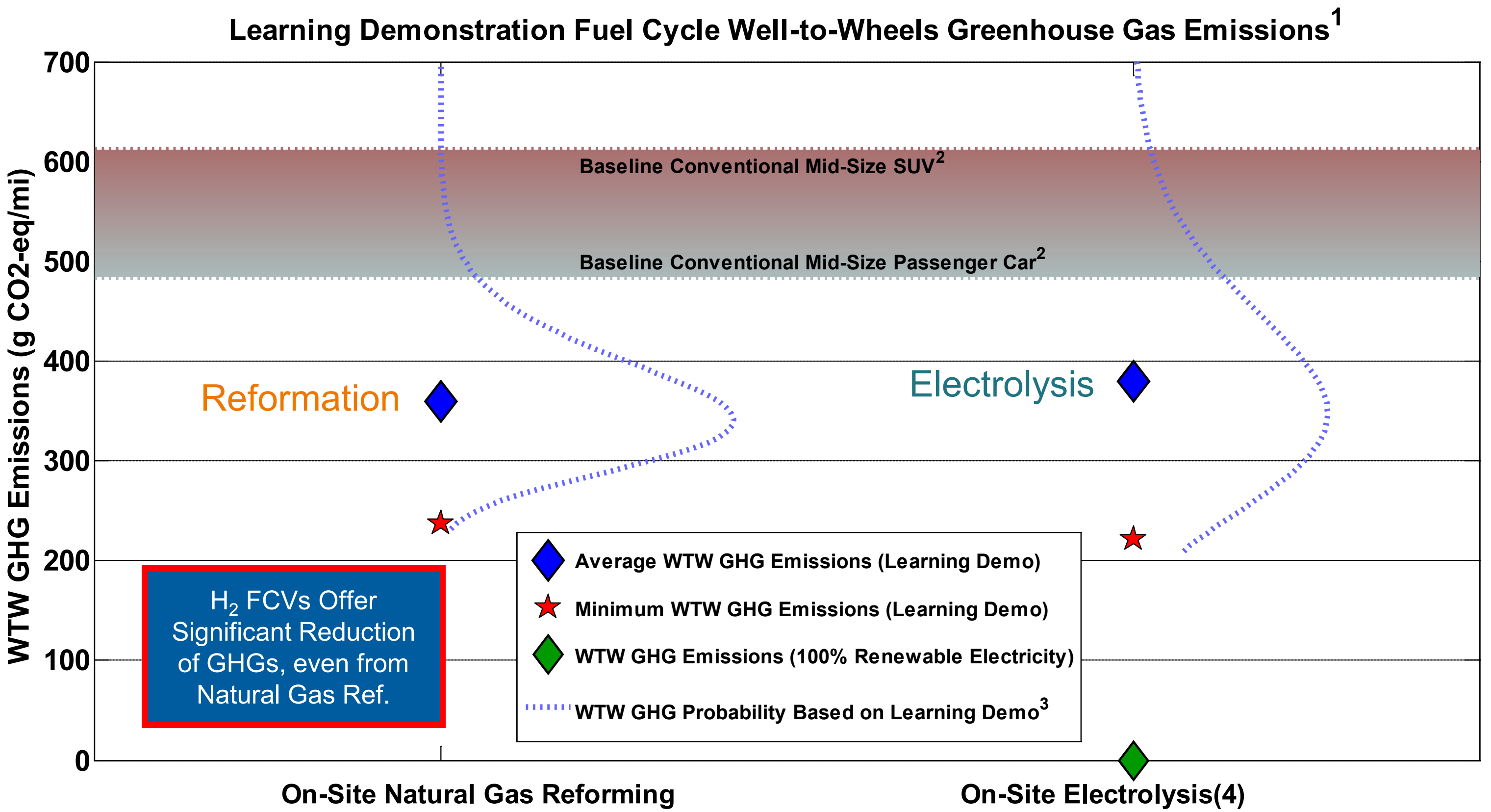
# Learning Demonstration Vehicle Greenhouse Gas Emissions Using Actual Production Efficiencies and Fuel Economies




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 1241 g/mile.

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# Summary

- Learning Demo evaluation is ~80% complete
  - 140 vehicles and 20 stations deployed
  - 1.9 million miles traveled, 90,000 kg $H_2$ produced or dispensed
  - 346,000 individual vehicle trips analyzed
  - Project to continue through 2010

- Emphasis from project has been on providing maximum value from the data collected during project
  - 60 results have been published
  - Updates every 6 months
  - Current results are always available on our web page

- Vehicle/Station Status
  - Roll-out of 2nd generation vehicles is now complete
  - Station deployment nearing completion

# Questions and Discussion


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

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