2008 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review

Controlled Hydrogen Fleet and Infrastructure Analysis

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Project ID# TV-5

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


Solar Electrolysis Station, Sacramento, CA

Photo: NREL

Project Overview

Timeline

- Project start: FY03
- Project end: FY10
- ~70% of Task III complete (see timeline slide)

Budget

- Context: Overall DOE project is ~$170M project over 5 years
  - Equal investment by industry
- NREL funding prior to FY07 : $2192K
- NREL FY07 funding: $850K
- NREL FY08 funding: $850K

Partners

- See partner slide

Tech. Val. Barriers

A. **Vehicles** – lack of controlled & on-road H_2 vehicle and FC system data

B. **Storage** – technology does not yet provide necessary 300+ mile range

C. **Hydrogen Refueling Infrastructure** – cost and availability

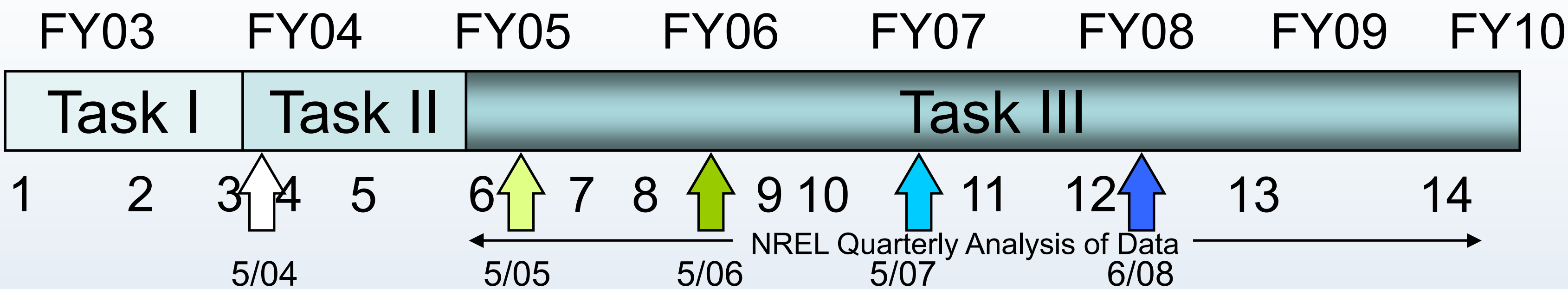
D. **Maintenance and Training Facilities** – lack of facilities and trained personnel

E. **Codes and Standards** – lack of adoption/validation

H. **Hydrogen Production from Renewables** – need for cost, durability, efficiency data for vehicular application

I. **H_2 and Electricity Co-Production** – cost and durability

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) [70% 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)

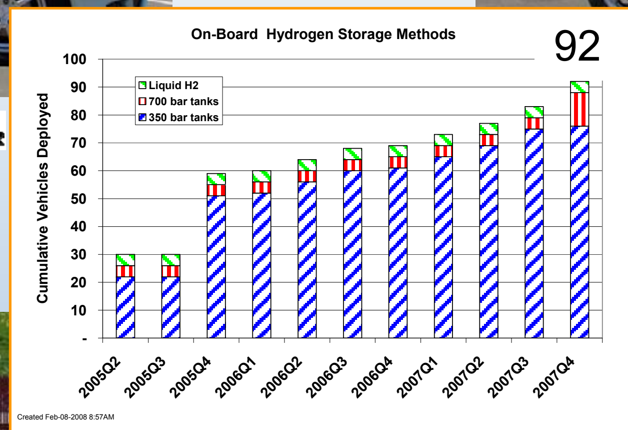
Industry Partners: 4 Automaker/Energy-Supplier Teams; Rollout: 2nd Generation FC Introduction in 2008 Has Begun

CHRYSLER

bp

Ford

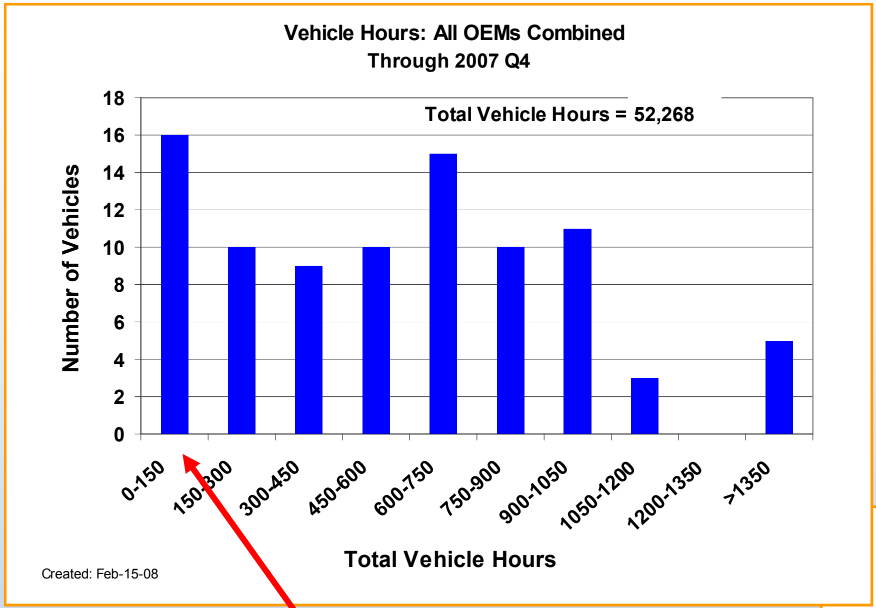
bp

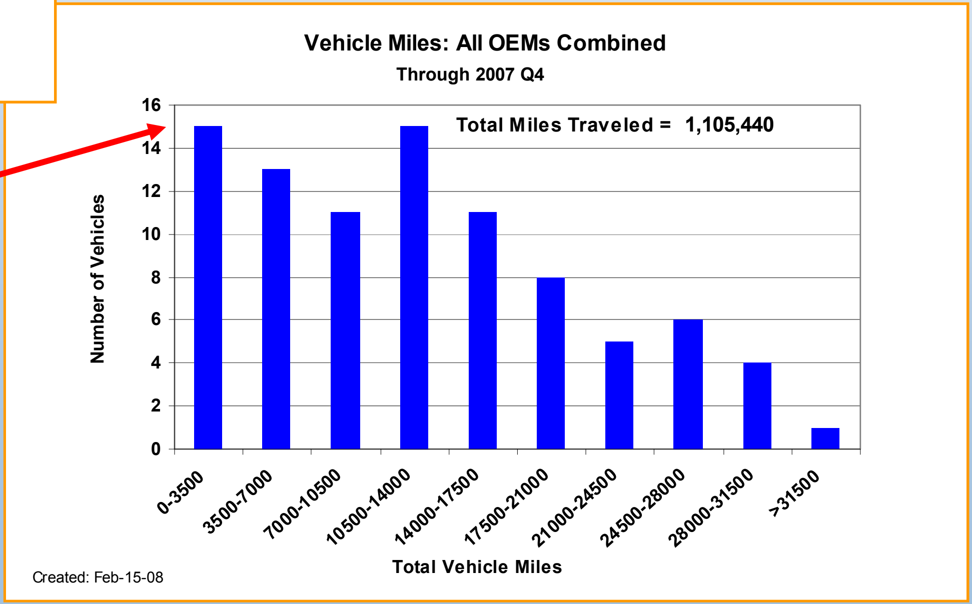


GM

Chevron HYUNDAI KIA UTC Power

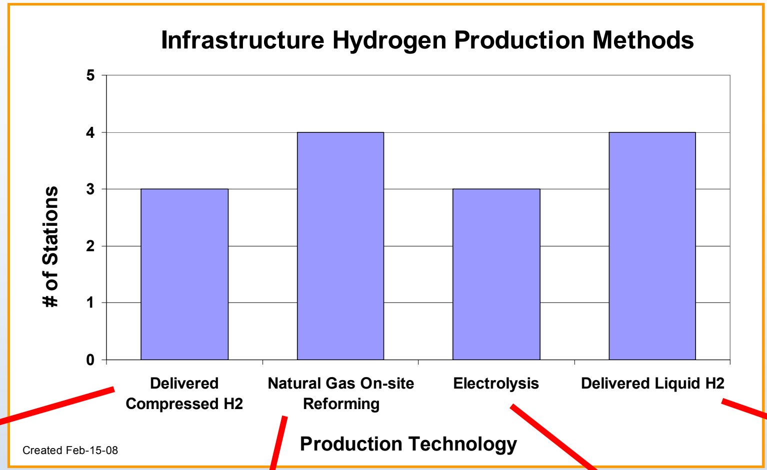
DOE Learning Demo Fleet Has Surpassed 50,000 Vehicle Hours and 1.1 Million Miles





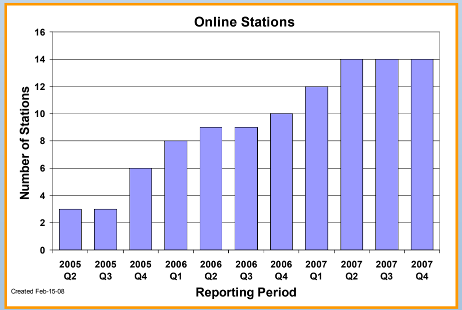
Gen 2 vehicle introduction now appears as the 2nd bulge at low hours/miles

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



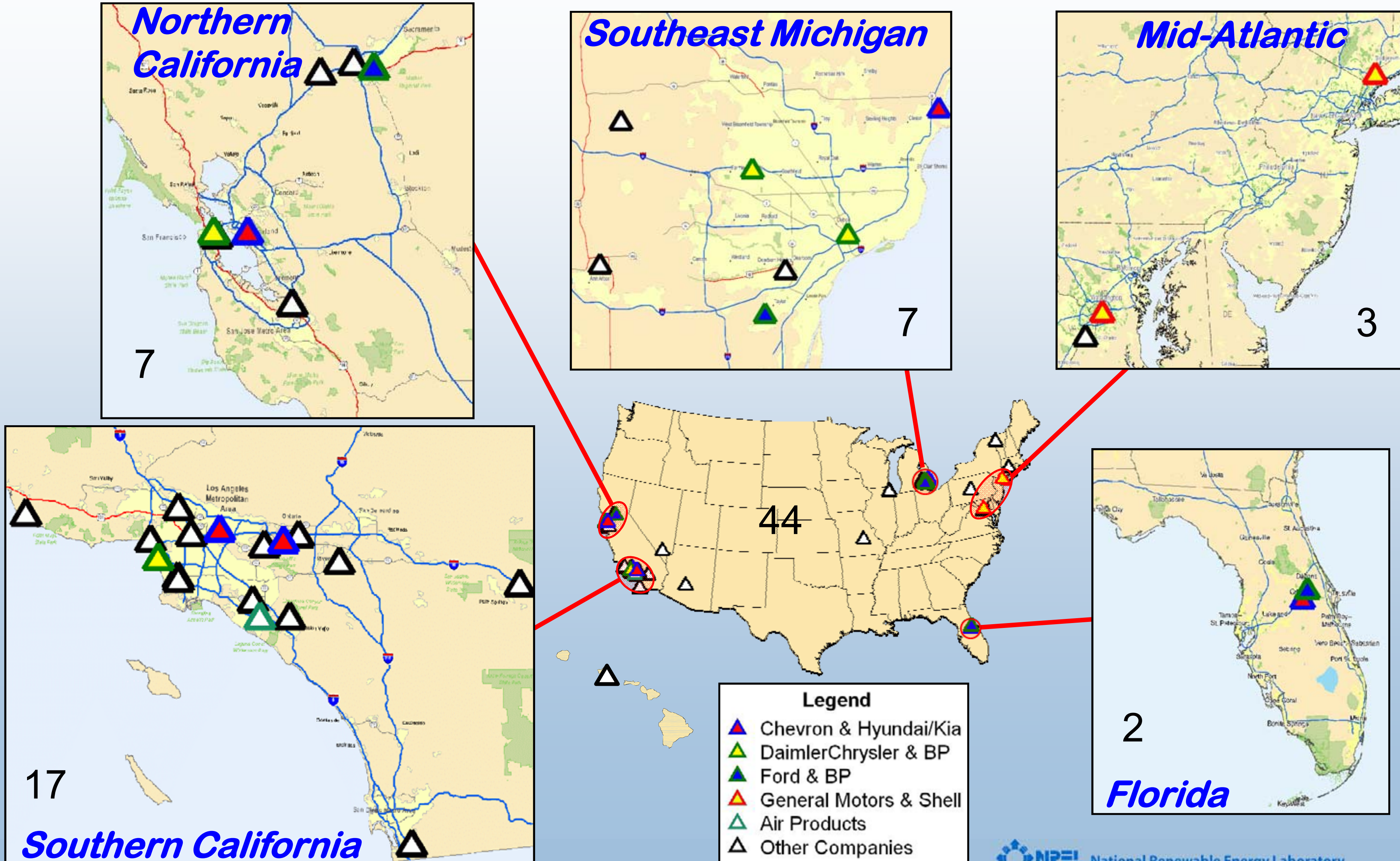
Steam Methane Reforming
Oakland, CA

Water Electrolysis
Rosemead, CA

Recent station additions include:
SMUD (BP) and White Plains, NY (Shell).
15 stations now deployed

Total of >40,000 kg H2 produced or dispensed

Refueling Stations Test Performance in Various Climates; Learning Demo Comprises ~1/3 of all US Stations



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
  - Feedback current technical challenges and opportunities into DOE H_2 R&D program
  - Provide analytical results to originating companies on their own data (detailed data products)
  - Collaborate with industry partners on new and more detailed analyses
- Publish/present progress of project to public and stakeholders (composite data products)

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

Raw Data, Reports

Hydrogen Secure Data Center (HSDC)

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

Composite Data Products

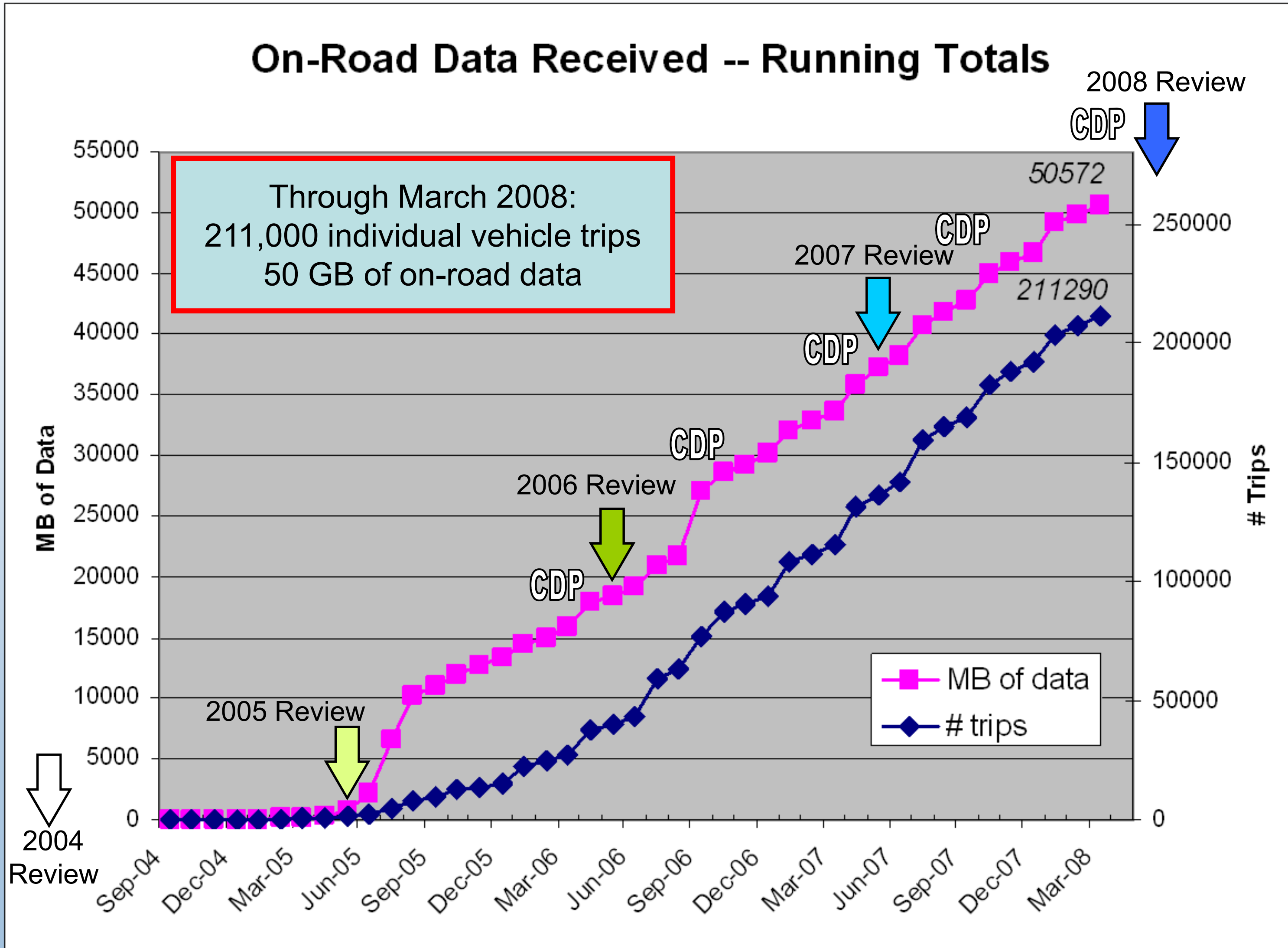
- Aggregate data results for public
- No confidential information

Detailed Data Products

- Only shared with company/team which originated the data

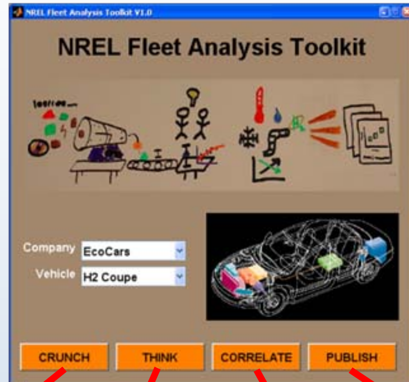
Accomplishment: Eleven Quarters of Data Analyzed to Date

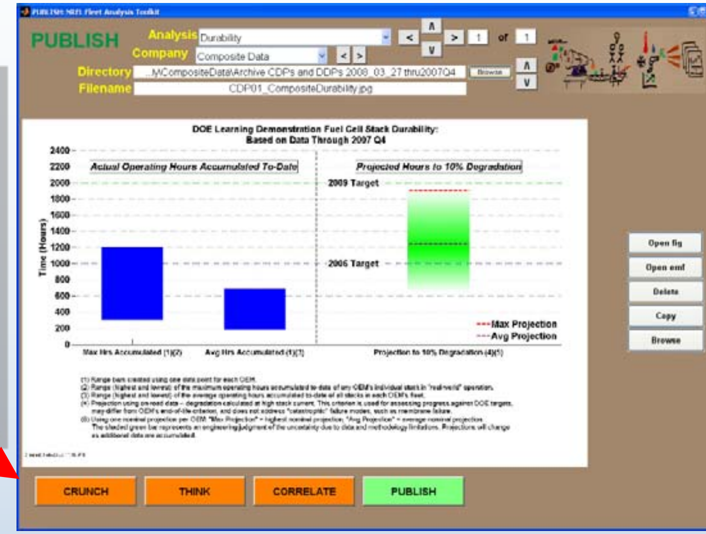
Current Status of Data Reporting to the Hydrogen Secure Data Center at NREL

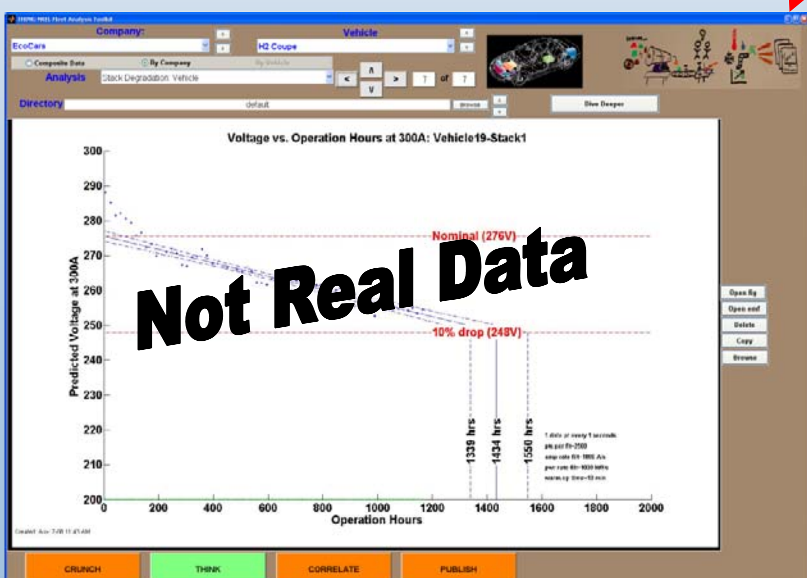


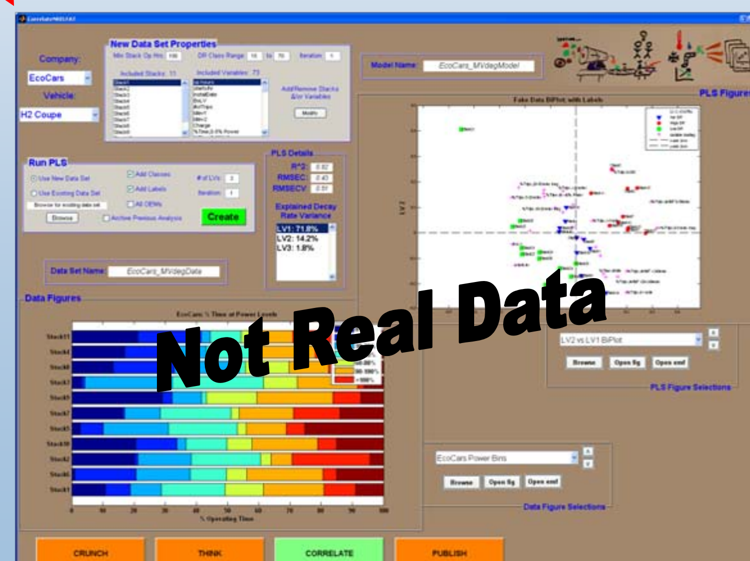
CDP = Composite Data Products Published

Accomplishment: Generated All Results Using NREL-Developed GUI – Fleet Analysis Toolkit (FAT)



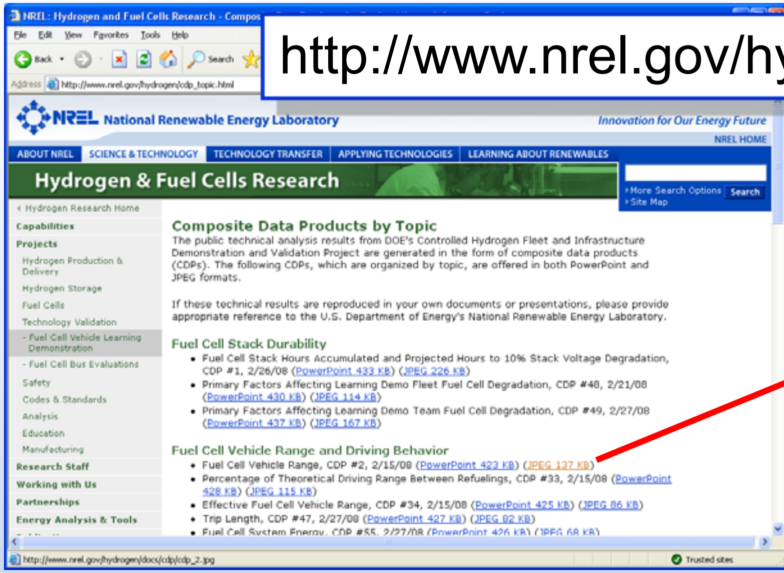




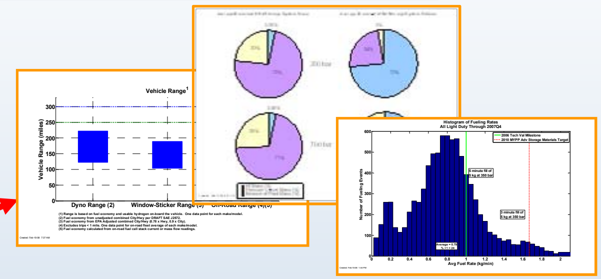


Accomplishment: In the Last Year Published Fall 2007 and Spring 2008 CDP Results through Conferences, Progress Reports, and Journals

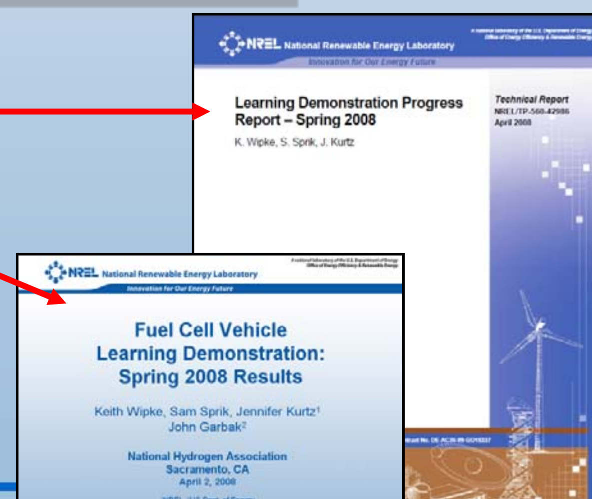
Accomplishment: NREL Web Site Provides Direct Access to All Composite Data Products (47), Reports, and Presentations



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

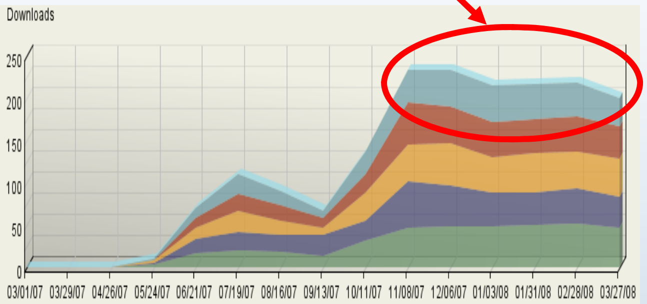


http://www.nrel.gov/hydrogen/proj_learning_demo.html



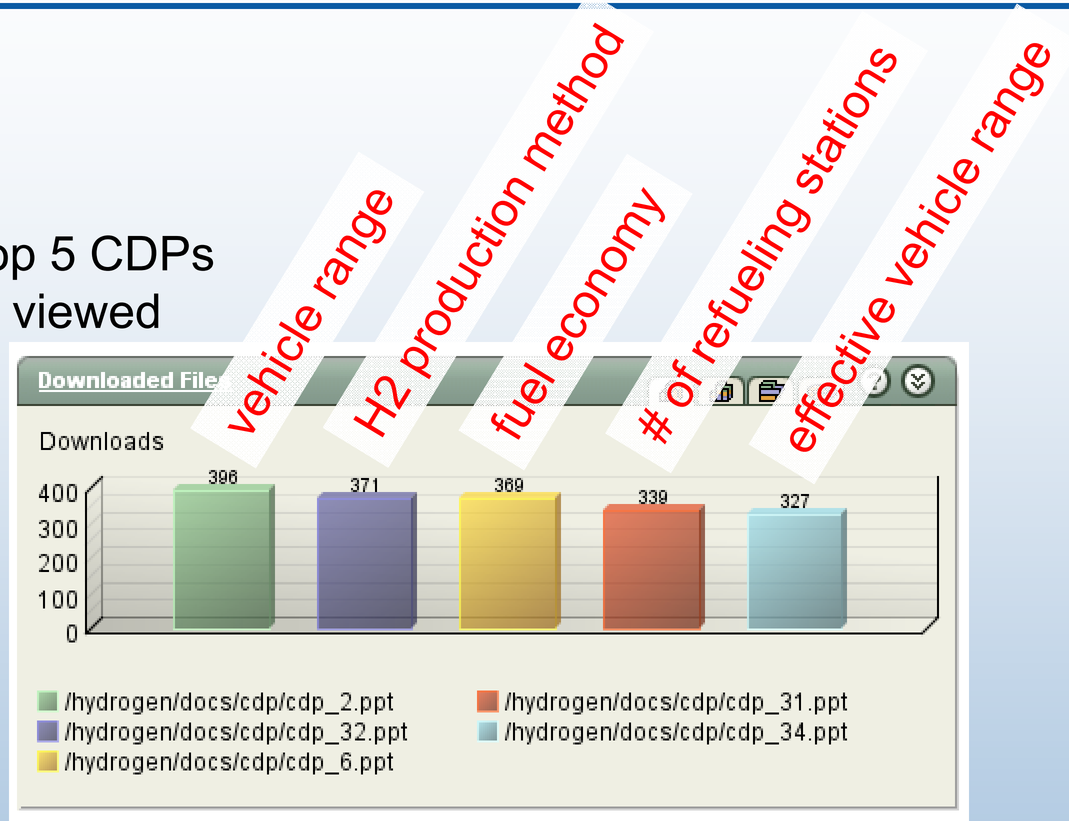
Accomplishment: Restructured CDP Web Site Files to Allow Tracking of Most Frequently Accessed Technical Results

Sustained activity in last 5-6 months



3/1/07 4/1/08

Top 5 CDPs viewed



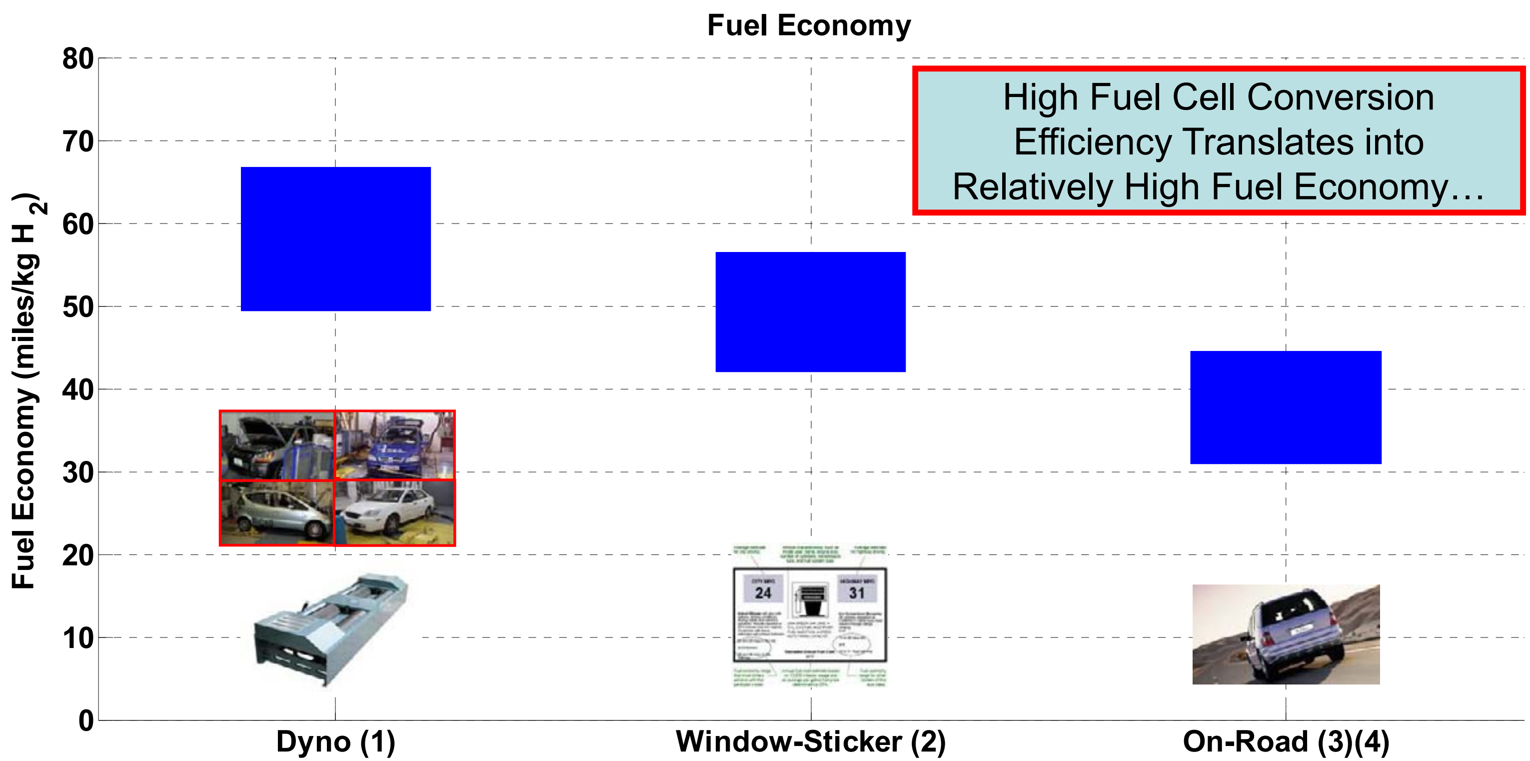
Summer 2007 Progress Report Downloaded 2,138 times; 6th most popular download from NREL's H2 website

Visitor Summary	
Visitors	703
Visitors Who Visited Once	605
Visitors Who Visited More Than Once	98
Average Visits per Visitor	1.62

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

Visit Summary	
Visits	1,136
Average per Day	2
Average Visit Duration	-
Median Visit Duration	-
International Visits	12.06%
Visits of Unknown Origin	51.94%
Visits from Your Country: United States (US)	36.00%

Dynamometer and On-Road Fuel Economy from Gen 1 Learning Demonstration Vehicles



(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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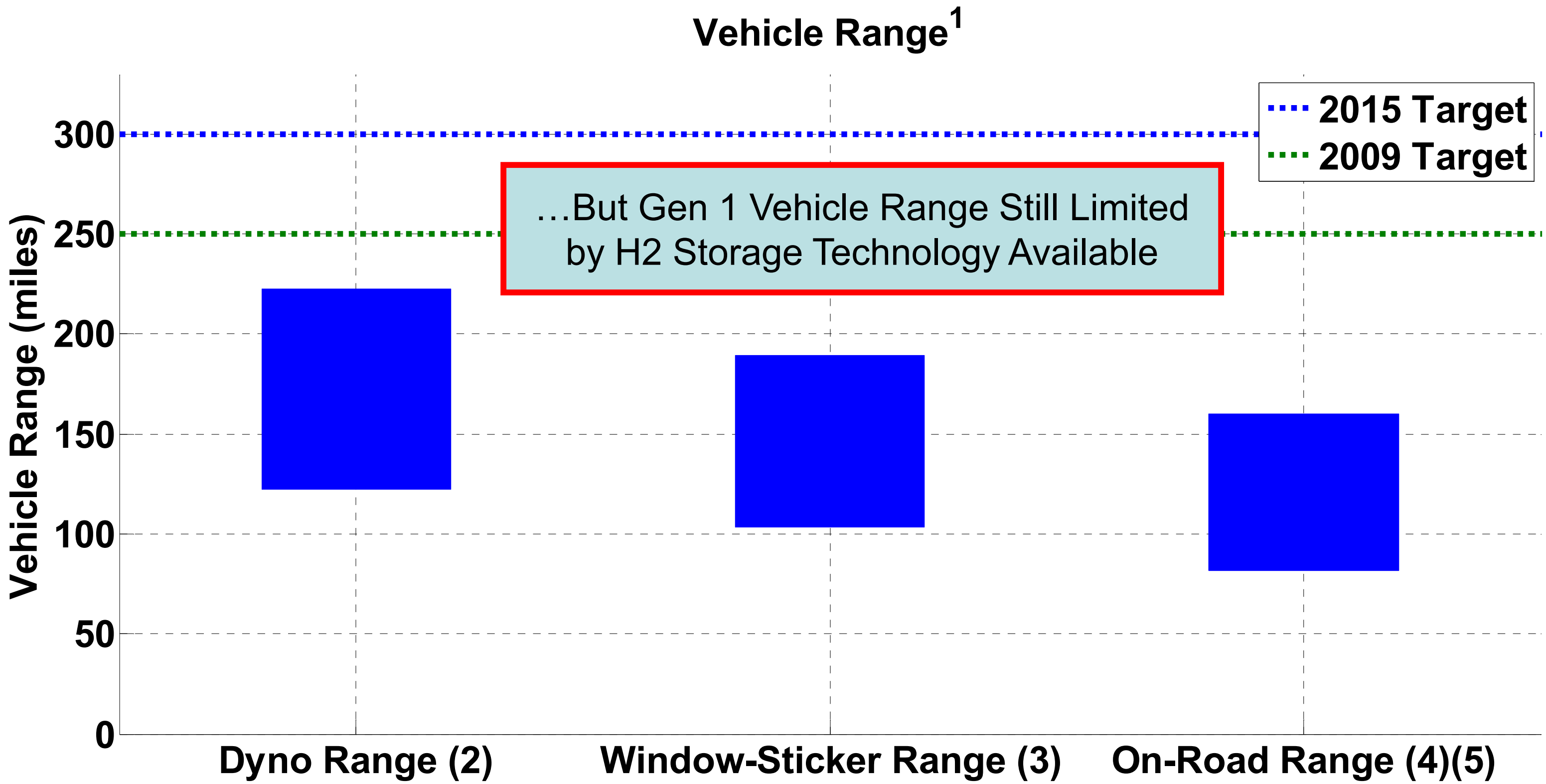
Gen 1 Vehicle Range Based on Dyno Results and Usable H_2 Fuel Stored On-Board



(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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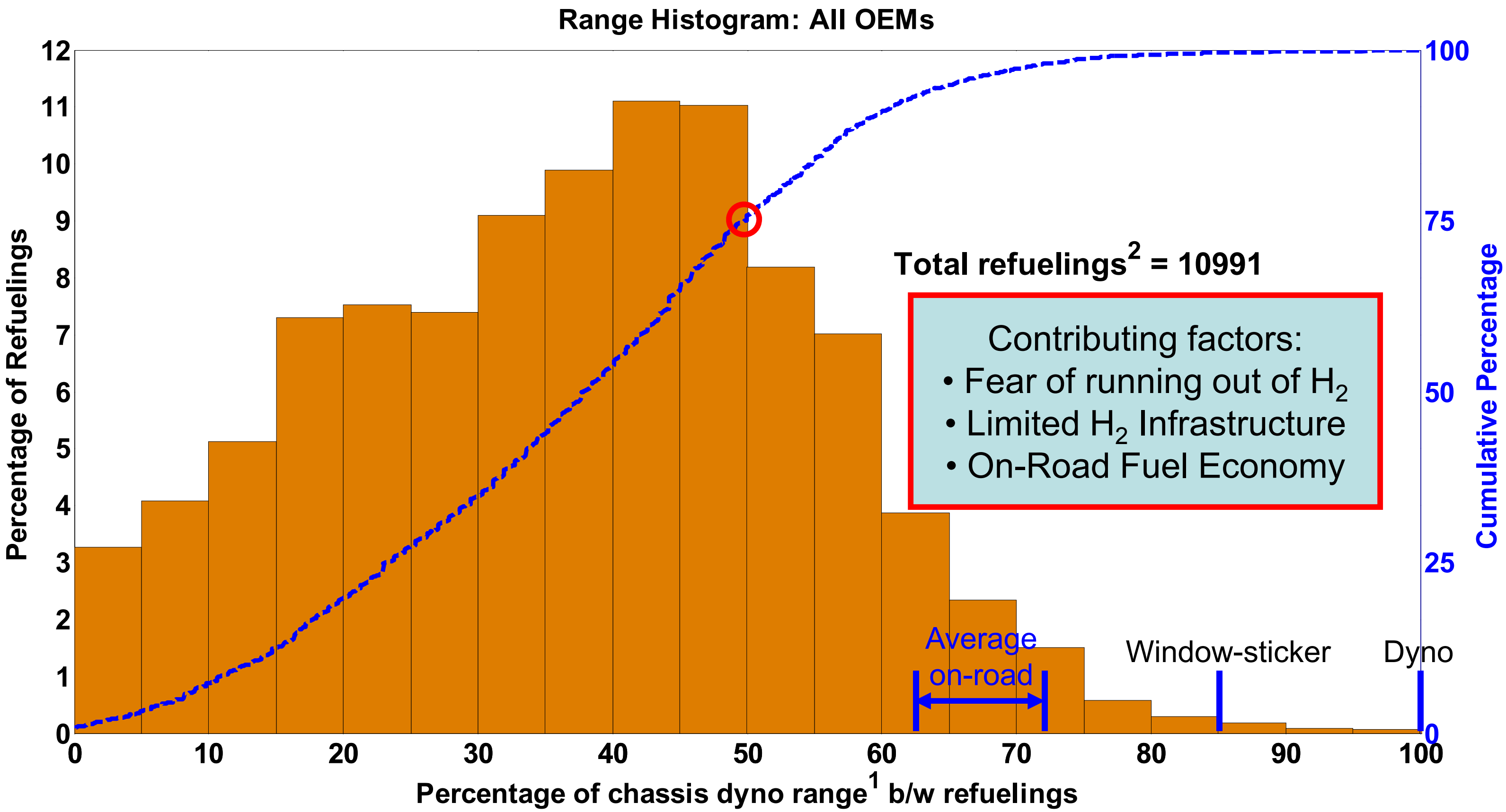
Majority (75%) of Vehicles Travel <50% of Dyno Range Between Refuelings



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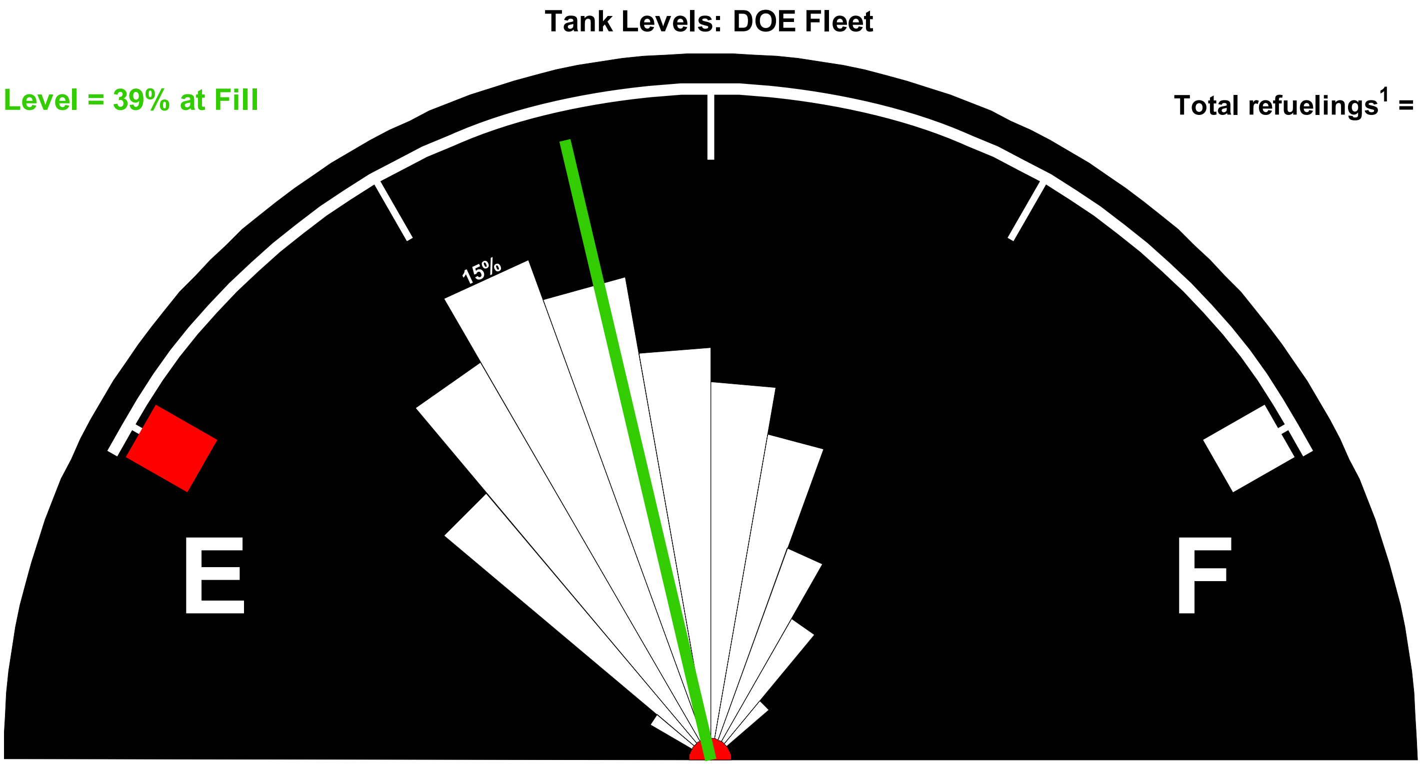
Large Spread in H2 Tank Level at Refueling Peak at ~1/4 Full, Median at ~3/8 Full



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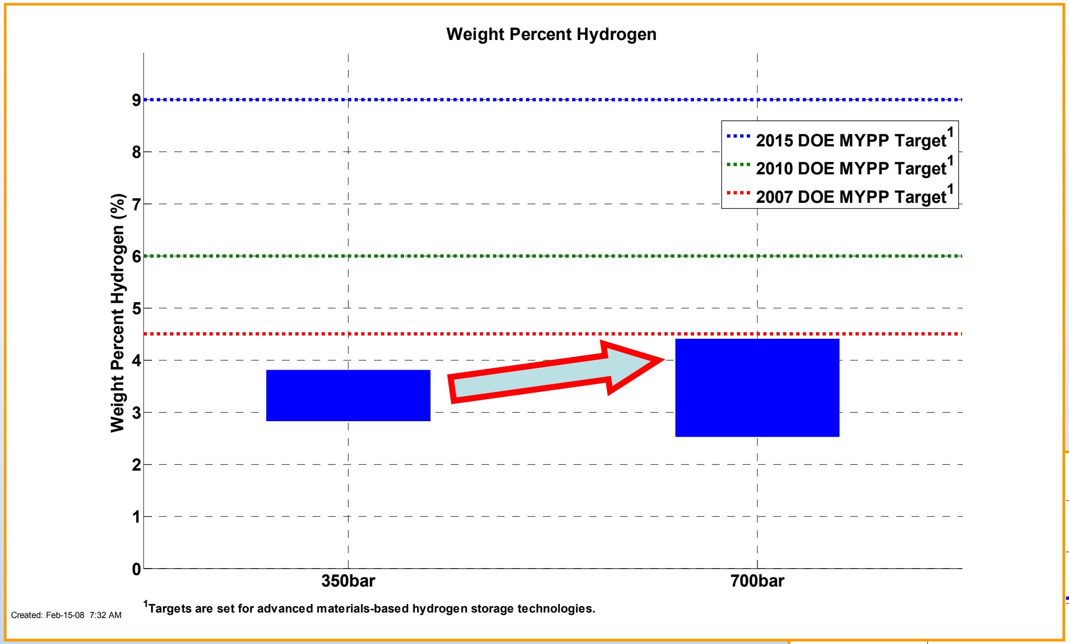
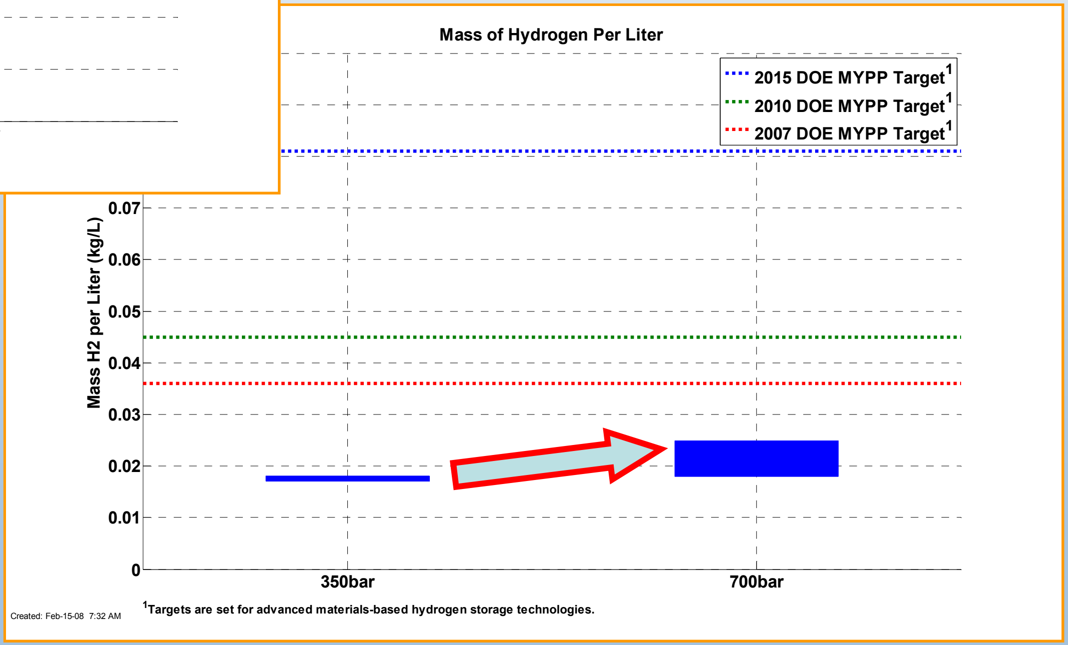
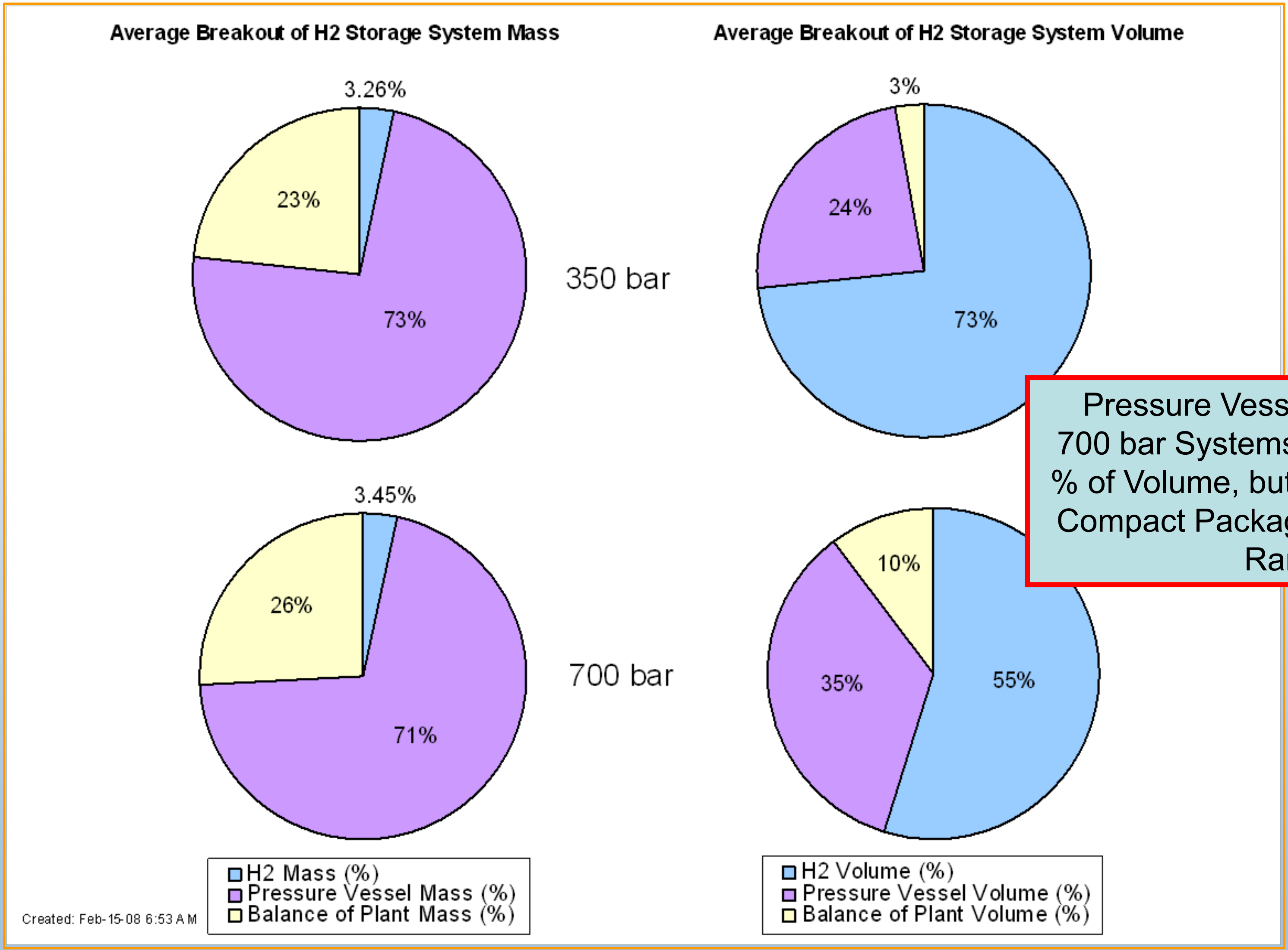
700 bar On-Board H2 Storage Systems Demonstrate Potential for Improved Performance Over 350 bar





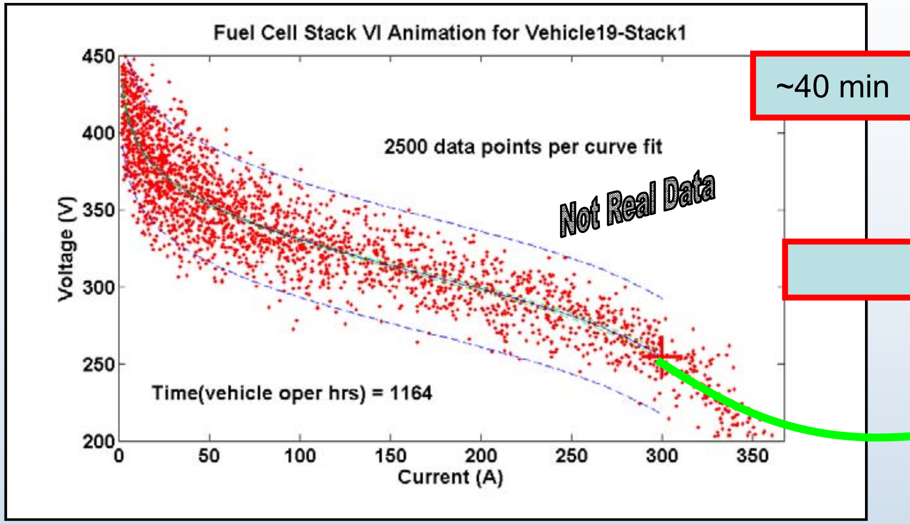
2nd Gen Vehicle Storage Data Collected;
Allows a Comparison of 350 bar vs. 700 bar

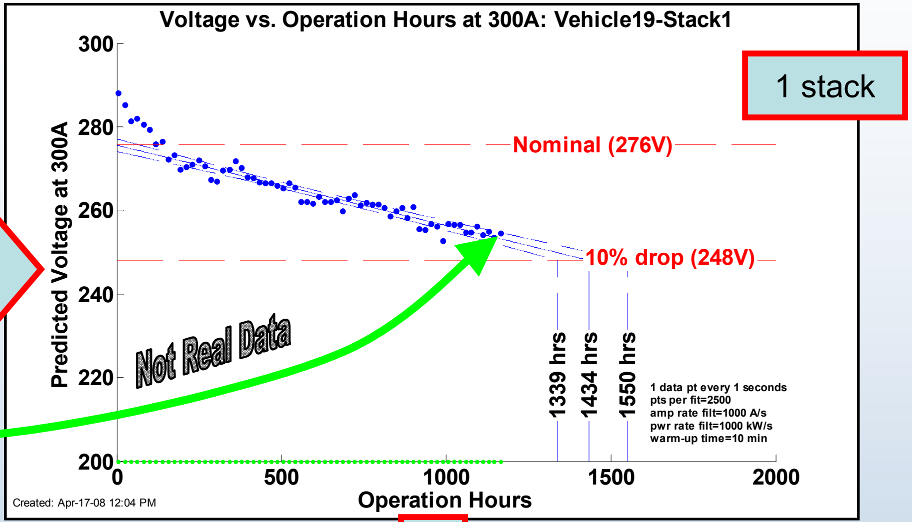
More Detailed Data Reporting Allows a Comparison of Mass and Volume of H2, Pressure Vessel, and BOP

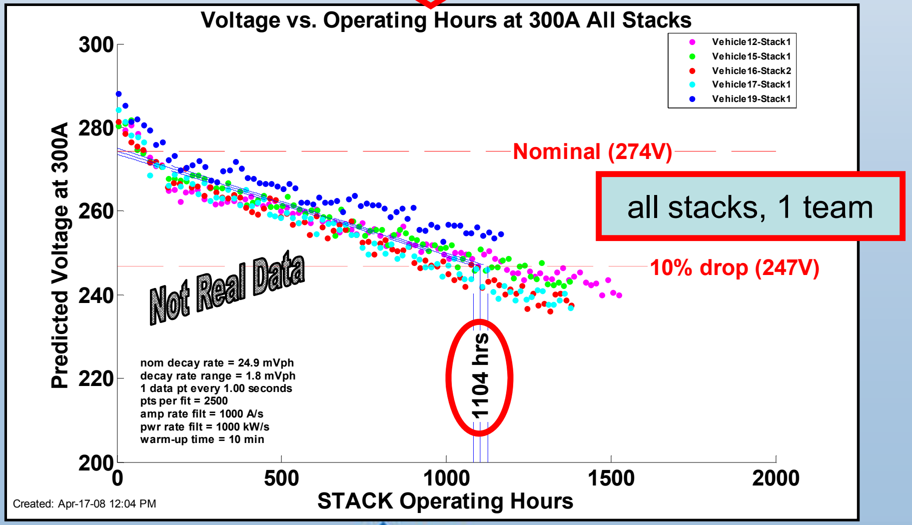


Pressure Vessel and BOP for 700 bar Systems Take Up Larger % of Volume, but Allow for a More Compact Package and Extended Range

Approach: Method for Projecting Time to 10% Fuel Cell Stack Voltage Degradation (Linear Decay Fit, Calculated Voltage at t_0)



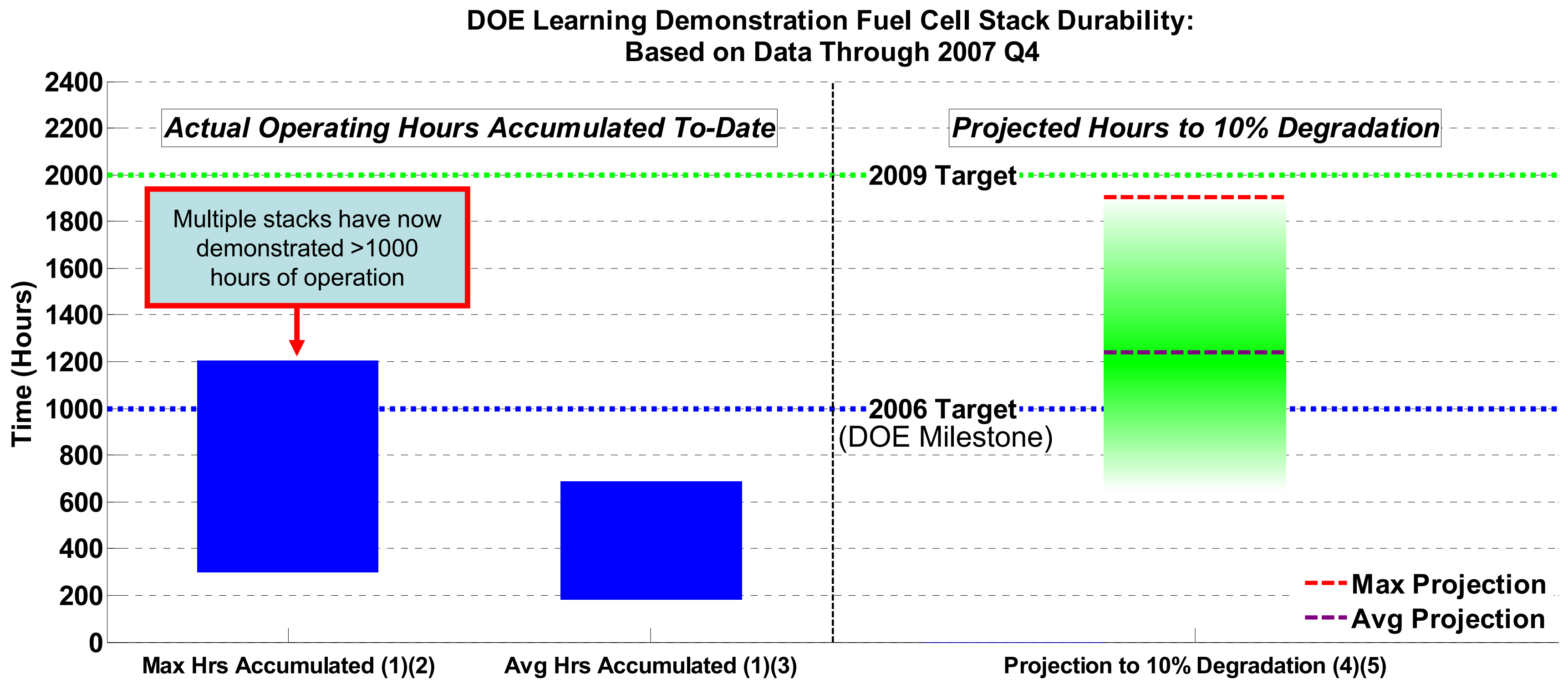




Note: 10% is an R&D metric for FC stack degradation. It does not necessarily indicate an end-of-life condition. OEMs may use other values or indicators.

Fixed t_0 voltages and non-linear decay fits will be investigated for Fall 2008 analysis of stacks with significant number of accumulated hours

As More Gen 1 Data Is Accumulated, Some Teams Are Demonstrating Long FC Durability



(1) Range bars created using one data point for each OEM.
(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 due to data and methodology limitations. Projections will change as additional data are accumulated.

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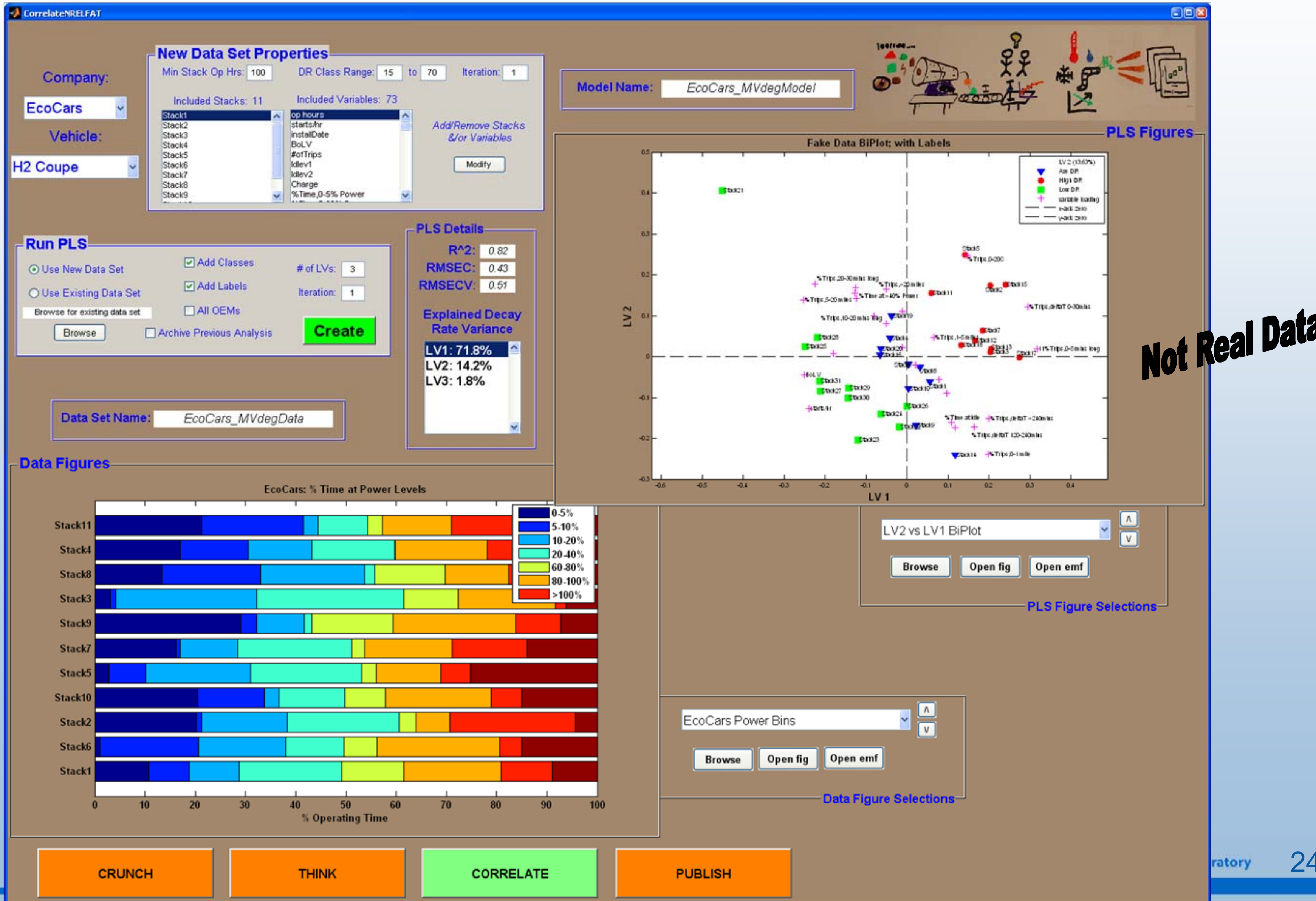
Approach: Use Multivariate Analysis to Determine Dominant Factors Affecting FC Degradation



Primary Factors Affecting Learning Demo Fleet Fuel Cell Degradation: FC Diversity (Between Teams) Limits Drawing Strong Conclusions

H*

Low Voltage Time
High Voltage Time
Cold Starts
Short Trips
0 Speed Trips
Hot Ambient Temp

DOE Fleet

High Current Time
Hot Starts
Starts/hour

H*

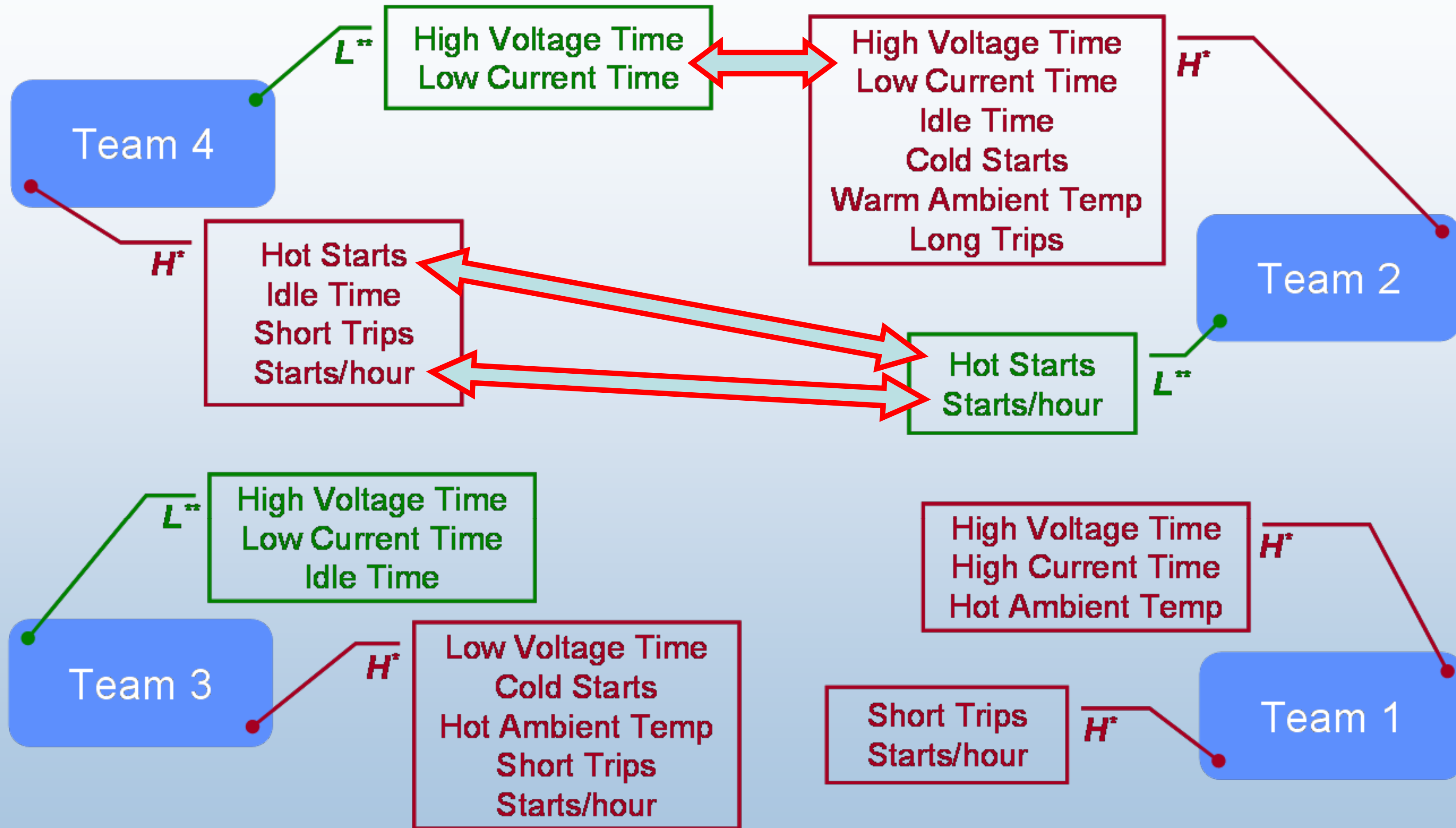
Due to differences among teams, the DOE Fleet Analysis results are spread out and concrete conclusions are difficult to draw.

Individual team analyses (CDP#49) focused on patterns within a fleet.

1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for combined Learning Demonstration Fleet.
2) DOE Fleet model has a low percentage of explained decay rate variance.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks

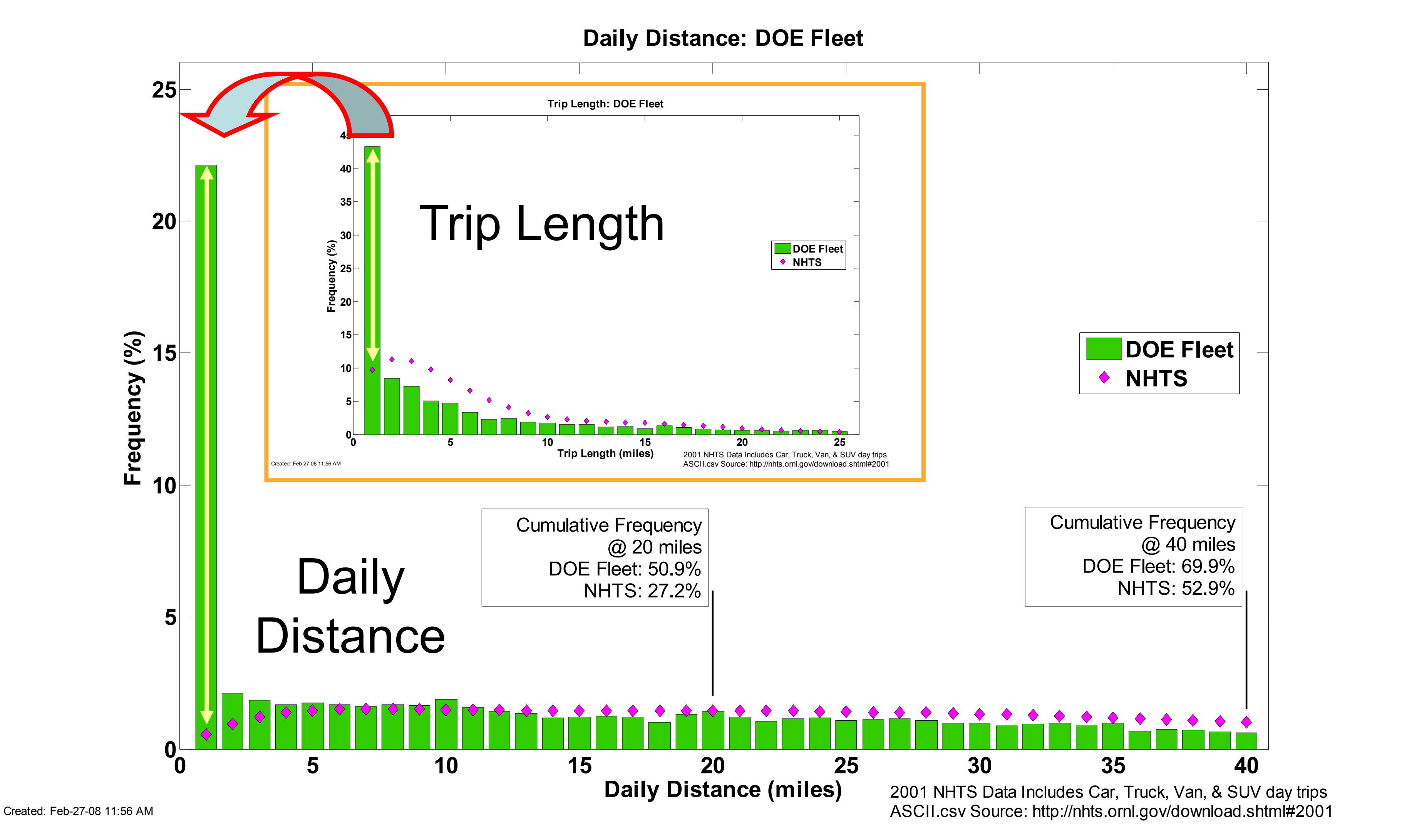
Primary Factors Affecting Fuel Cell Degradation are Hard to Extract, and Different (sometimes opposite) for Each Team



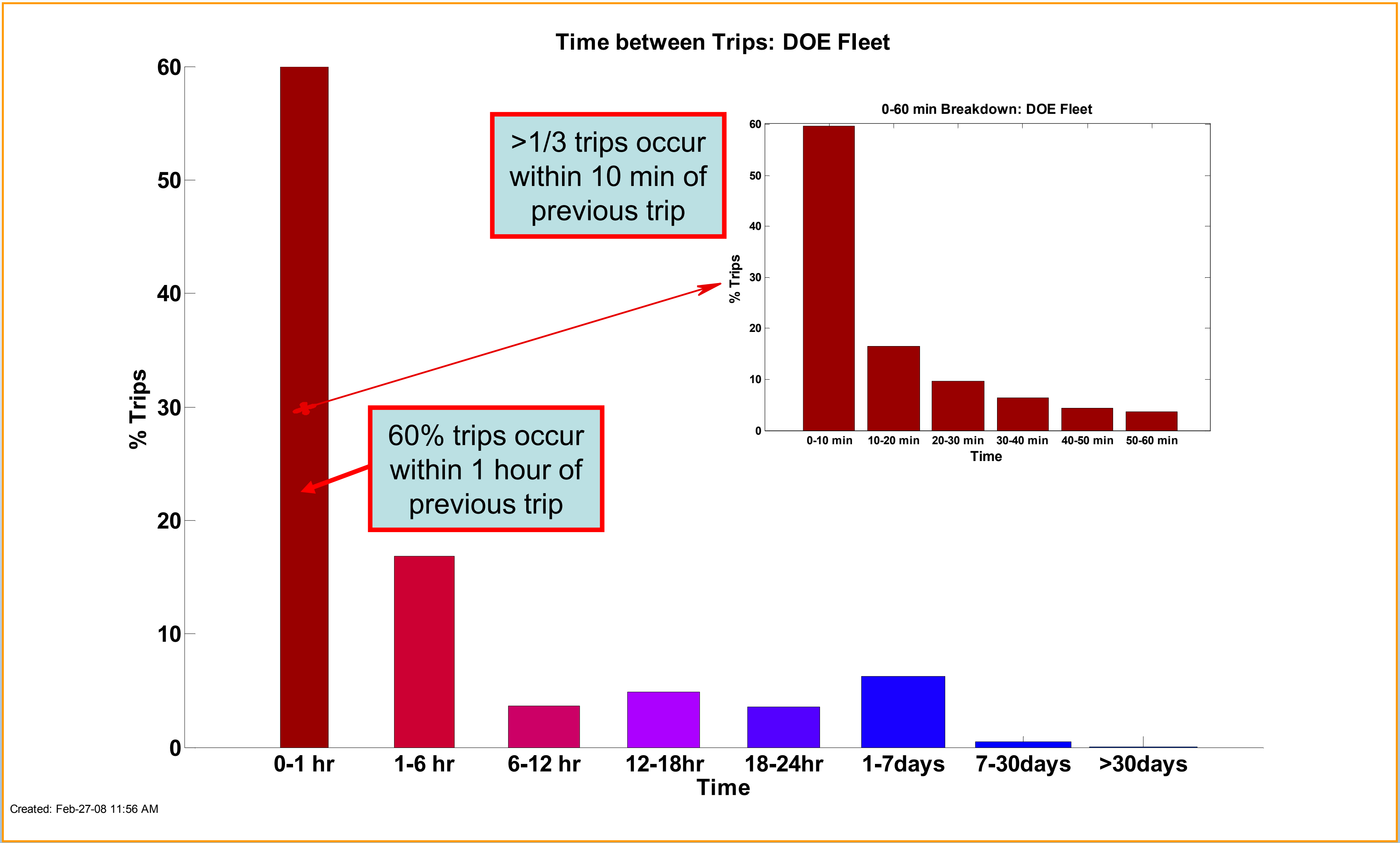
1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team.
2) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.

H*: Factor group associated with high decay rate fuel cell stacks
L**: Factor group associated with low decay rate fuel cell stacks

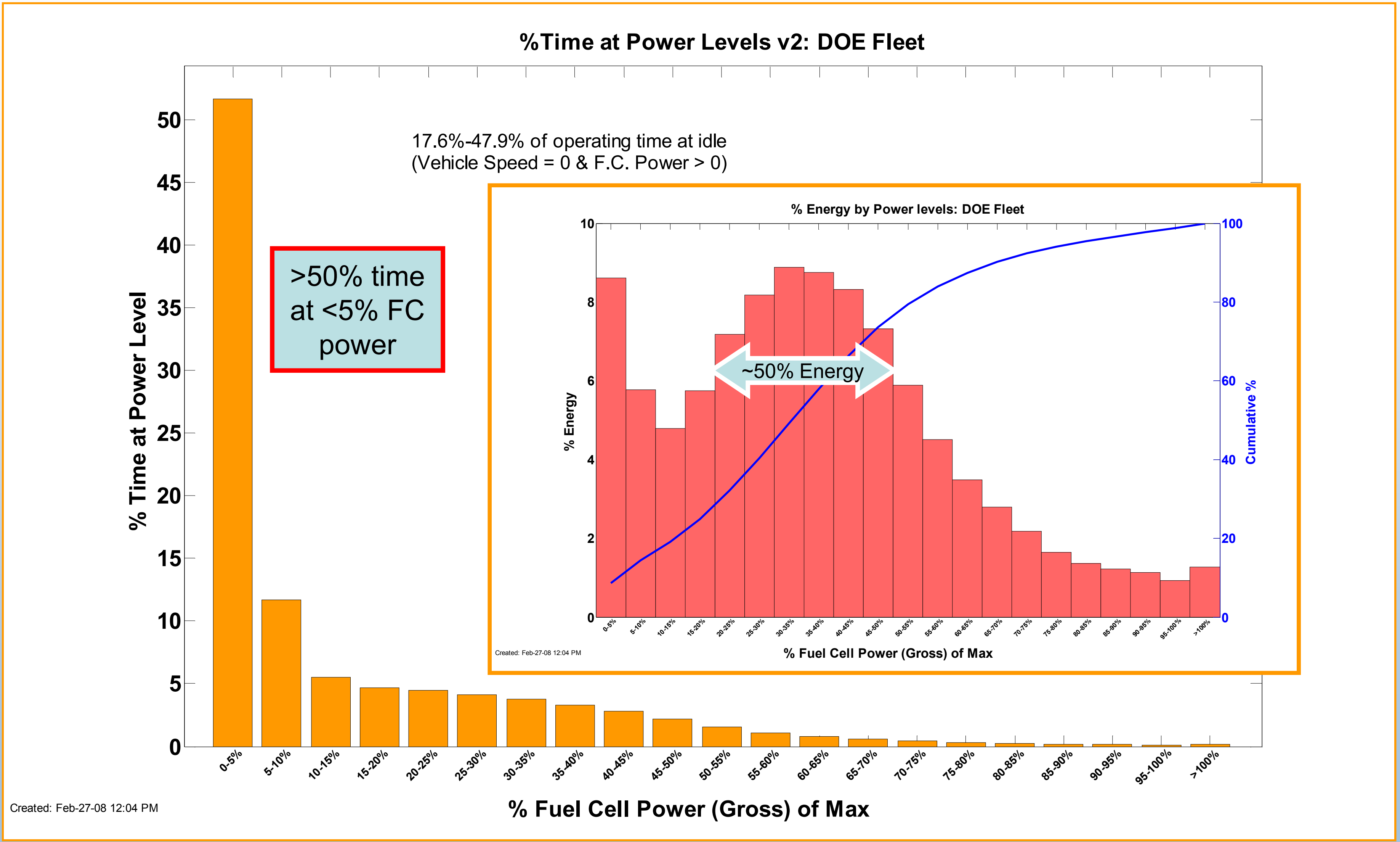
Large Number of Short Trips Contribute to a Lower Daily Distance than National Average



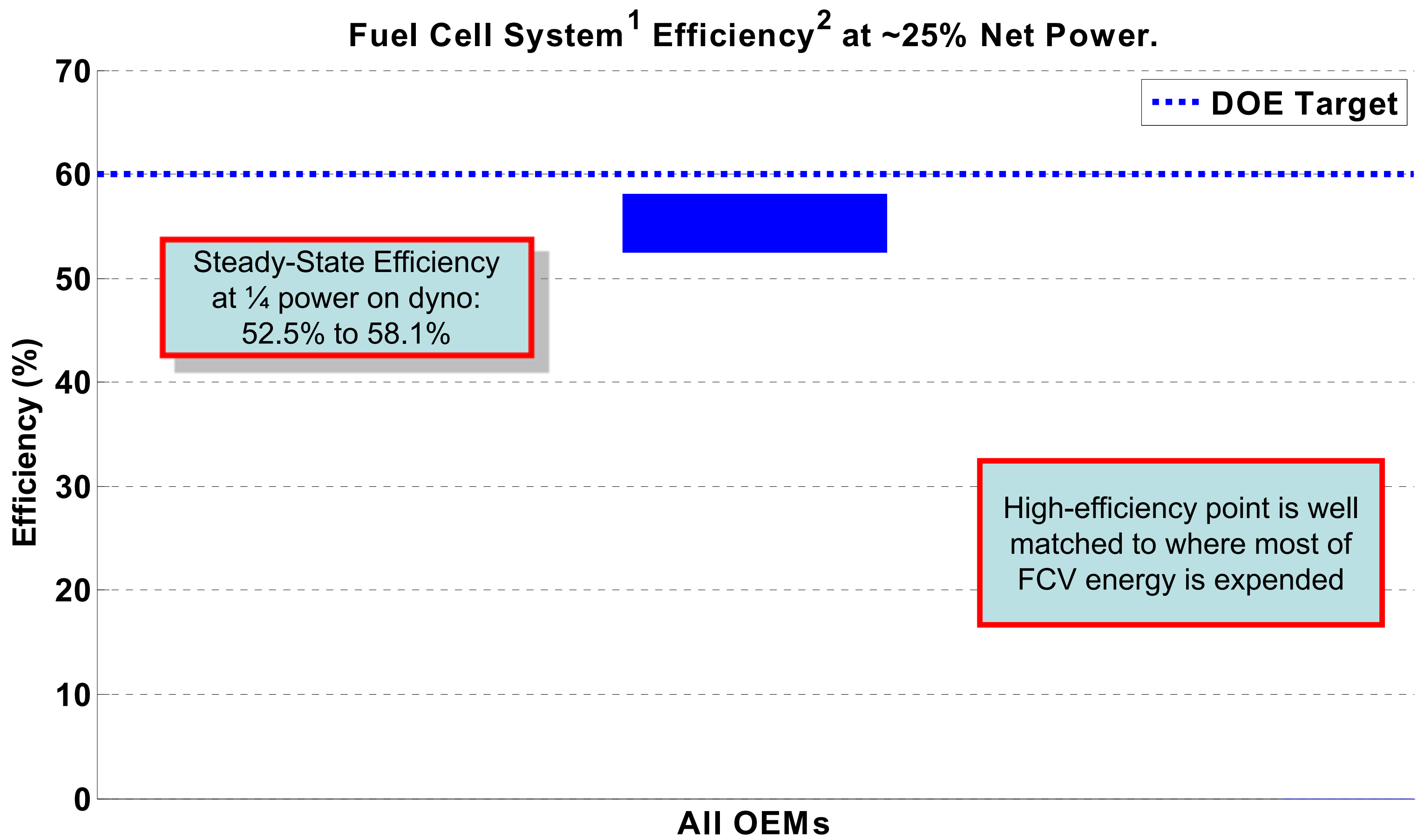
Examining Time Between Trips Shows Fuel Cells Experiencing Large # Hot Starts



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



Gen 1 Baseline Dyno Tests Validated High Efficiency at ¼ Power Point – Gen 2 Tests to Occur in 2008



[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.

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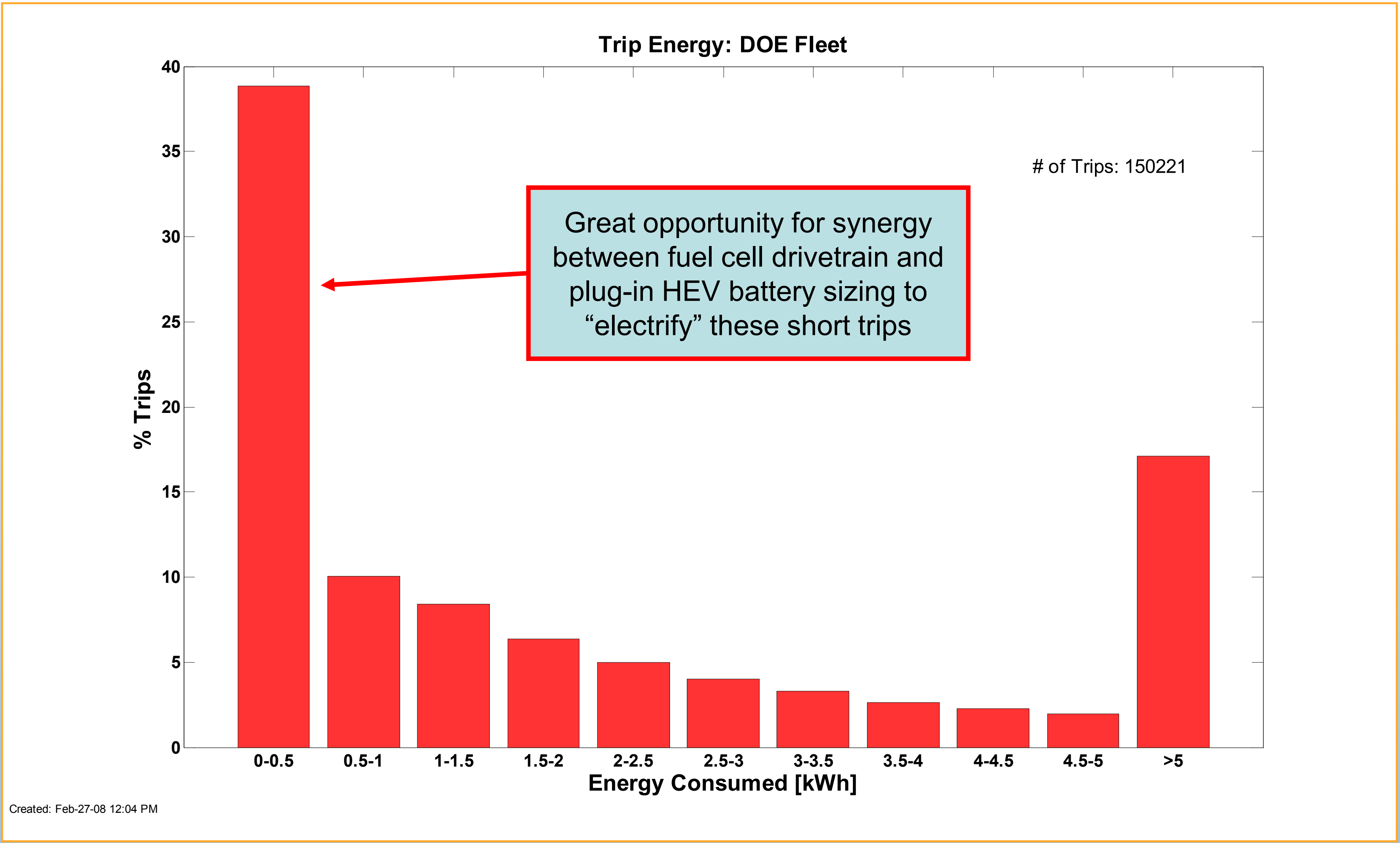
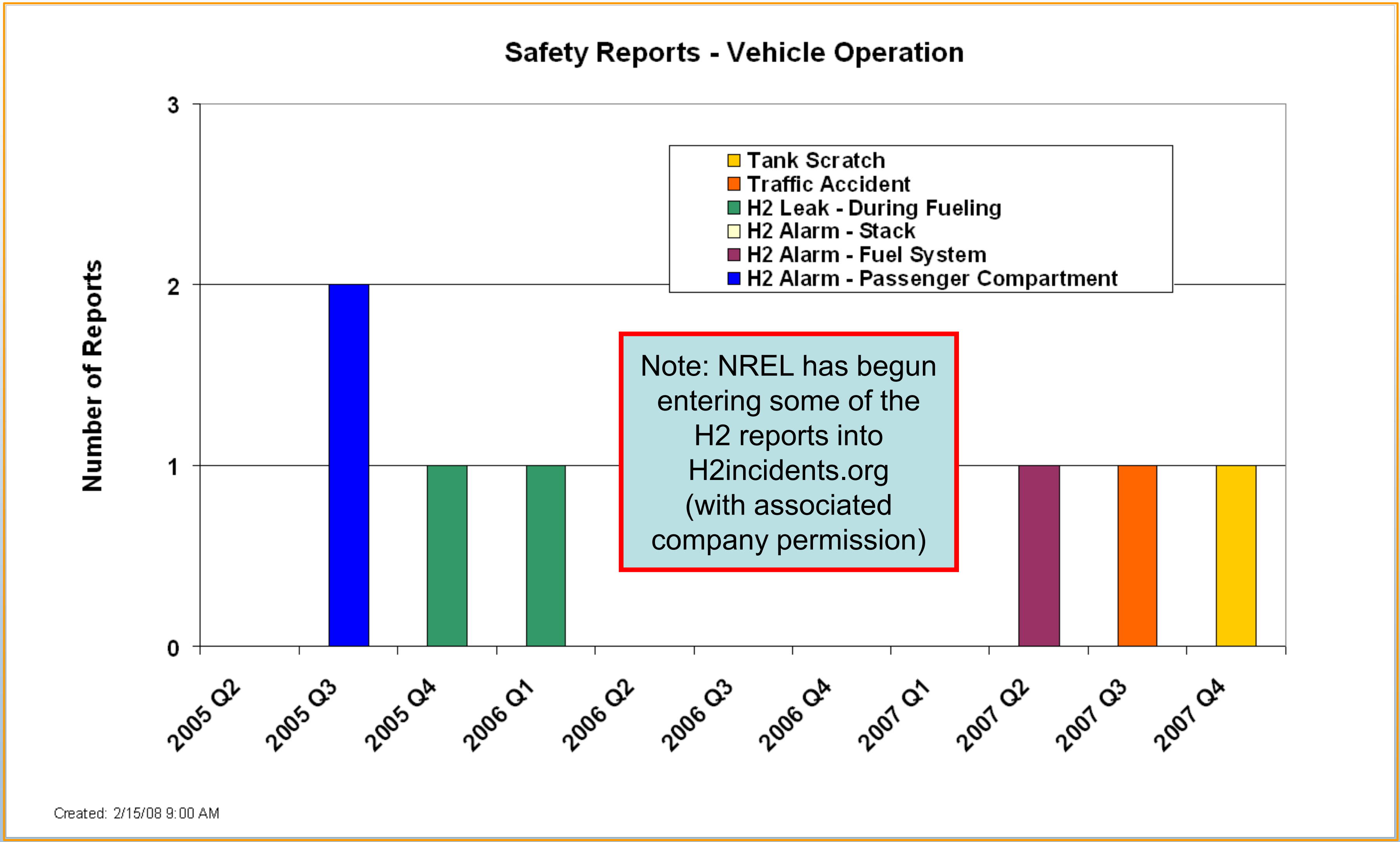
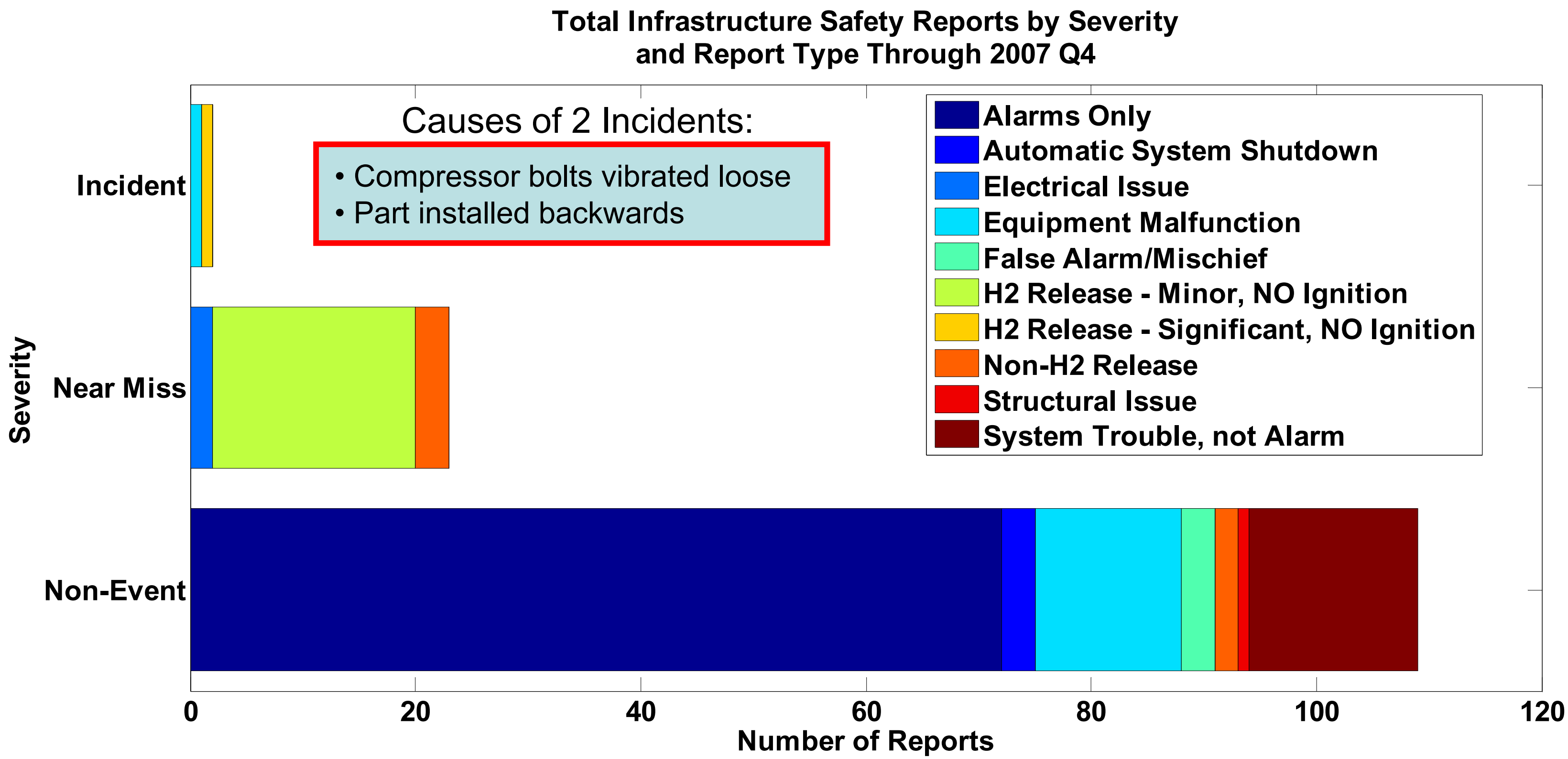
~40% of Learning Demo Trips Require <0.5 kWh of Fuel Cell Output Energy



Minimal Vehicle Safety Reports Continue to Demonstrate a Strong Safety Record



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



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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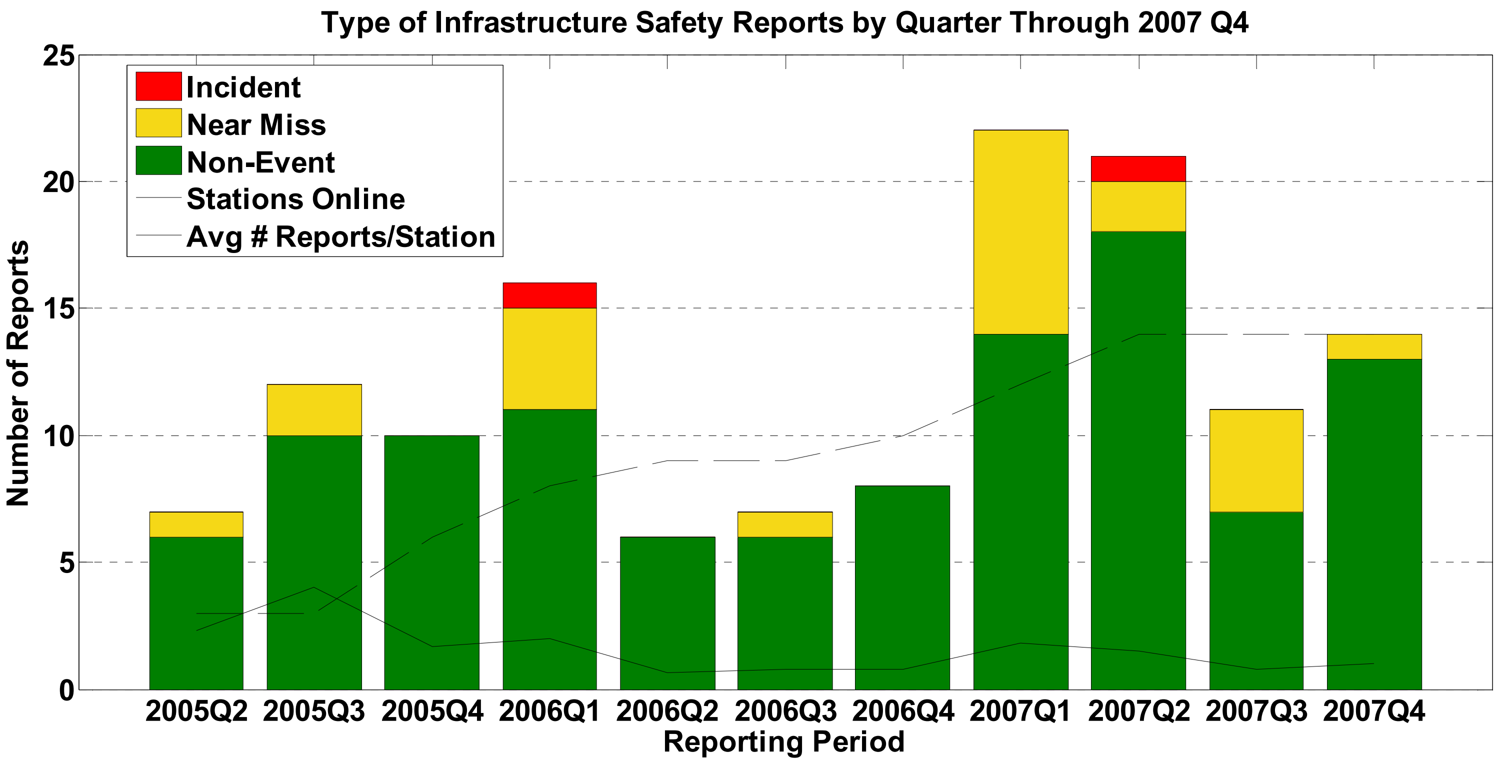
Overall Infrastructure Safety Reports Correlated with Increase in New Stations Coming Online



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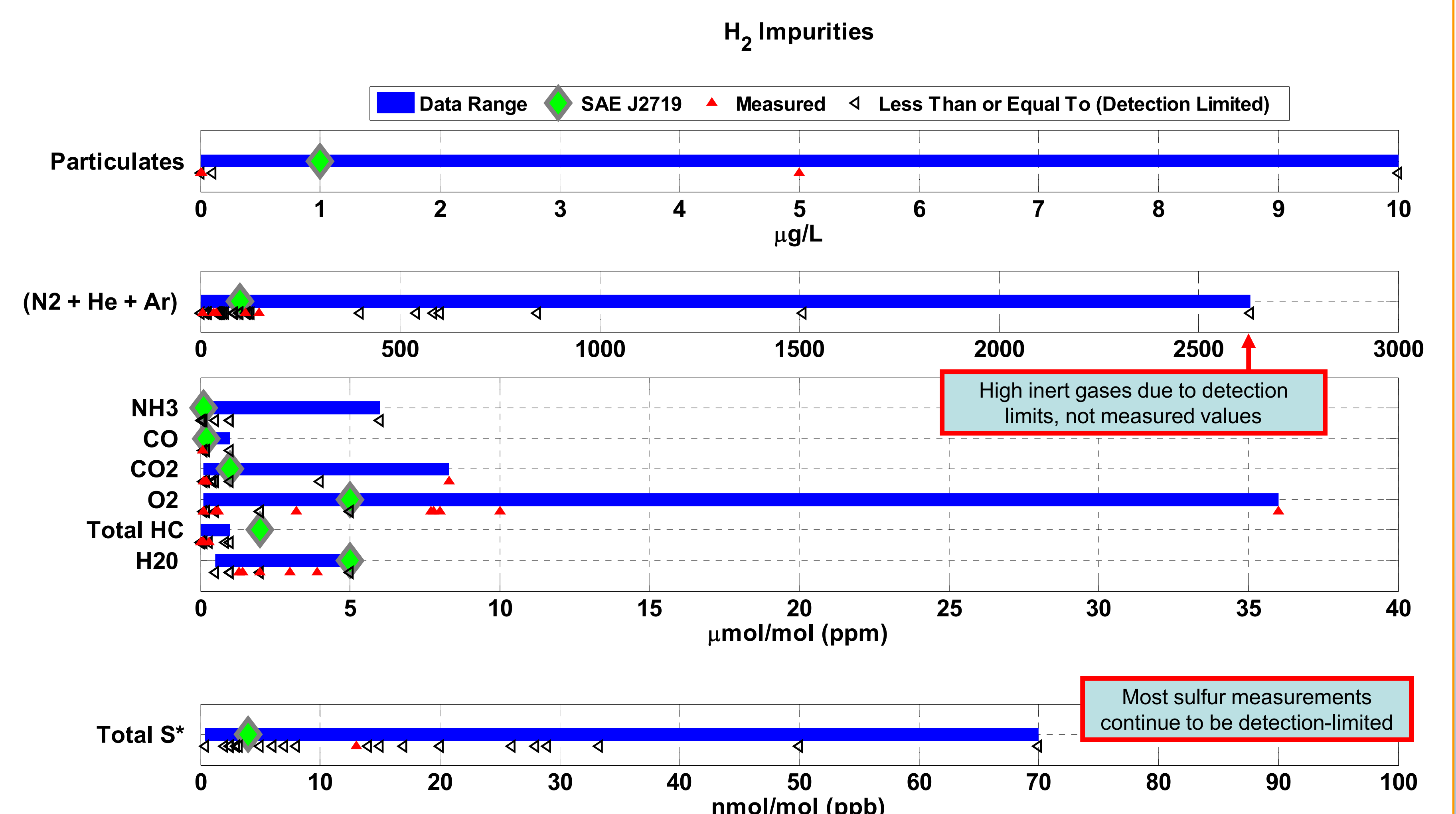
Hydrogen Impurities Sampled from All Stations to Date
In General, Inert Gases and Sulfur Have Had High Detection Limits



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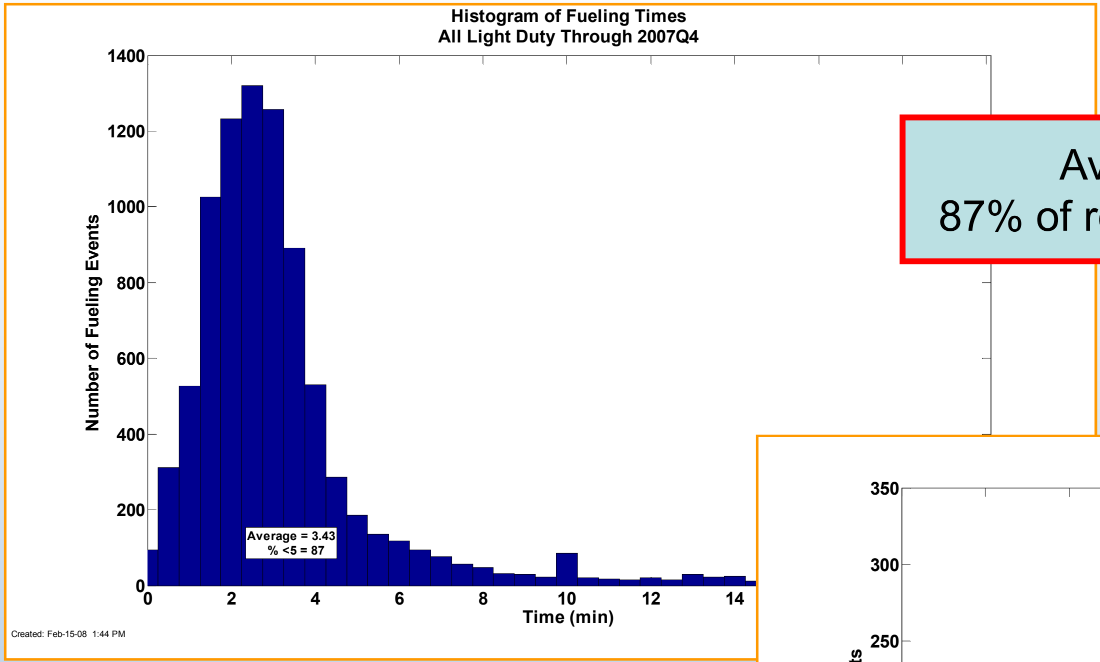
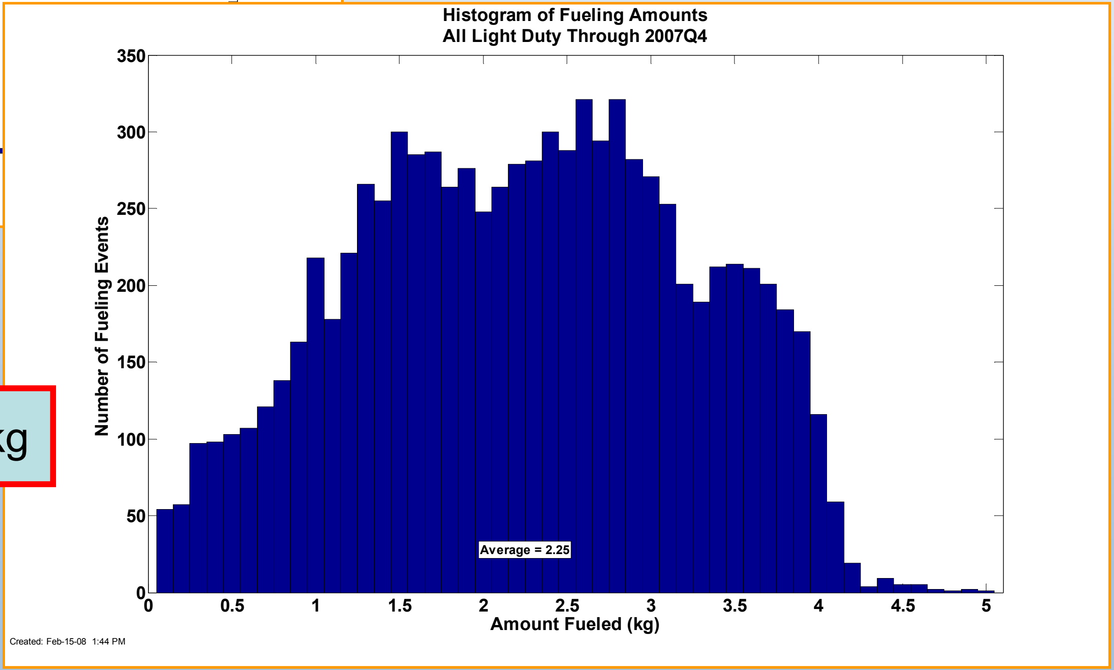
*Calculated from SO2, COS, H2S, CS2, and Methyl Mercaptan (CH3SH).

New Fall 2008 CDPs will include impurities by production technology and time

Actual Vehicle Refueling Times and Amounts from 8,700 Events: Measured by Stations or by Vehicles



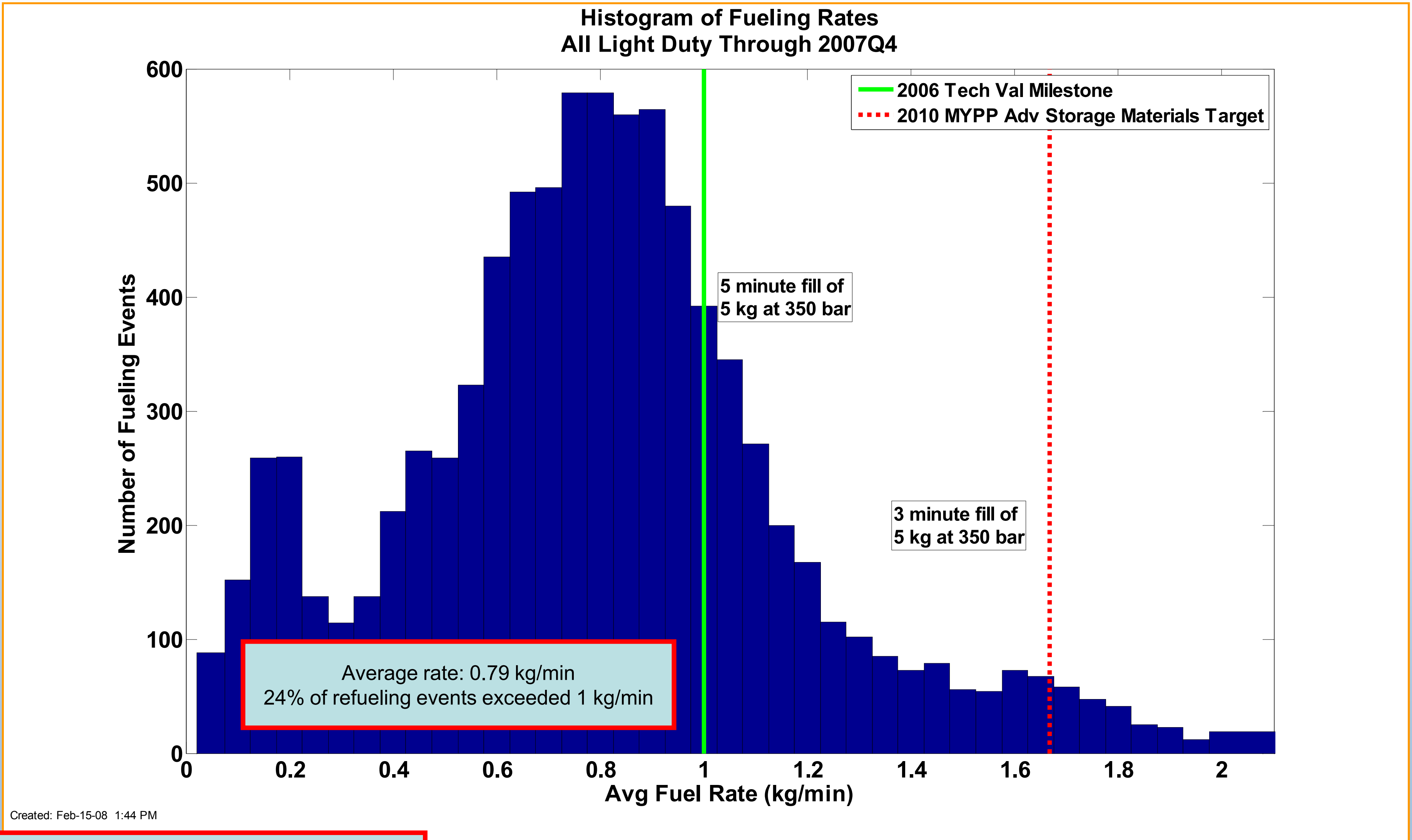
Average time: 3.43 min
87% of refueling events took <5 min



Average fill amount: 2.25 kg

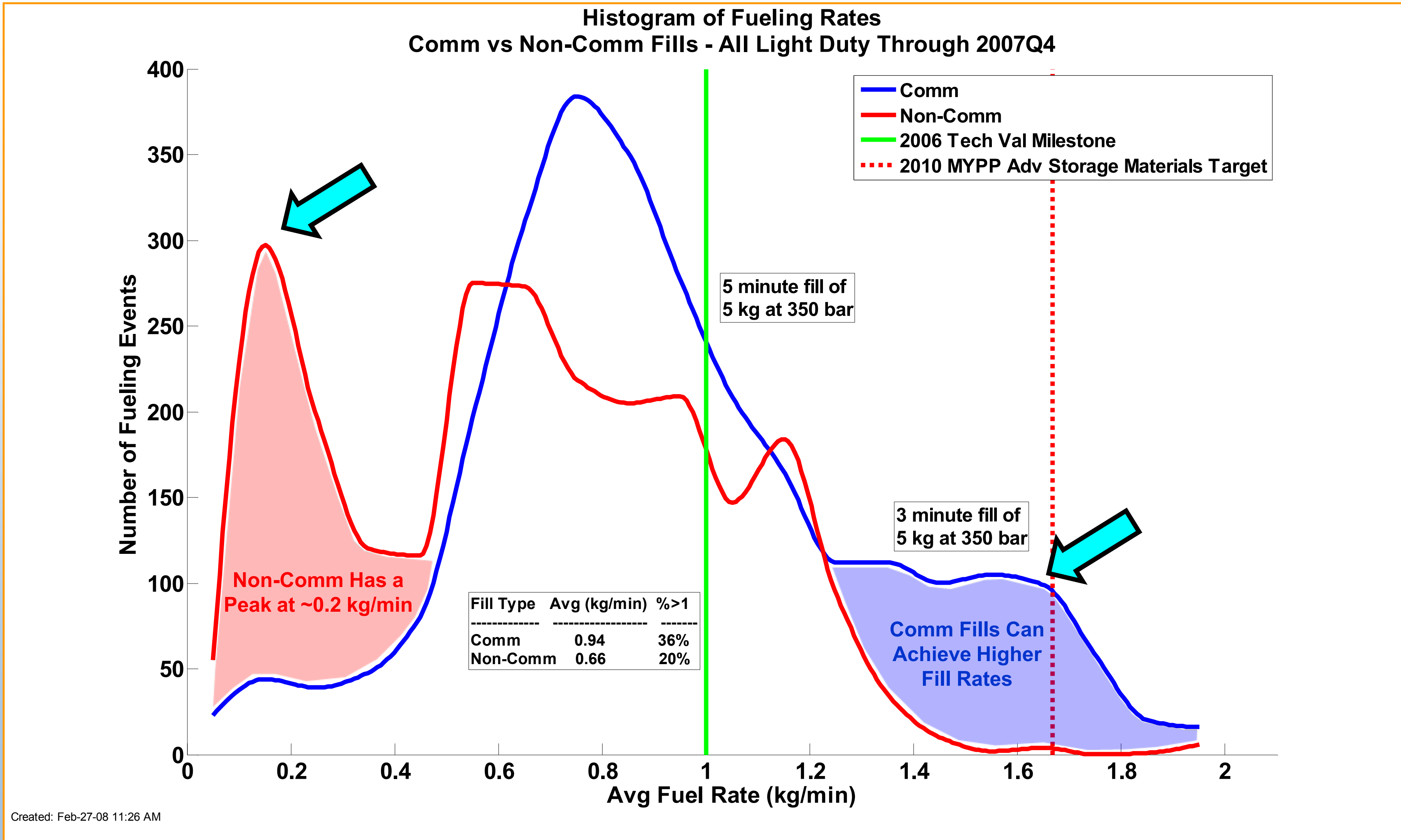
Includes Communication and Non-Communication Fills

Actual Vehicle Refueling Rates from >8,700 Events: Measured by Stations or by Vehicles

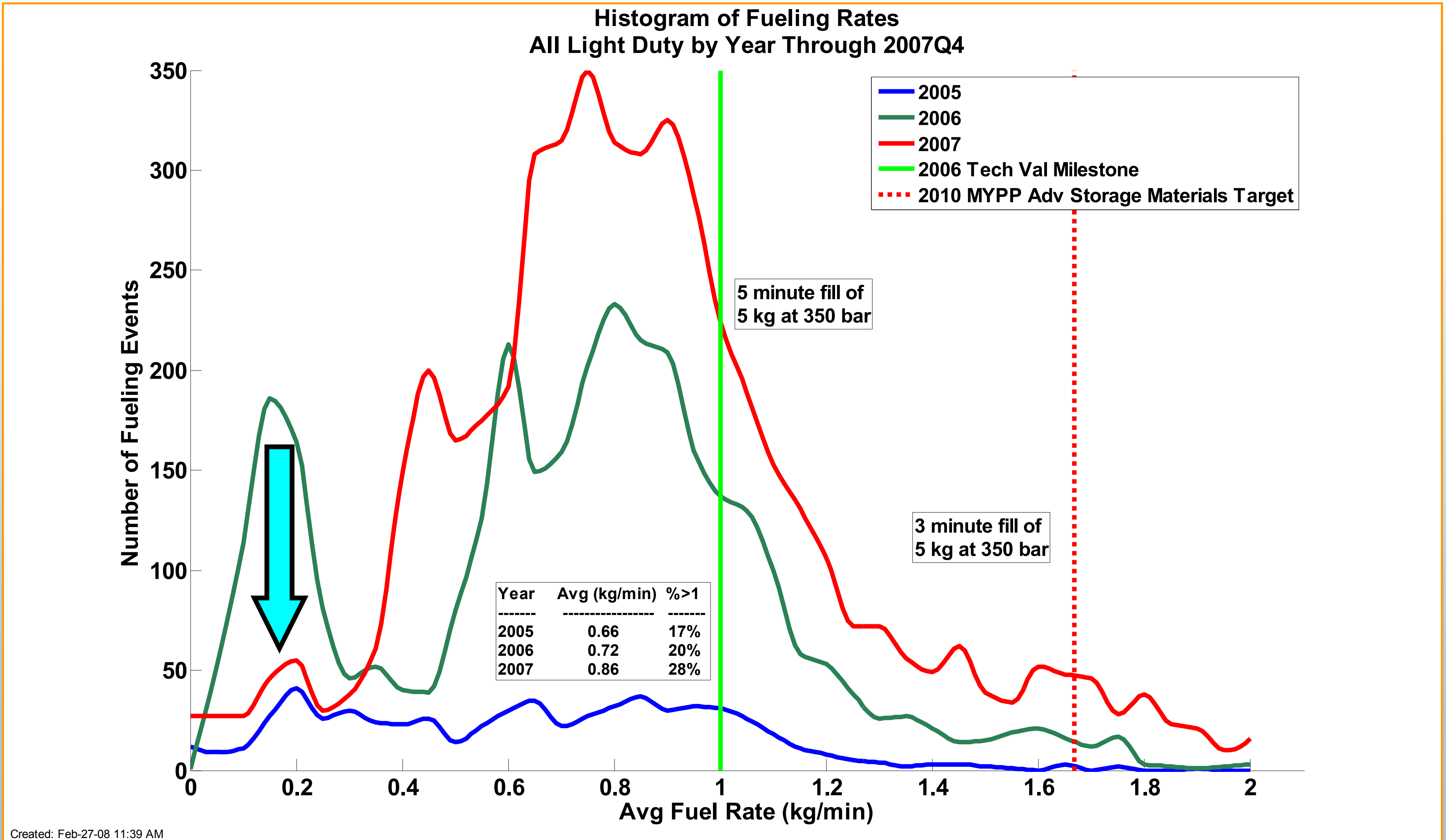


Includes Communication and Non-Communication Fills

Communication H2 Fills Achieving Higher Fill Rate than Non-Communication

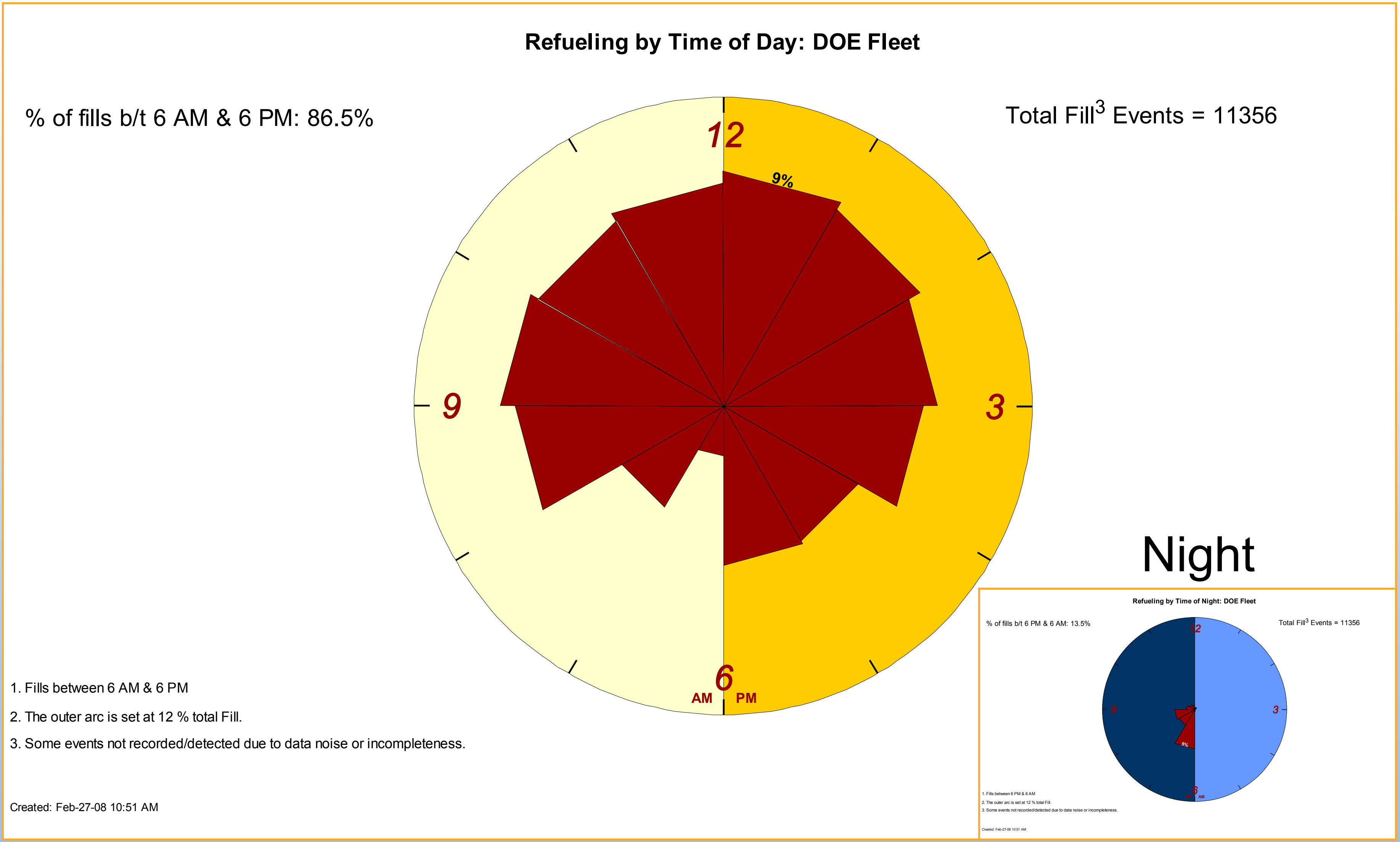


Examining Refueling Data by Year Shows 0.2 kg/min Rate Phased Out

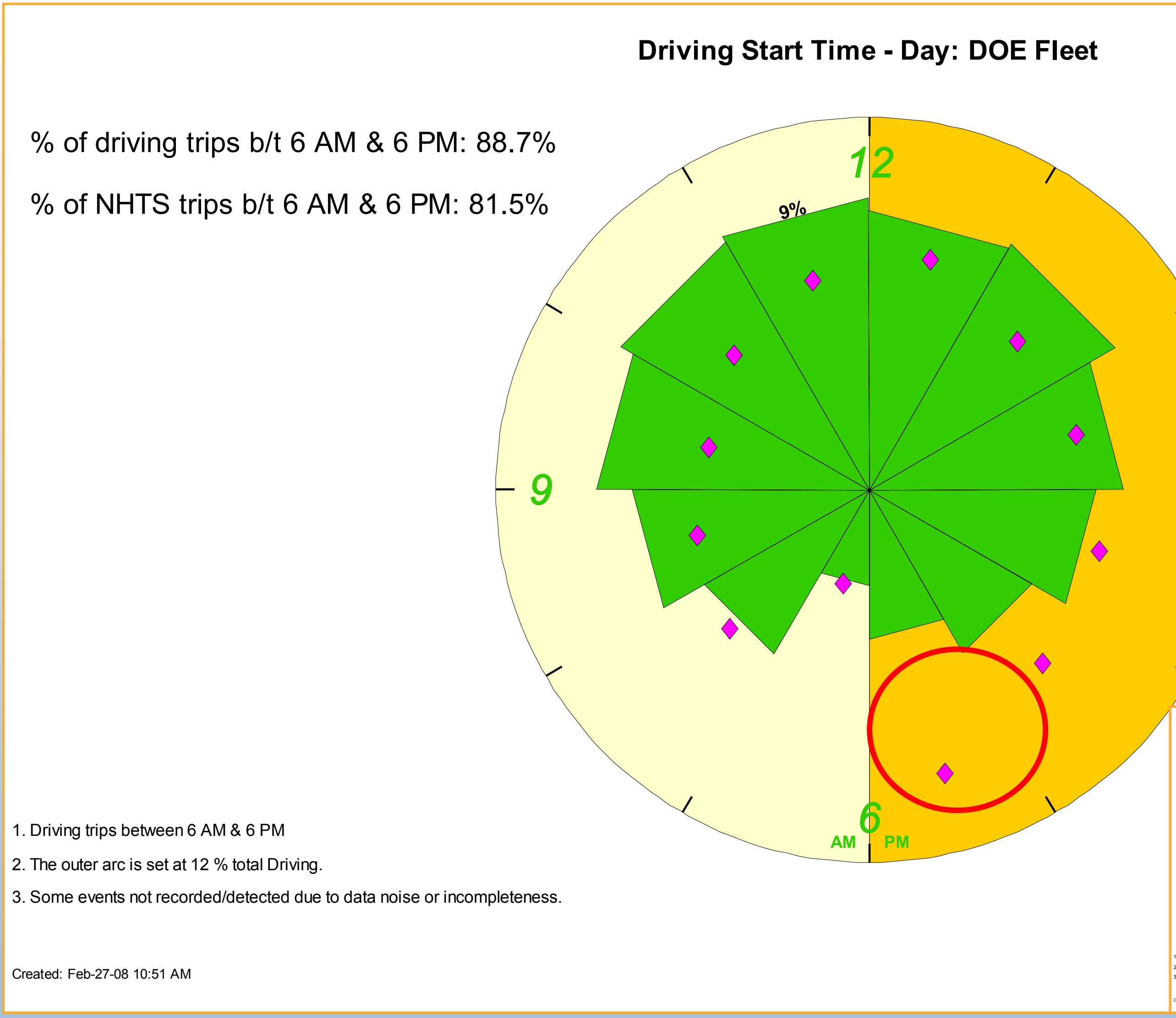


Includes Communication and Non-Communication Fills

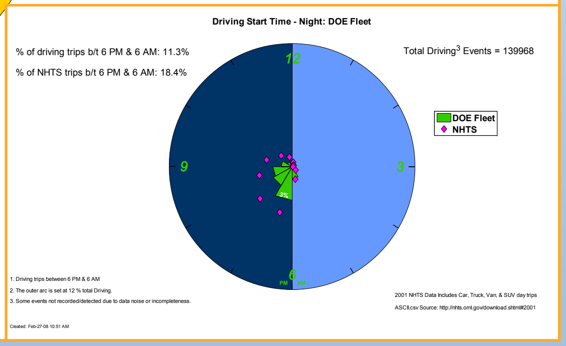
Refueling by Time of Day; Relatively Uniform Refueling Infrastructure Demand Between 8-4



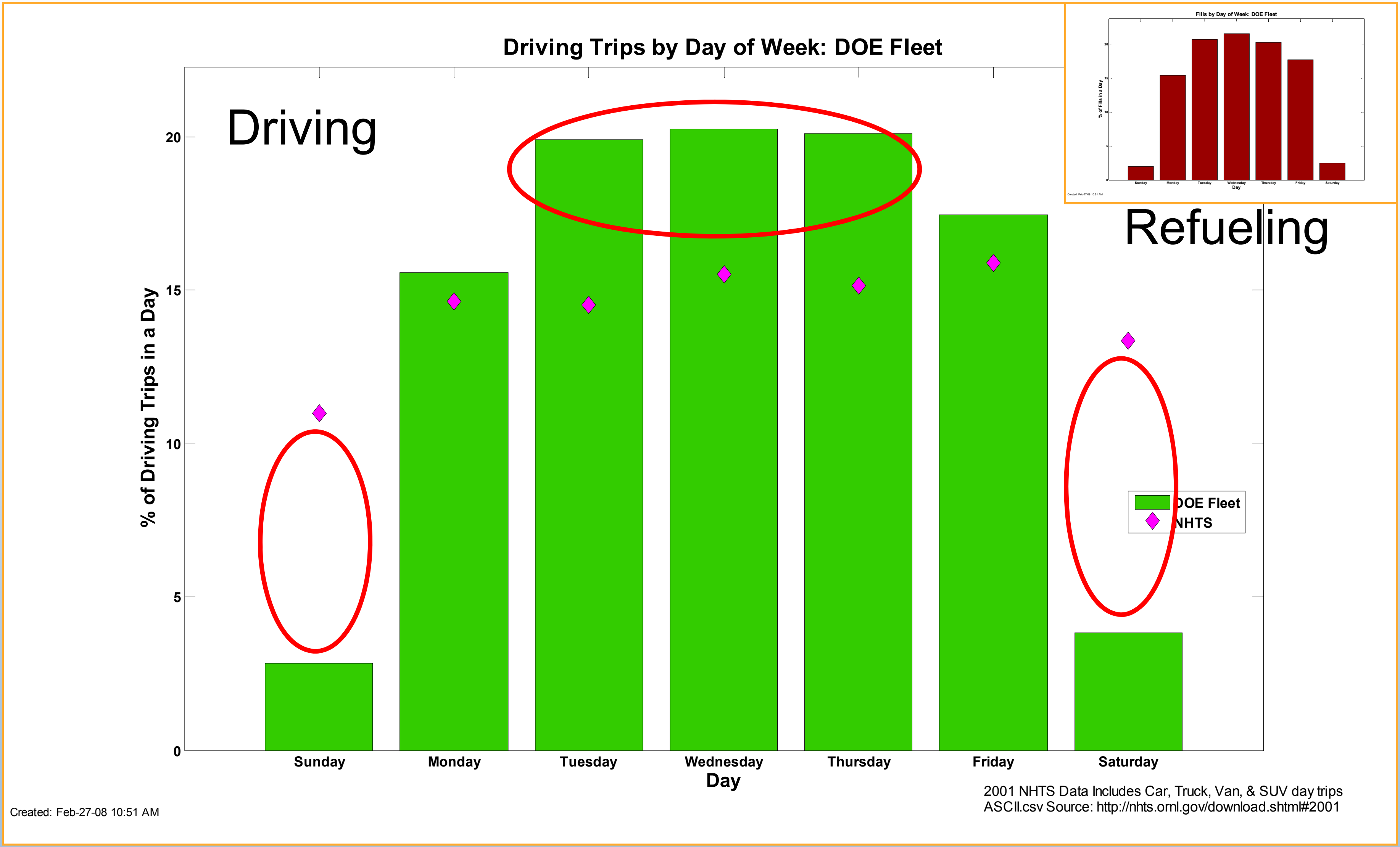
Driving Trip Start Time – Day; Roughly Matches National Statistics Except for 5-6 PM



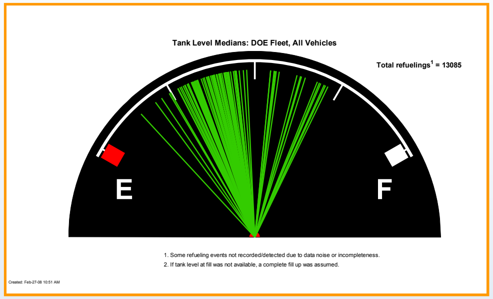
Night



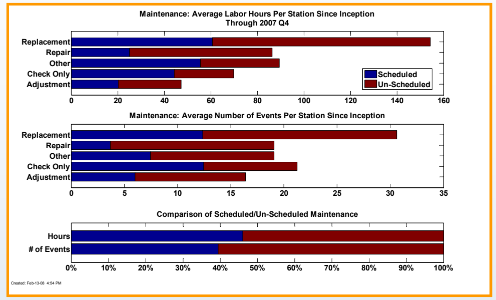
Gen 1 Learning Demo FCV Travel Has Been Primarily Weekday Driving; Differs from NHTS



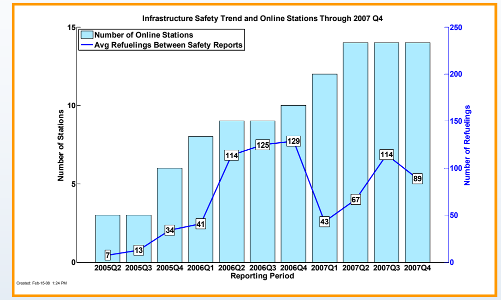
Other CDP Results Not Discussed Here Today



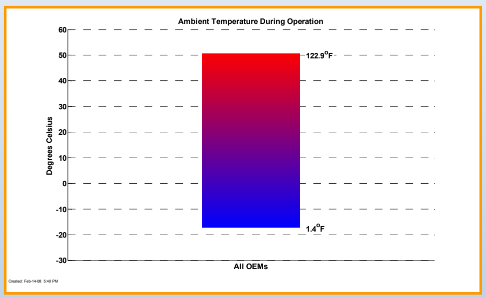
Refueling Tank Levels - Medians



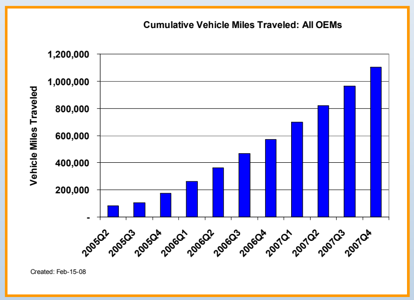
Infrastructure Maintenance



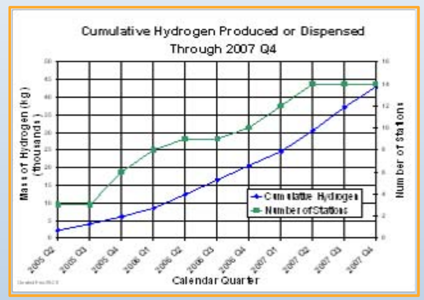
Refuelings per H2 Safety Report



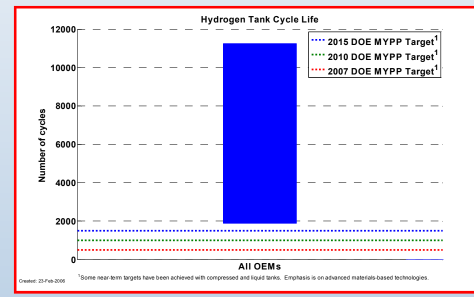
Range of Ambient Temperature During Vehicle Operation



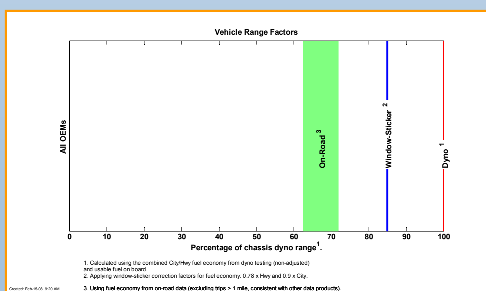
Cumulative Vehicle Miles



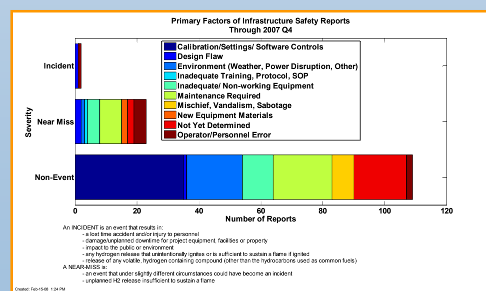
Cumulative H2 Produced or Dispensed



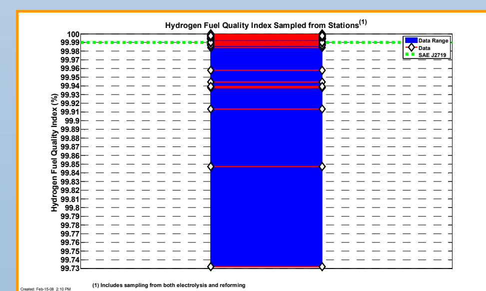
H2 Tank Cycle Life



Effective Driving Range



H2 Safety Primary Factors



H2 Quality Index

Highlights of Interactions and Collaborations in 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 stack degradation multivariate work
  - Validated NREL's on-road stack degradation analysis technique and results with two OEMs
  - Improved methodology for producing detailed data results and CDPs at same time for easier industry review
- **FreedomCAR and Fuel Technical Teams**
  - H2 Storage (10/07) and Delivery (11/07) Tech Teams
  - DOE's Vehicle Technologies Program and HFCIT Program (10/07)
- **US Fuel Cell Council Technical Working Groups**
  - Transportation Working Group – Focus on CA series
  - Joint H2 Quality Task Force
- **California Organizations**
  - CaFCP: NREL will include H2 impurity test results in future CDPs
  - CARB: Discussing data from new stations being sent to NREL for inclusion in analysis results

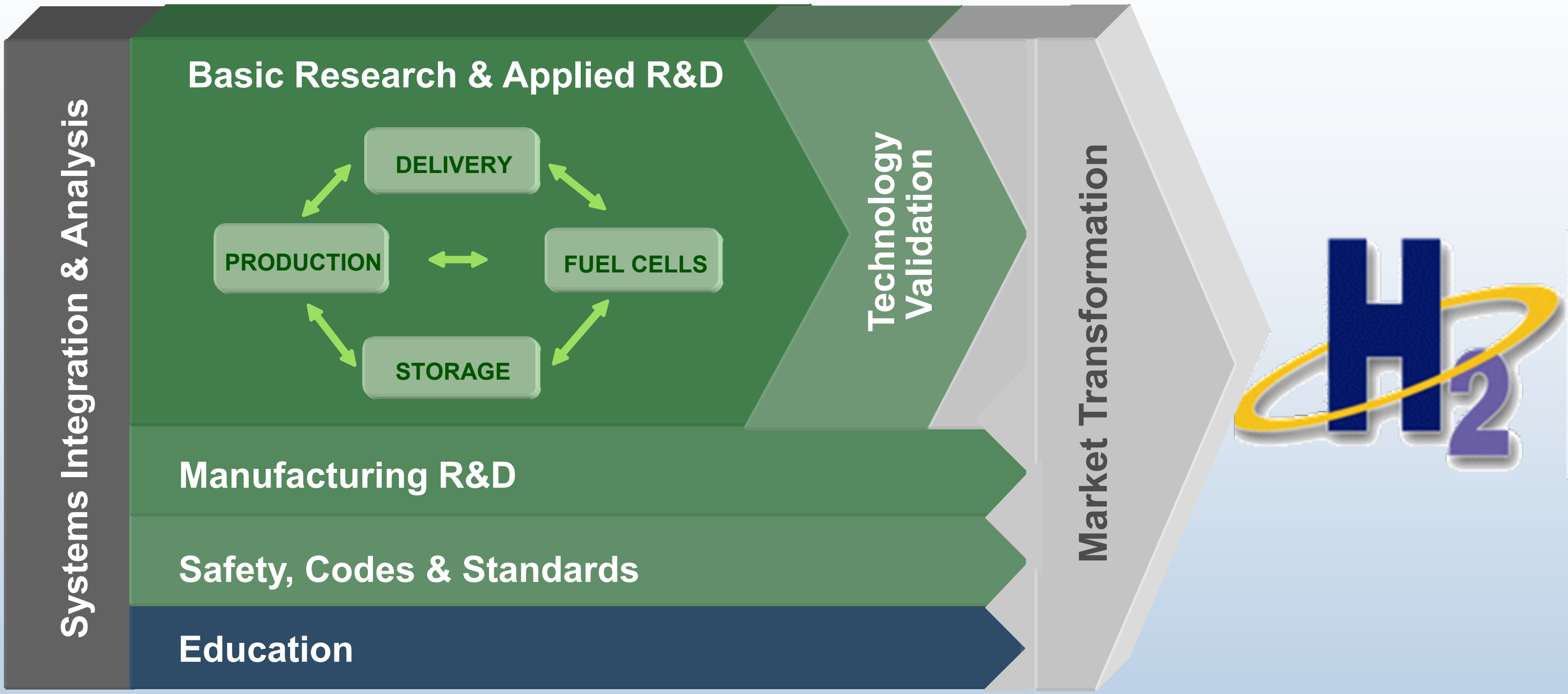
Future Work

- **Remainder of FY08:**
  - Continue to investigate correlations of real-world factors influencing fuel cell degradation
  - Create new and updated composite data products (CDPs) based on data through June 2008
    - Prepare results for publication at 2008 Fuel Cell Seminar
  - For 2nd generation vehicles, begin to evaluate improvements in FC durability, range, fuel economy, and safety
  - Key upcoming September 2008 DOE MYPP and Joule milestone to validate 250-mile range from 2nd generation vehicles
  - Support OEMs, energy companies, and state organizations in California in coordinating early infrastructure plans
- **FY09:**
  - Semi-annually (spring/fall) compare technical progress to program objectives and targets and publish results
    - Production cost, production efficiency, FC freeze startup and freeze tolerance, 2nd gen stack durability
  - Identify opportunities to feed findings from project back into HFCIT program and industry R&D activities to maintain project as a “learning demonstration”
  - Help DOE prepare plans for Phase II of project

Summary

- More than half of project completed
  - 92 vehicles and 15 stations deployed
  - 1.1 million miles traveled, 40,000 kg H_2 produced or dispensed
  - 211,000 individual vehicle trips analyzed
  - Project to continue through 2010
- Examination of Factors Affecting FC Degradation Continues
  - NREL collaborating with each team to understand results and refine inputs and analysis
  - Triggered more thorough analysis of vehicle/stack duty cycles, such as time between trips, trip length, FC power levels
- Total of 47 composite data products published to date
  - This presentation only covered some of the new/updated results
  - Web site allows direct web access to all CDPs
- Roll-out of 2^{nd} generation vehicles has begun
  - 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

Responses to Previous Year (FY07) Reviewers' Comments

- Q: "Refueling time, amount, capacity factors, and availability factor should be analyzed for greater value of the data"
  - Extensive analysis has been performed on refueling time, amount, and rates: comm. vs. non-comm., changes in distribution with time
  - Station capacity and availability factor data is not provided to NREL; may also be of limited extended value with such a sparse network of stations and limited vehicles at this stage.

- Q: "Try to include more projects, even those not in the DOE program"
  - Vehicles: Difficult to obtain detailed data from non-DOE projects due to IP
  - Infrastructure: Data from CHIP project (Air Products) now included; potential for obtaining data from new/upgraded California Stations from CARB and CaFCP

- Q: "Benchmark against European and Japanese initiatives" and "Build a global record of FCV demonstration results"
  - Little public technical data (outside of number of vehicles and locations) exists publicly from these foreign demonstration projects
  - An IPHE Demonstration Working Group (DWG) has been formed to facilitate this type of data sharing and has met 3 times; we've published US results, and DOE is working through the DWG to assemble data from other countries.

Publications and Presentations
(Since FY07 Review, Key Text in Bold)

1. Wipke, K., Sprik, S., Kurtz, J., "Learning Demonstration **Progress Report—Spring 2008**," National Renewable Energy Laboratory Technical Report NREL/TP-560-42986, April 2008.
2. Wipke, K., Sprik, S., Kurtz, J., Garbak, J., "Fuel Cell Vehicle Learning Demonstration: Spring 2008 Results Presentation," **National Hydrogen Association** Annual Hydrogen Conference, March 2008. (paper and presentation)
3. Wipke, K., Sprik, S., Kurtz, J., "**Composite Data Products** for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, updated March 2008. (presentation)
4. Wipke, K., "**Hydrogen Secure Data Center: Procedures** to Protect Technical Data Submitted under the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," Golden, CO: National Renewable Energy Laboratory, updated December 2007. (HSDC document)
5. Wipke, K., Sprik, S., Kurtz, J., Thomas, H., "FCV Learning Demonstration: Project Midpoint Status and Fall 2007 Results," **EVS-23 Conference**, Anaheim, CA, December 2007. (paper and presentation)
6. Kurtz, J., Wipke, K., Sprik, S., "FCV Learning Demonstration: Factors Affecting Fuel Cell Degradation," **Fuel Cell Durability & Performance Conference**, Miami, Florida, November 2007. (presentation).
7. Wipke, K., Sprik, S., Kurtz, J., Thomas, H., Garbak, J., "FCV Learning Demonstration: Project Midpoint Status and First-Generation Vehicle Results," **ZERO REGIO Conference**, Montecatini Terme, Italy, November 2007. (presentation)
8. Wipke, K., Sprik, S., Thomas, H., Welch, C., Kurtz, J., "Controlled Hydrogen Fleet and Infrastructure Analysis Project," 2007 DOE HFCIT Program **Annual Progress Report**, System Analysis Section VI.D.1, November 2007. (paper)
9. Wipke, K., presentation of Learning Demonstration results to **FreedomCAR and Fuels Delivery Tech Team**, November, 2007. (presentation)
10. Wipke, K., Sprik, S., Kurtz, J., Thomas, H., Garbak, J., "FCV Learning Demonstration: First-Generation Vehicle Results and Factors Affecting Fuel Cell Degradation," **Fuel Cell Seminar**, San Antonio, TX, October 2007. (presentation and extended abstract).
11. Wipke, K., Sprik, S., Kurtz, J., Thomas, H., Garbak, J., "Fuel Cell Vehicle and Infrastructure Learning Demonstration: Activities in California," H2 **Infrastructure Forum** Between National & Local Governments and Industry, hosted by USFCC, Washington, DC, October 2007. (presentation)
12. Wipke, K., Sprik, S., Kurtz, J., Thomas, H., "Learning Demonstration **Progress Report – September 2007**," National Renewable Energy Laboratory Technical Report NREL/TP-560-42264, October 2007. (paper)
13. Wipke, K., presentation of Learning Demonstration results to **Vehicle Technologies Program at DOE**, October 2007. (presentation)
14. Wipke, K., presentation of Learning Demonstration results to **FreedomCAR and Fuels Hydrogen Storage Tech Team**, October, 2007. (presentation)
15. Wipke, K., presentation of Learning Demonstration results to **HFCIT Program at DOE**, October 2007. (presentation)
16. Wipke, K., Sprik, S., Thomas, H., Welch, C., Kurtz, J., "Learning Demonstration Interim **Progress Report – Summer 2007**," National Renewable Energy Laboratory Technical Report NREL/TP-560-41848, July 2007. (paper)
17. Wipke, K., Welch, C., Thomas, H., Sprik, S., Kurtz., J., "DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: **Quarterly Validation Assessment Reports**," (HSDC papers only)
    - 1Q 2007, June 2007.
    - 2Q 2007, September 2007.

Critical Assumptions and Issues

- Assumption: Linear fit for stack degradation slope and calculated beginning of life voltage (under load) used for projecting time to 10% voltage drop
  - When just a few hundred hours of data existed, no shape other than linear was justifiable
  - As more data was received, some stacks showed an initial drop in the first few hundred hours with a more gradual slope after that
  - With more data, a linear fit with a calculated initial voltage will tend to overestimate the projected time to a 10% voltage drop.
  - Proposed solution:
    - NREL is investigating using a fixed initial voltage under load for each stack, as well as potentially a non-linear or two-slope fit to the degradation curve
    - NOTE: Several Gen 1 stacks have already achieved over 1,000 hours of demonstrated durability, and as more stacks achieve their full life, the emphasis on projecting time to 10% voltage drop (durability metric) will shift to Gen 2 stacks to enable a comparison to 2,000 hour target. Gen 1 data can be used to test improved methodology.

- Issue: Influences from fuel quality and climate on stack degradation may not be strong enough to draw conclusions for 1st gen vehicles
  - Fuel quality good at all sites…have not had a site with bad fuel quality to track stack degradation of vehicles refueling there
  - First gen stacks not freeze-tolerant, so vehicles are not left to soak in cold. Therefore data not likely to show strong impact of different climates yet
  - Proposed solution:
    - 2nd gen vehicles will be operated and soaked in cold environments to not only verify freeze tolerance but also look at impact on stack durability.
    - Separate activities (codes and standards) are looking at impact of fuel impurities on durability, which is probably most direct/controlled way to examine impurity impacts.