



National Renewable Energy Laboratory

Innovation for Our Energy Future

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Spring 2010

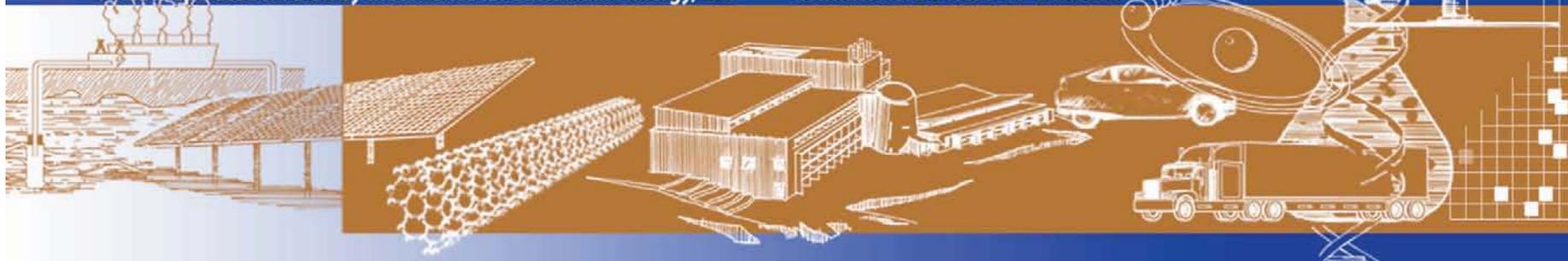
Composite Data Products
Final Version March 29, 2010

Keith Wipke, Sam Sprik, Jennifer Kurtz, and Todd Ramsden

Technical Report
NREL/TP-560-48173
May 2010

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Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

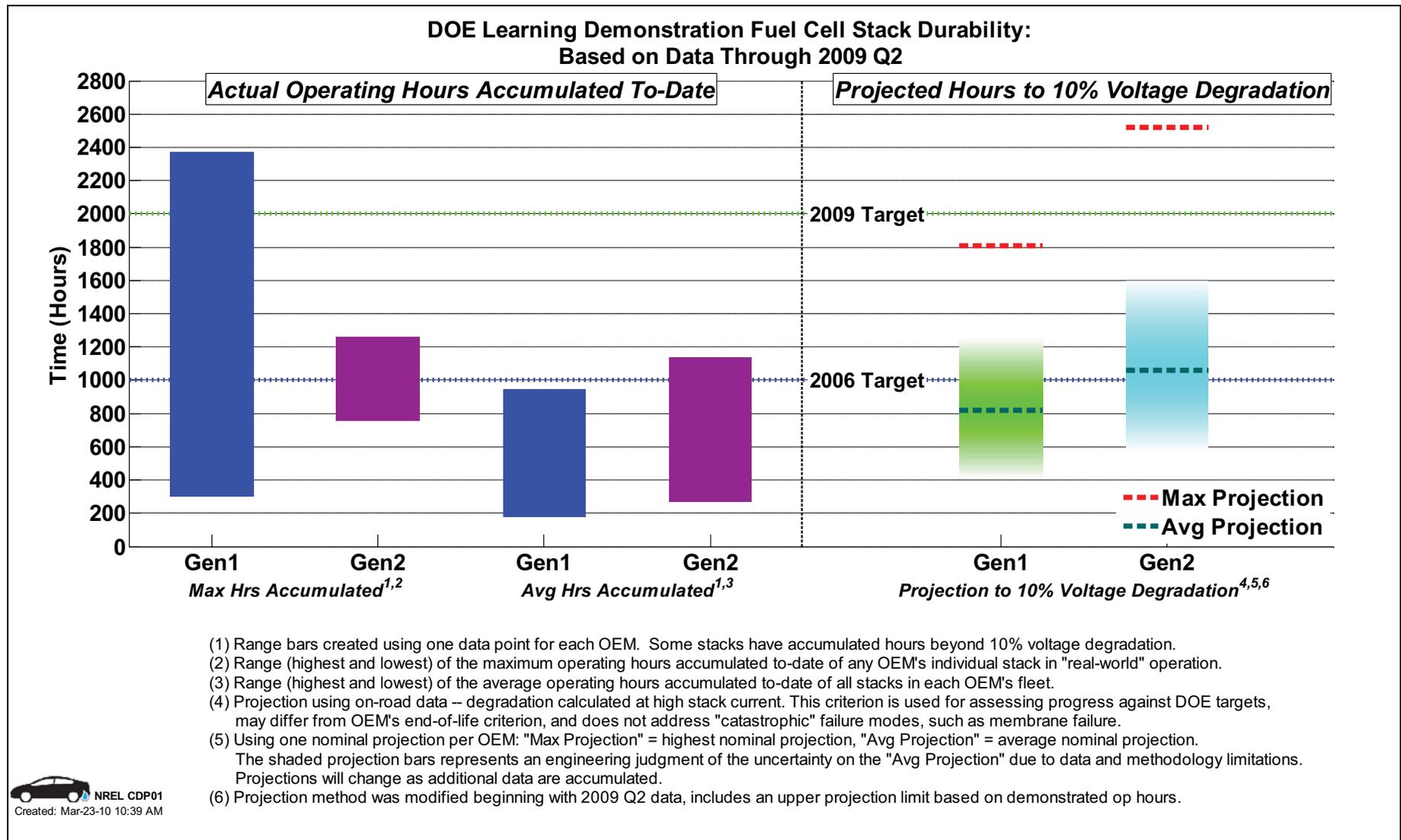


**Spring 2010
Composite Data
Products**

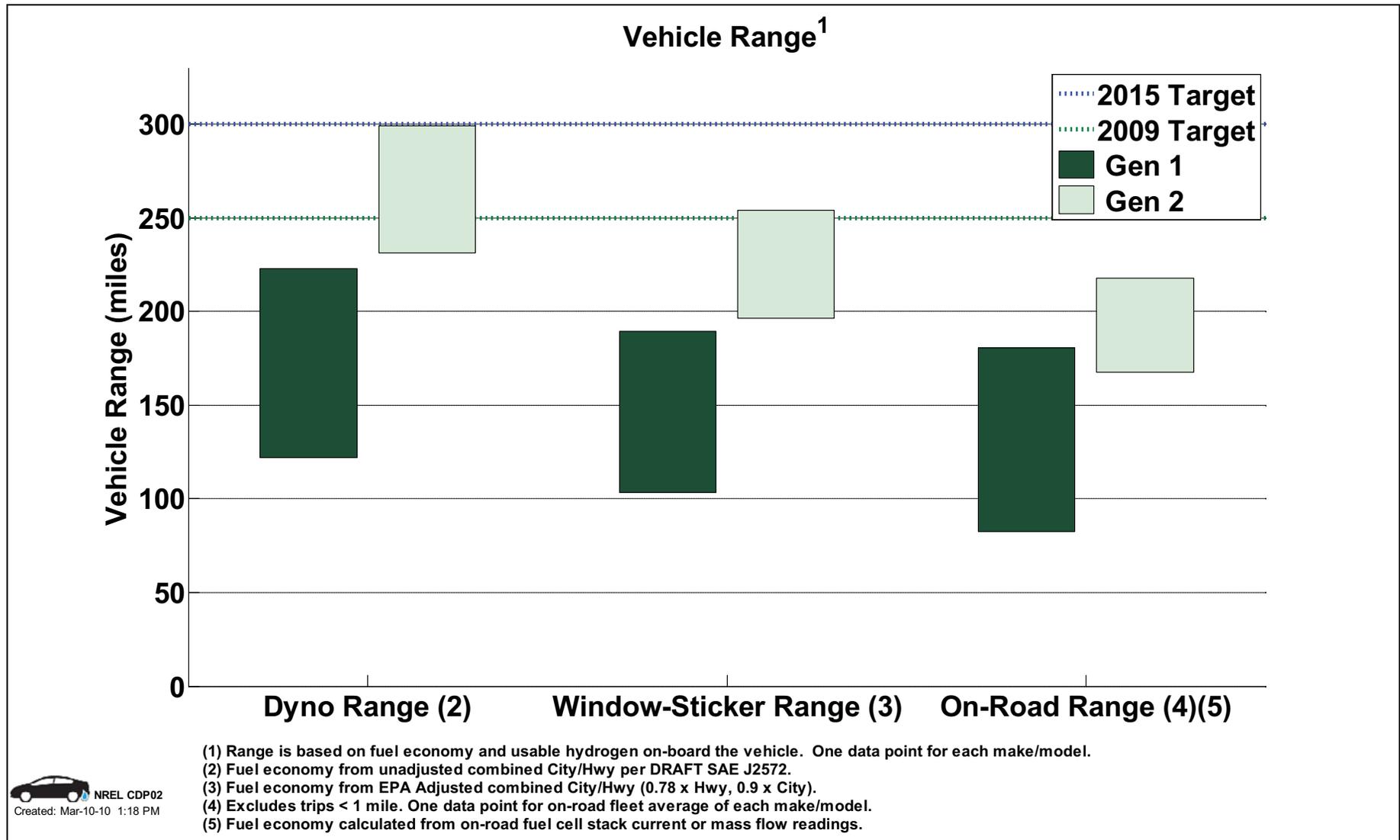
March 29, 2010

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

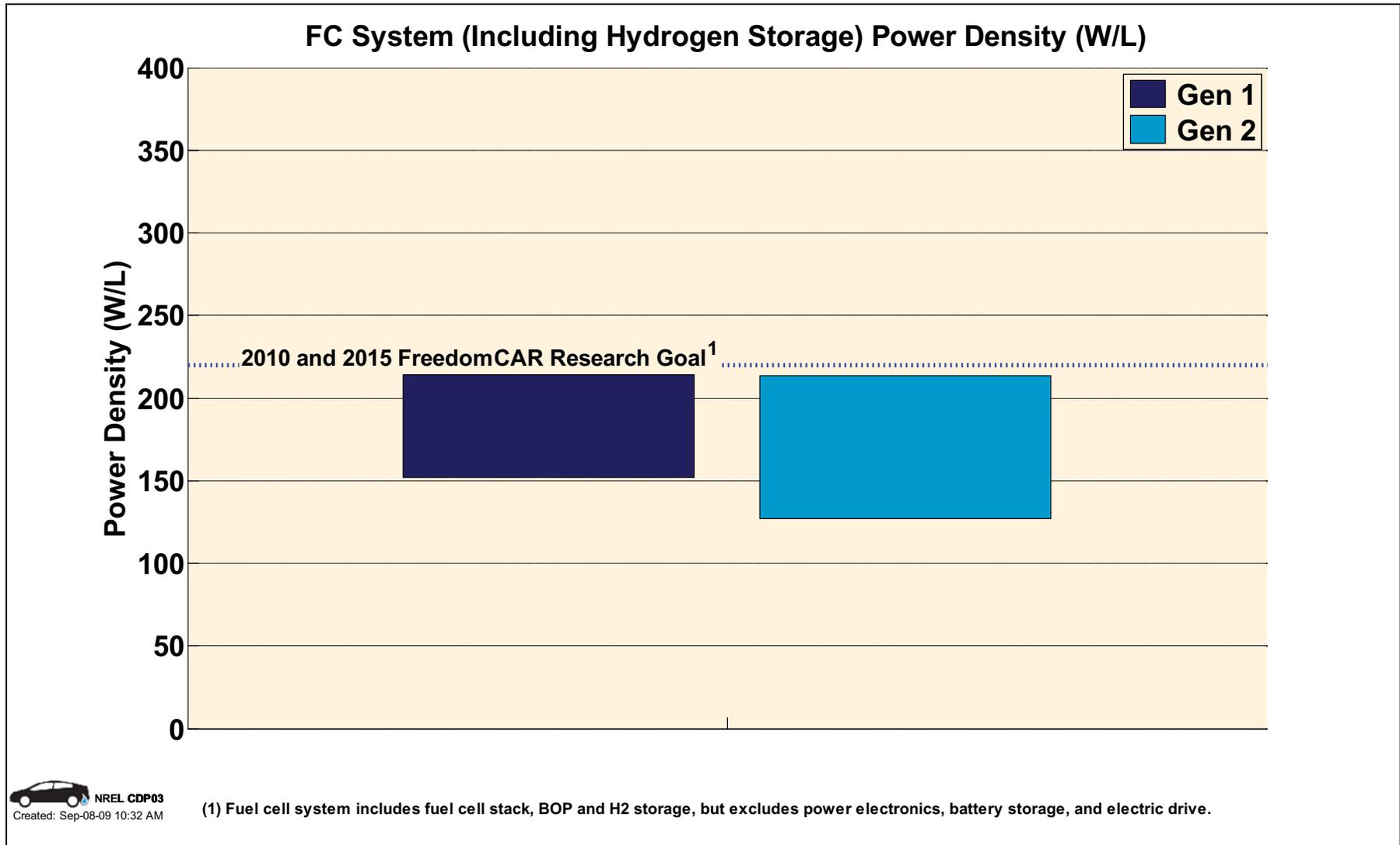
CDP#1: Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation



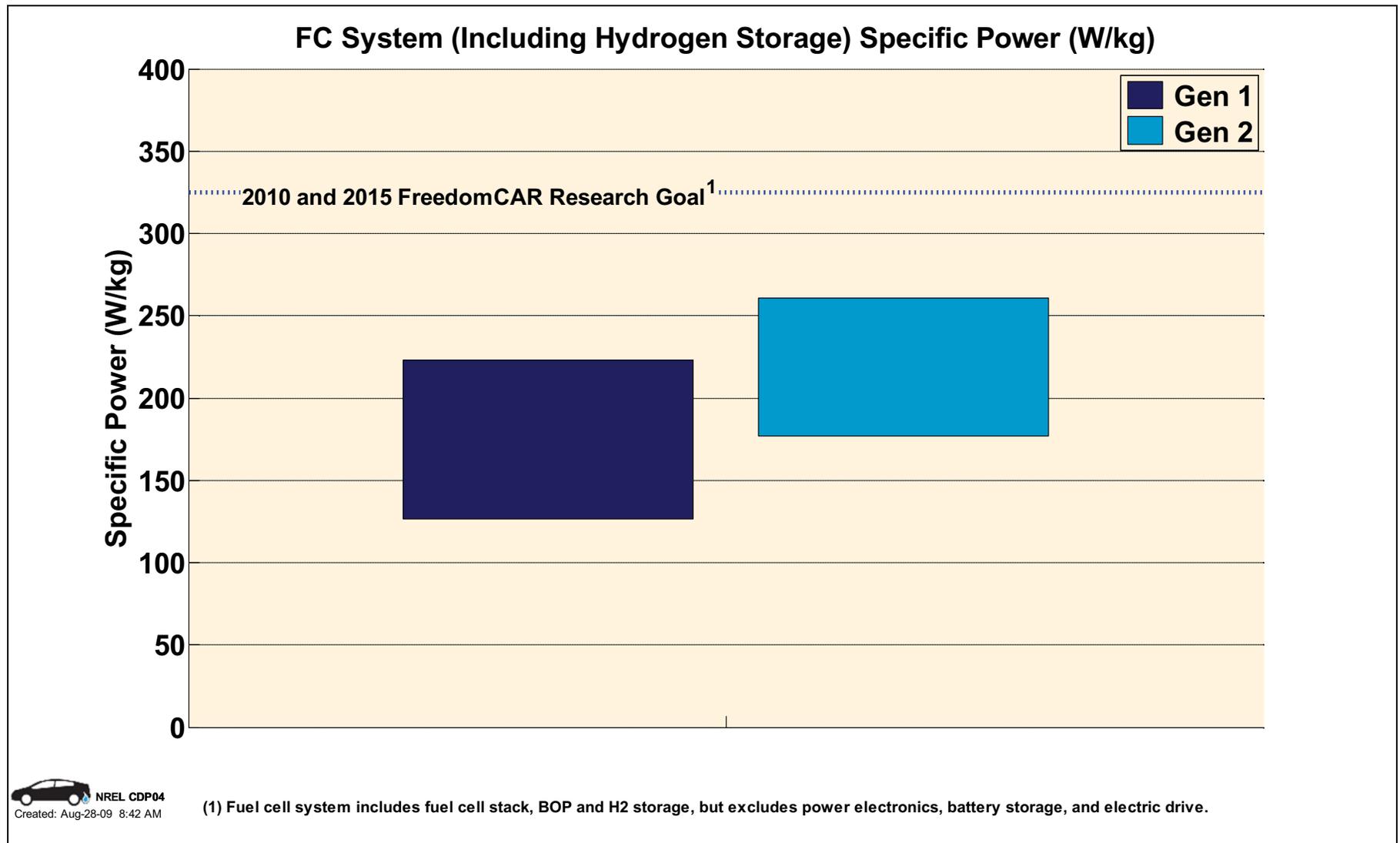
CDP#2: Vehicle Range



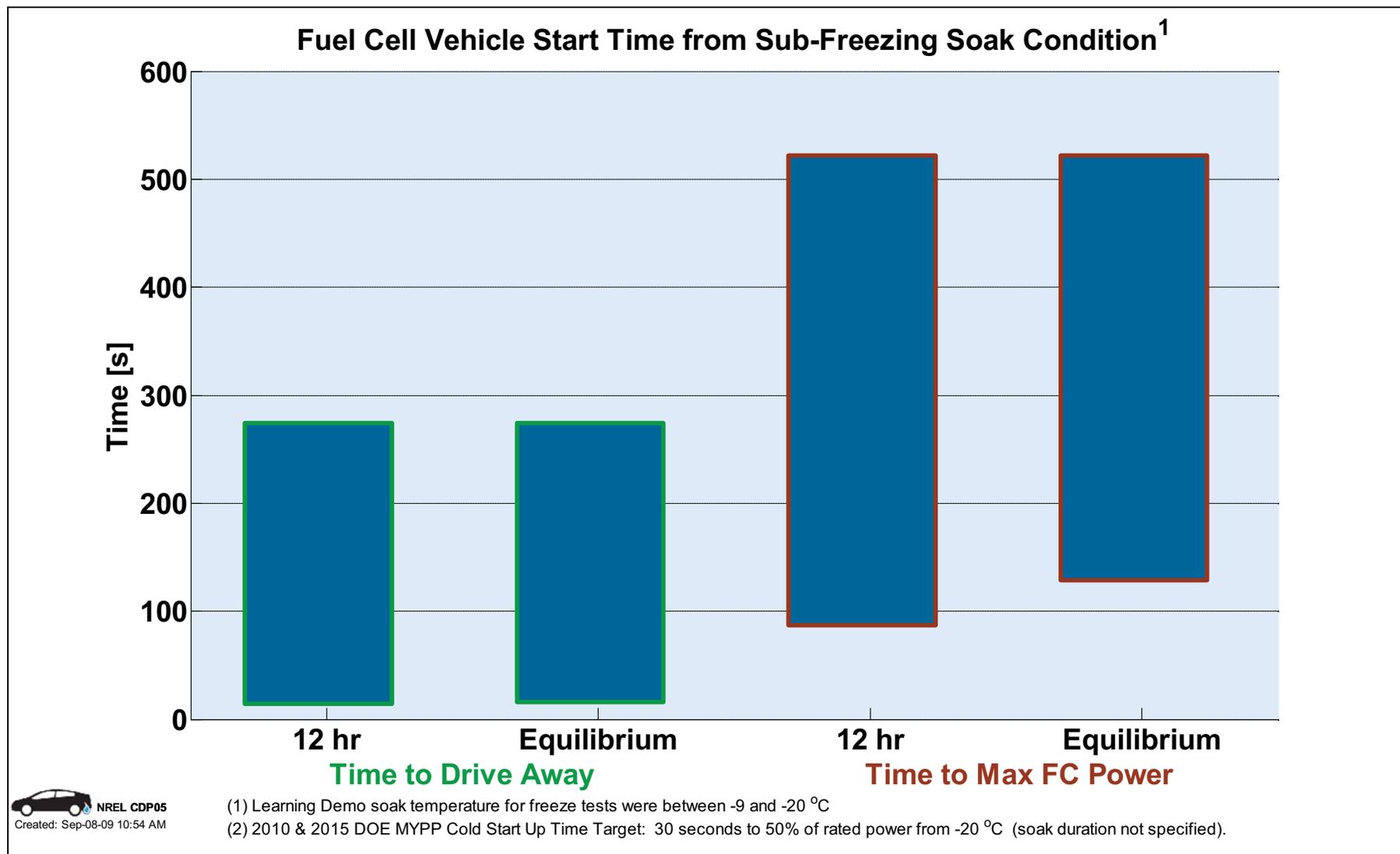
CDP#3: Fuel Cell System Power Density, Including Hydrogen Storage



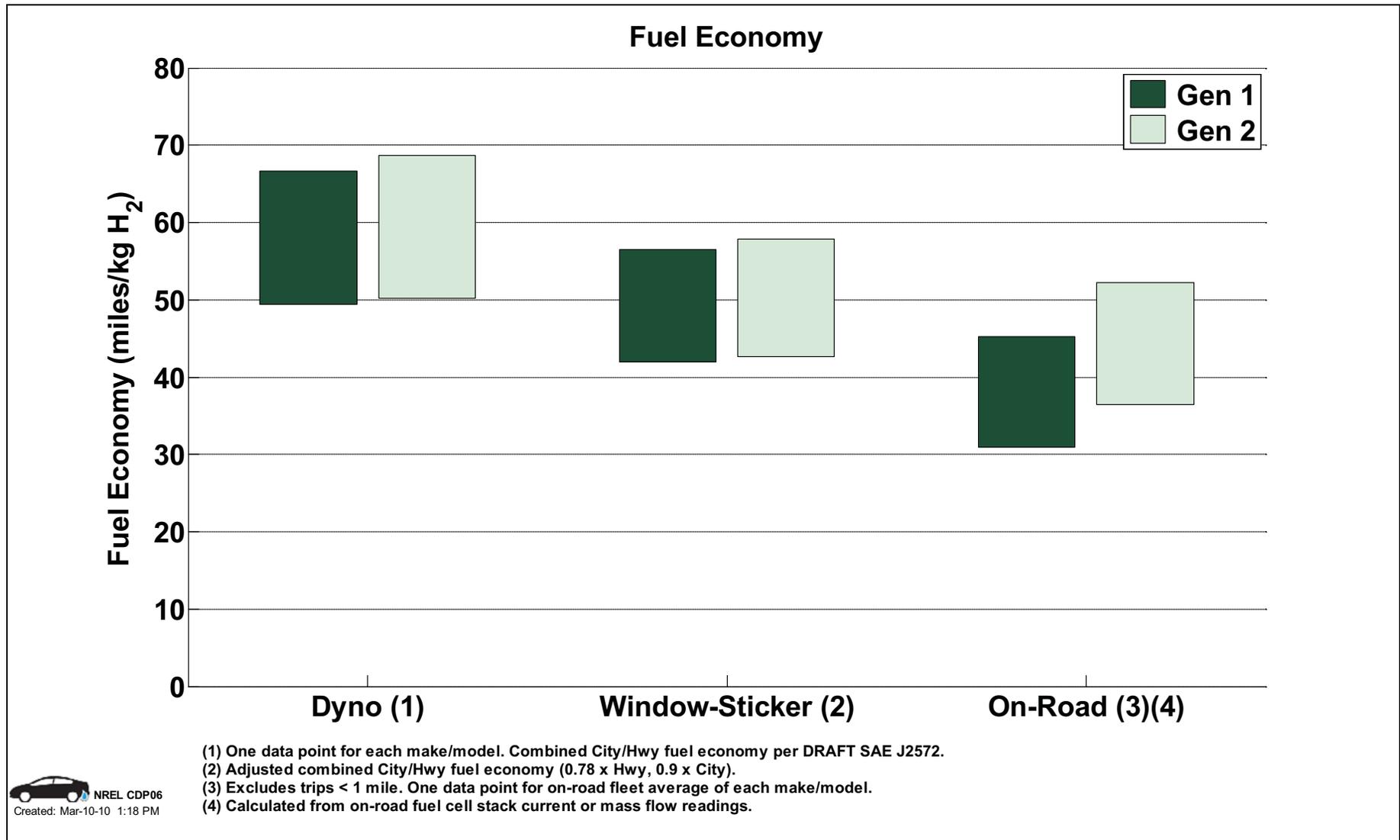
CDP#4: Fuel Cell System Specific Power, Including Hydrogen Storage



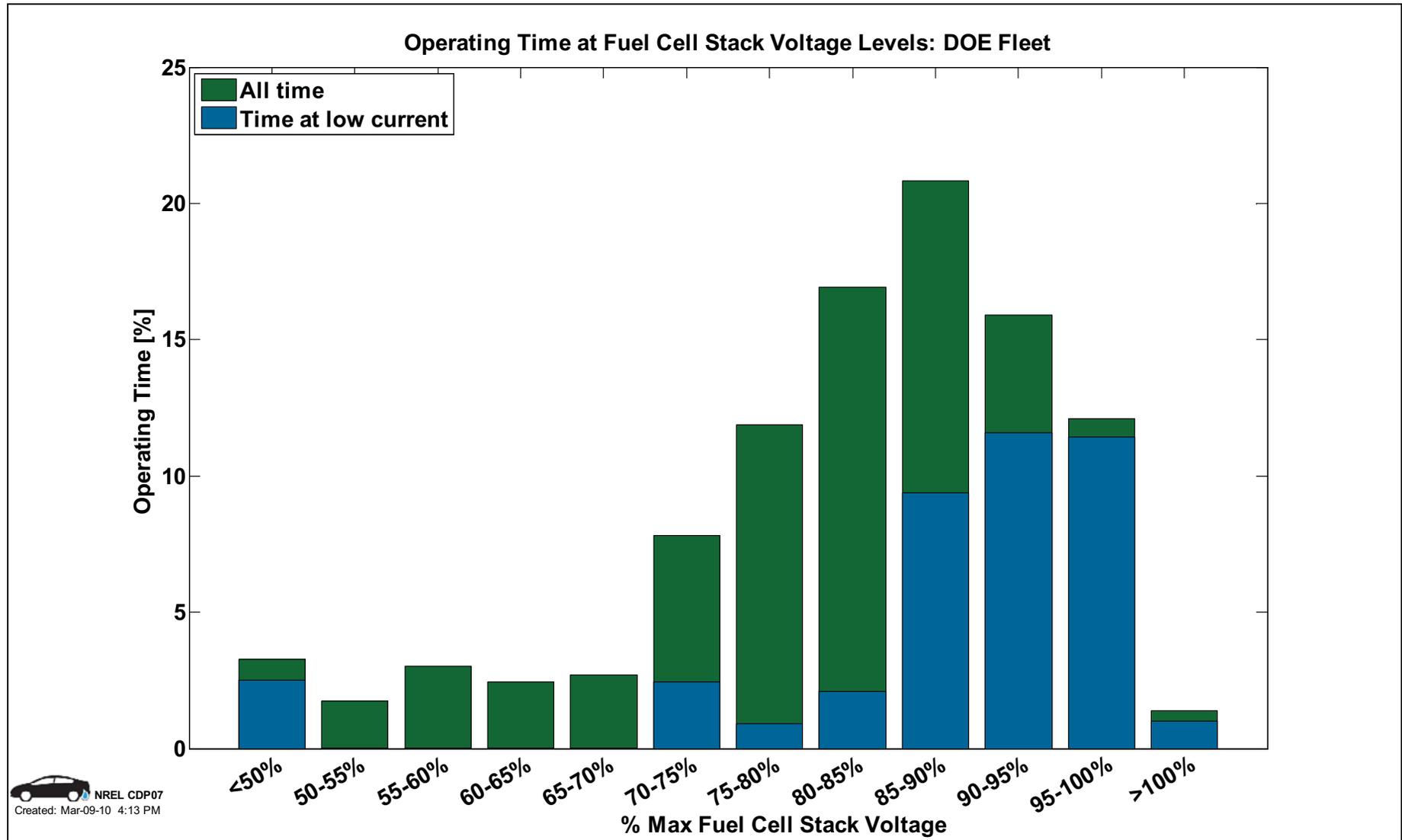
CDP#5: Fuel Cell Start Times from Sub-Freezing Soak Conditions



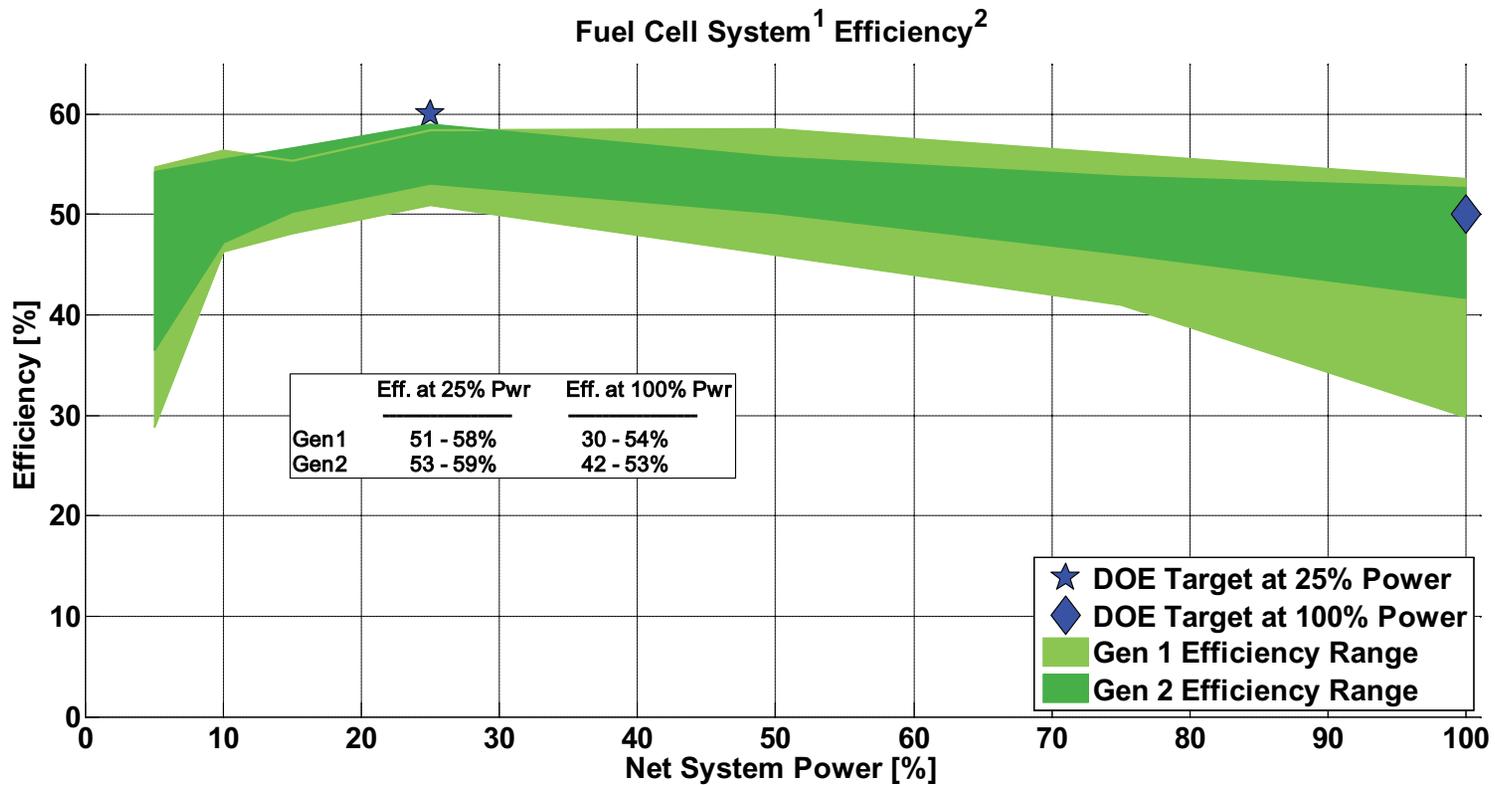
CDP#6: Fuel Economy



CDP#7: Fuel Cell Voltage



CDP#8: FC System Efficiency

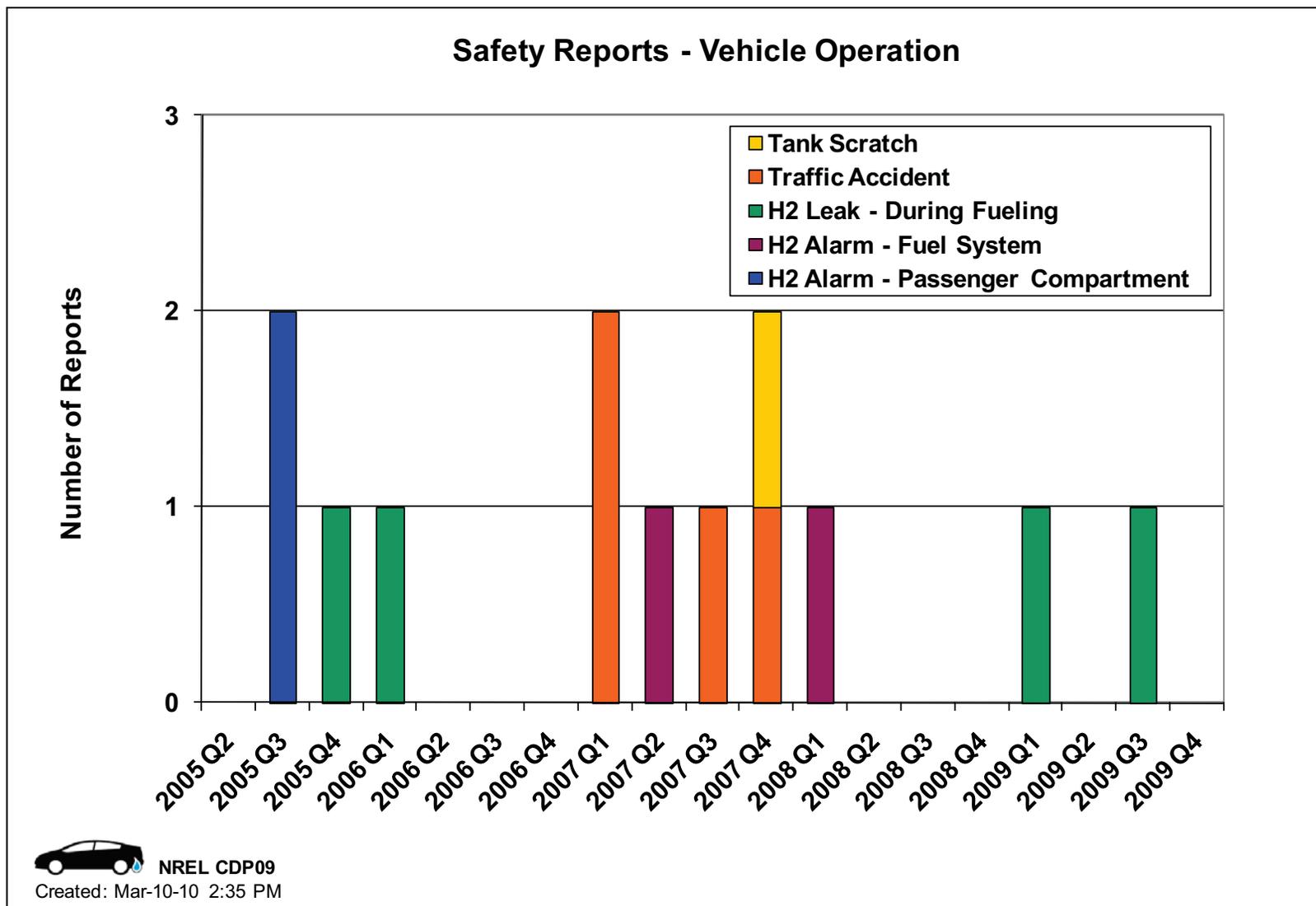


¹ Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.

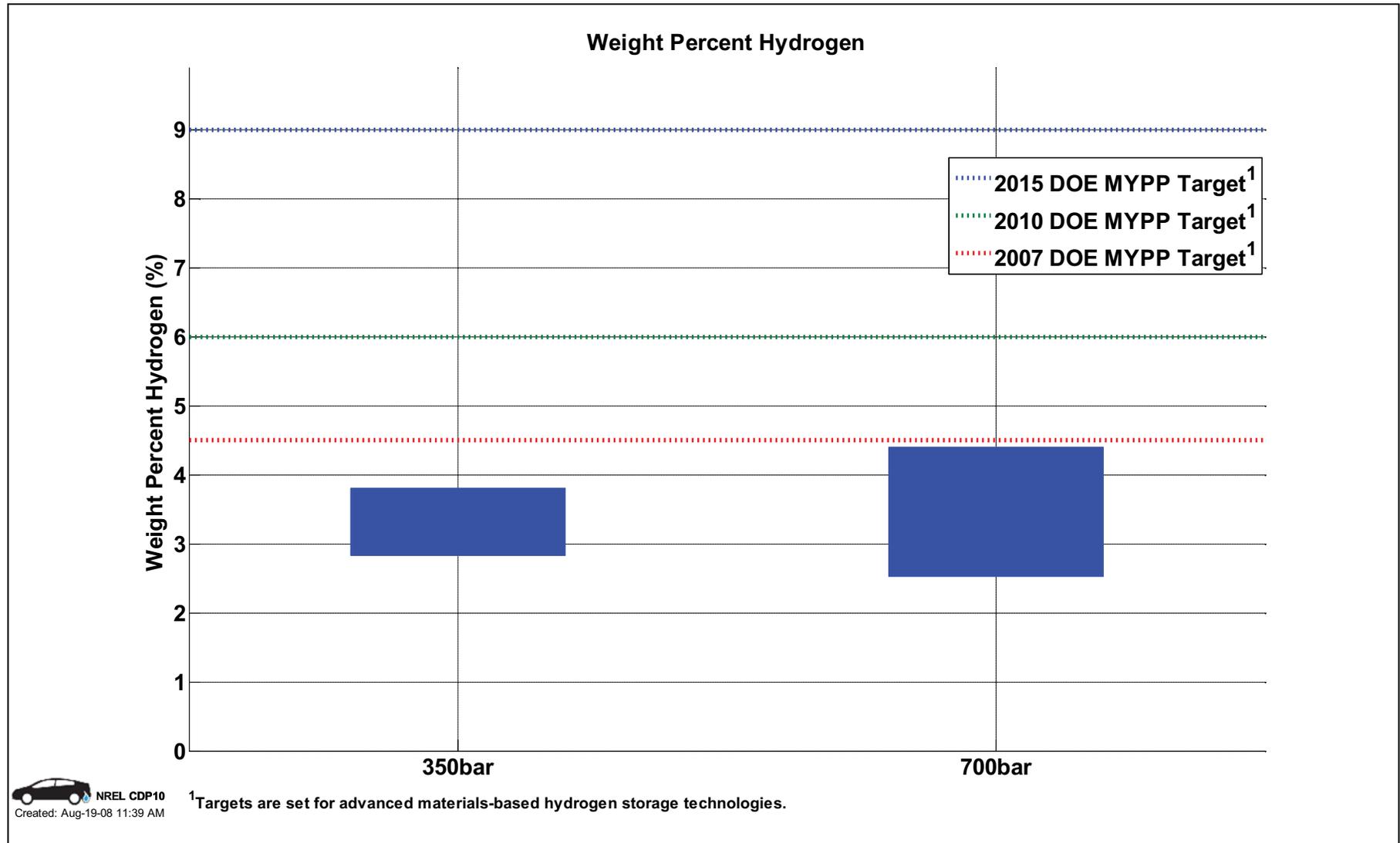
² Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).

³ Individual test data linearly interpolated at 5,10,15,25,50,75, and 100% of max net power. Values at high power linearly extrapolated due to steady state dynamometer cooling limitations.

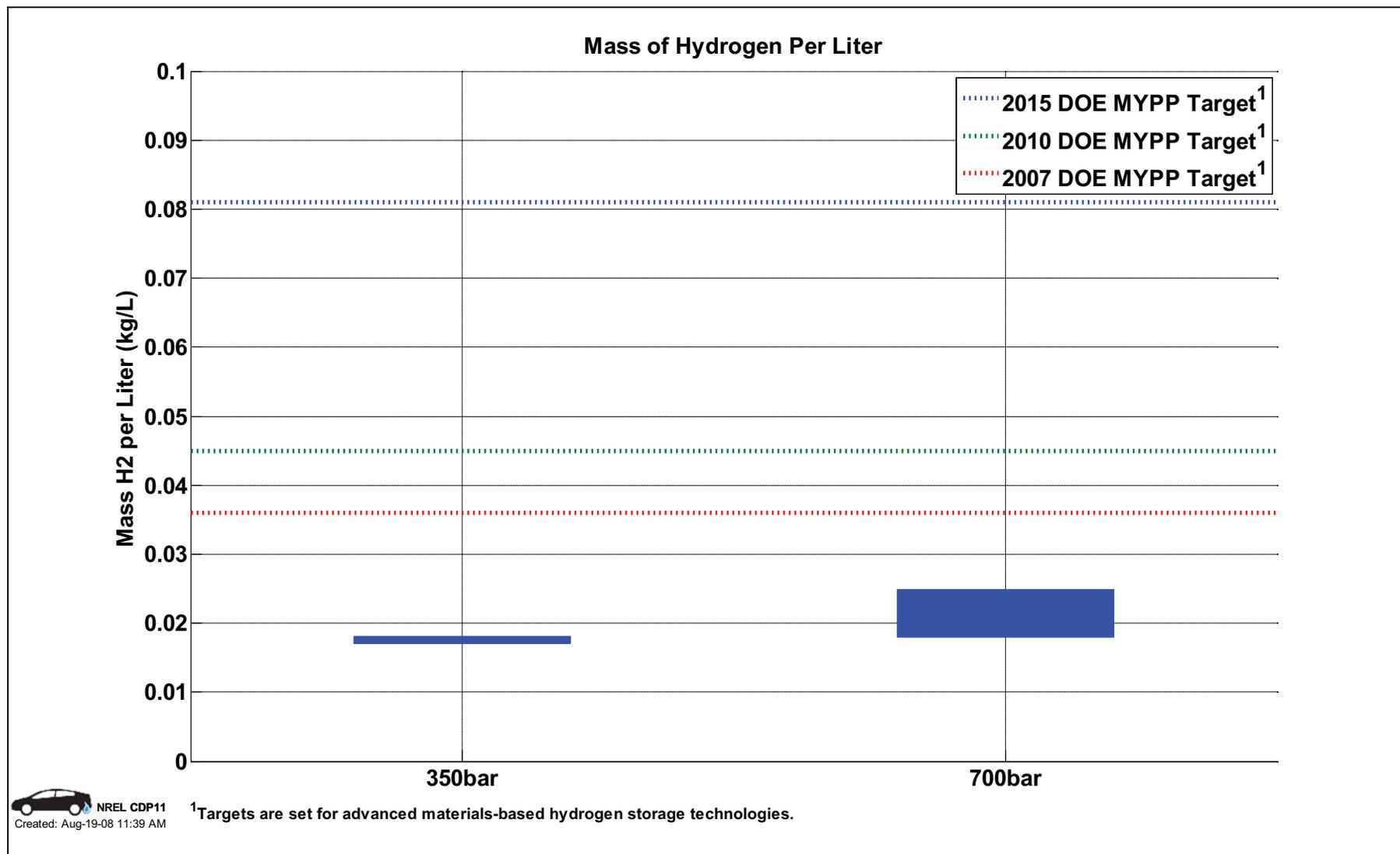
CDP#9: Safety Reports – Vehicles



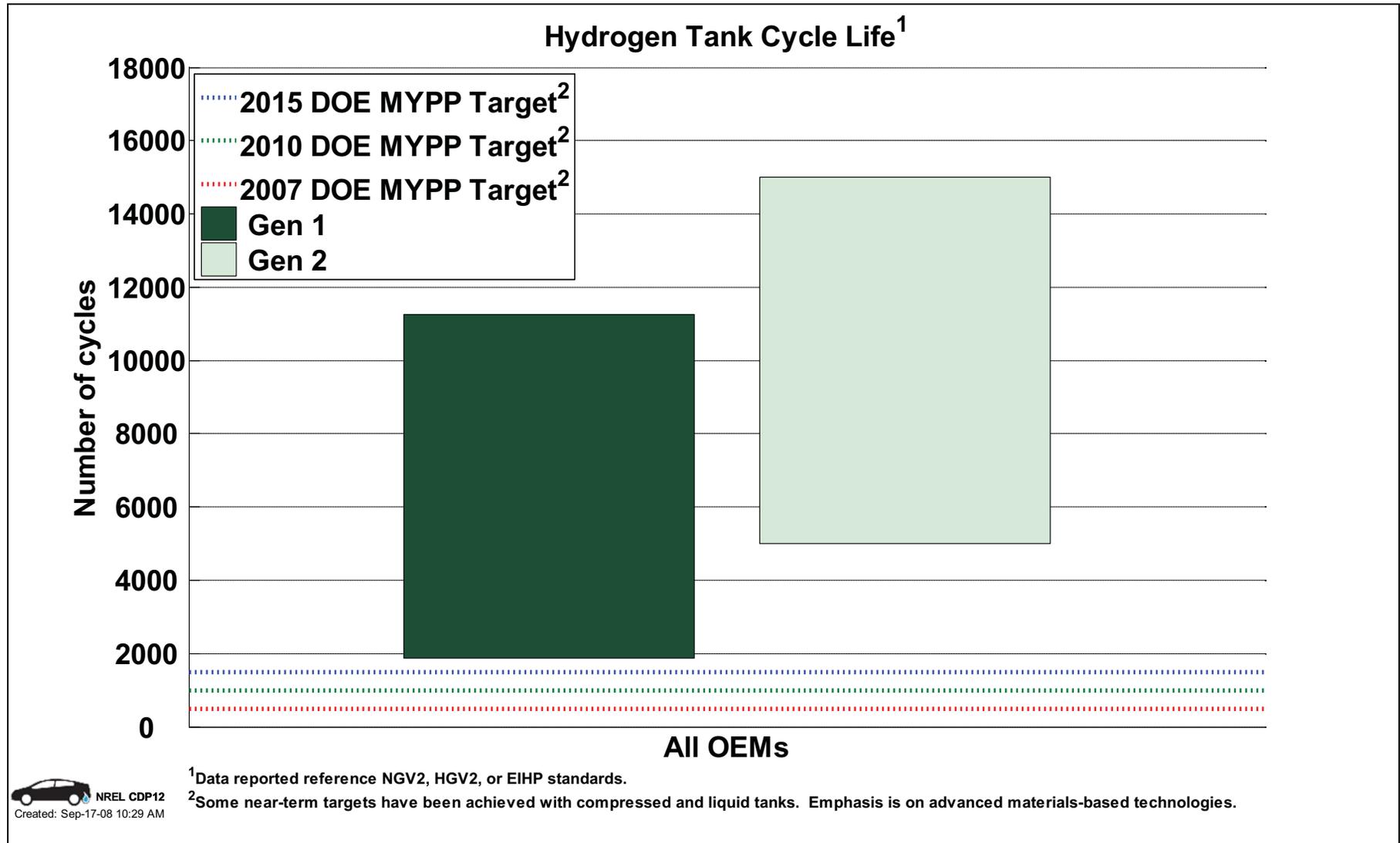
CDP#10: Storage Weight % Hydrogen



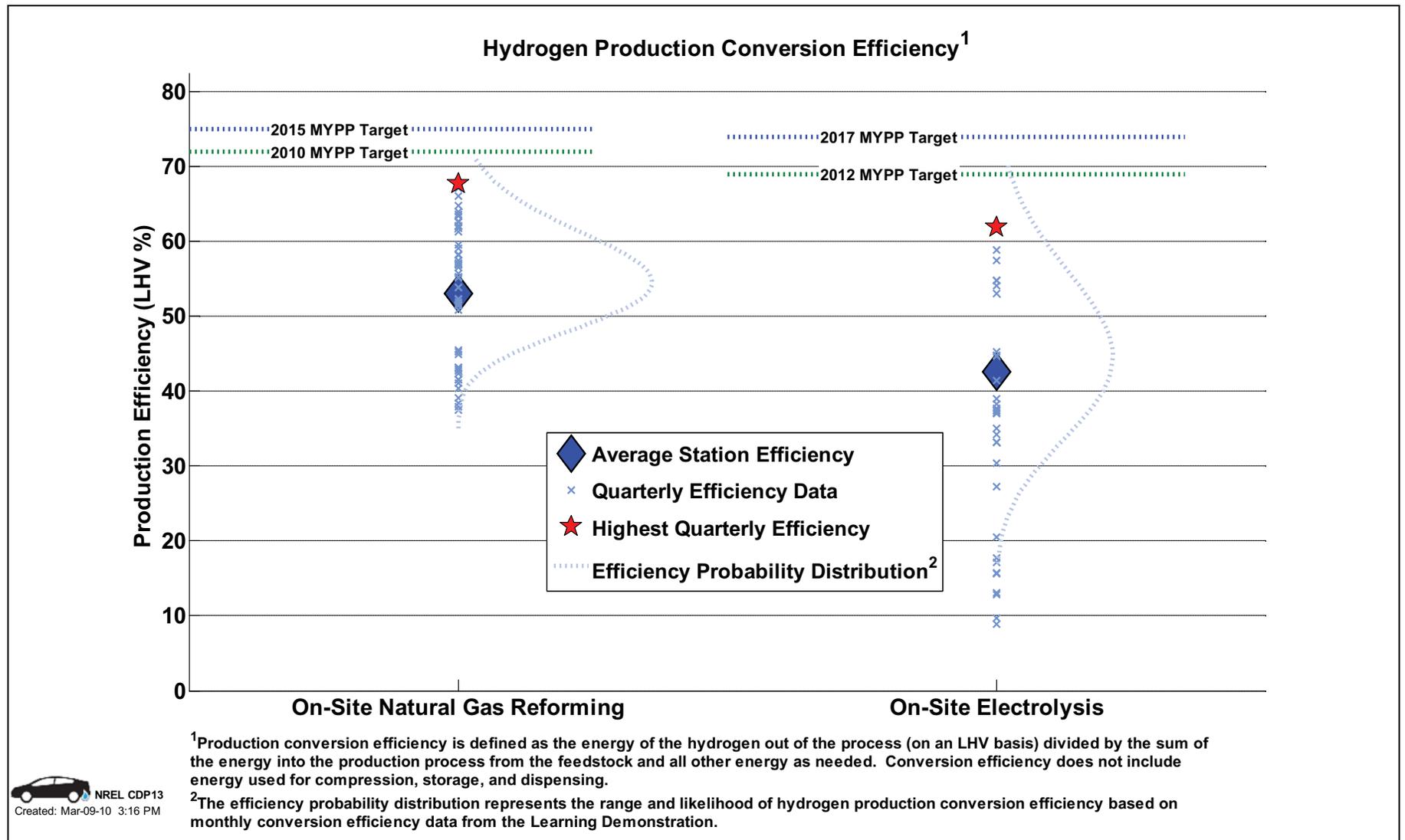
CDP#11: Volumetric Capacity of H2 Storage



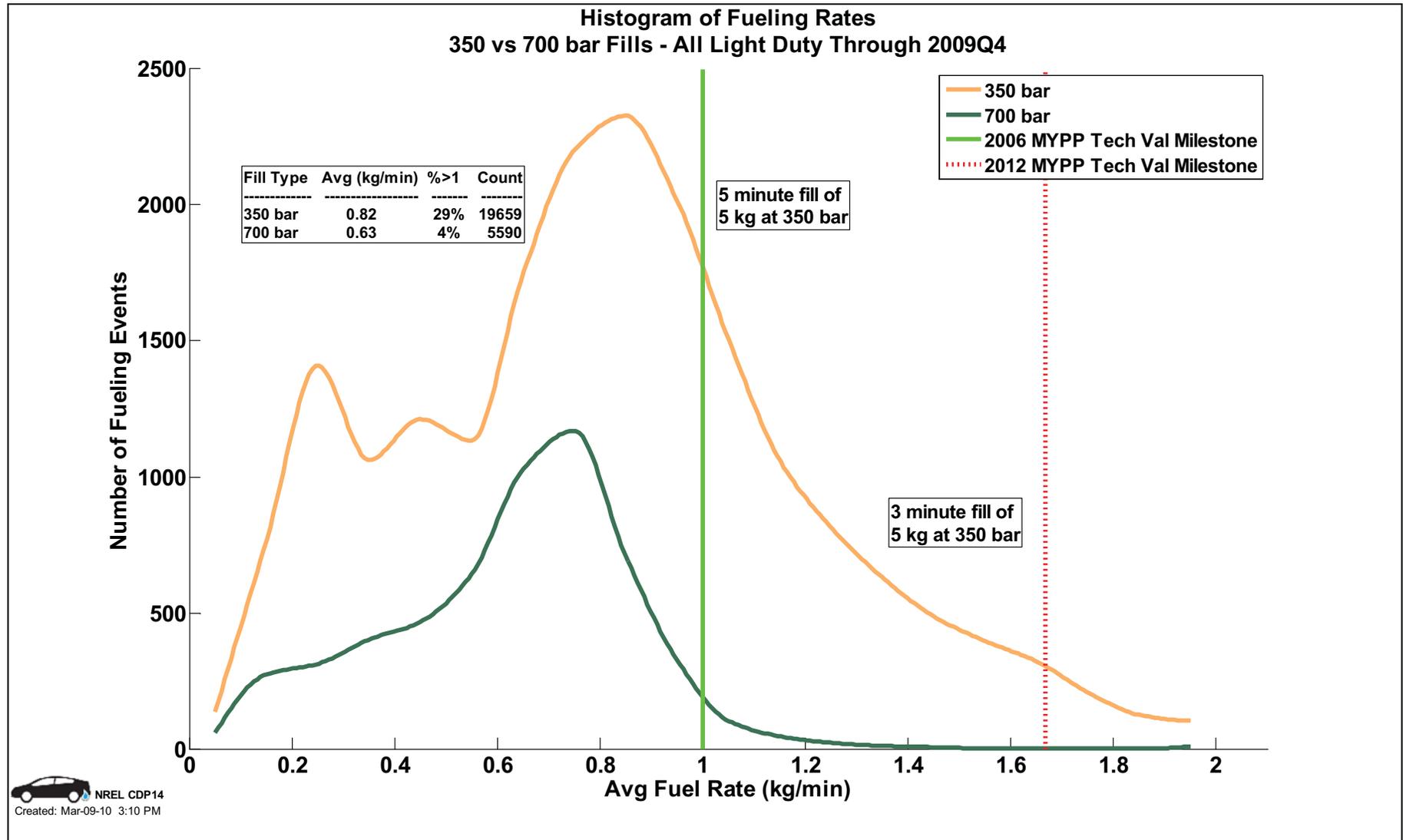
CDP#12: Vehicle Hydrogen Tank Cycle Life



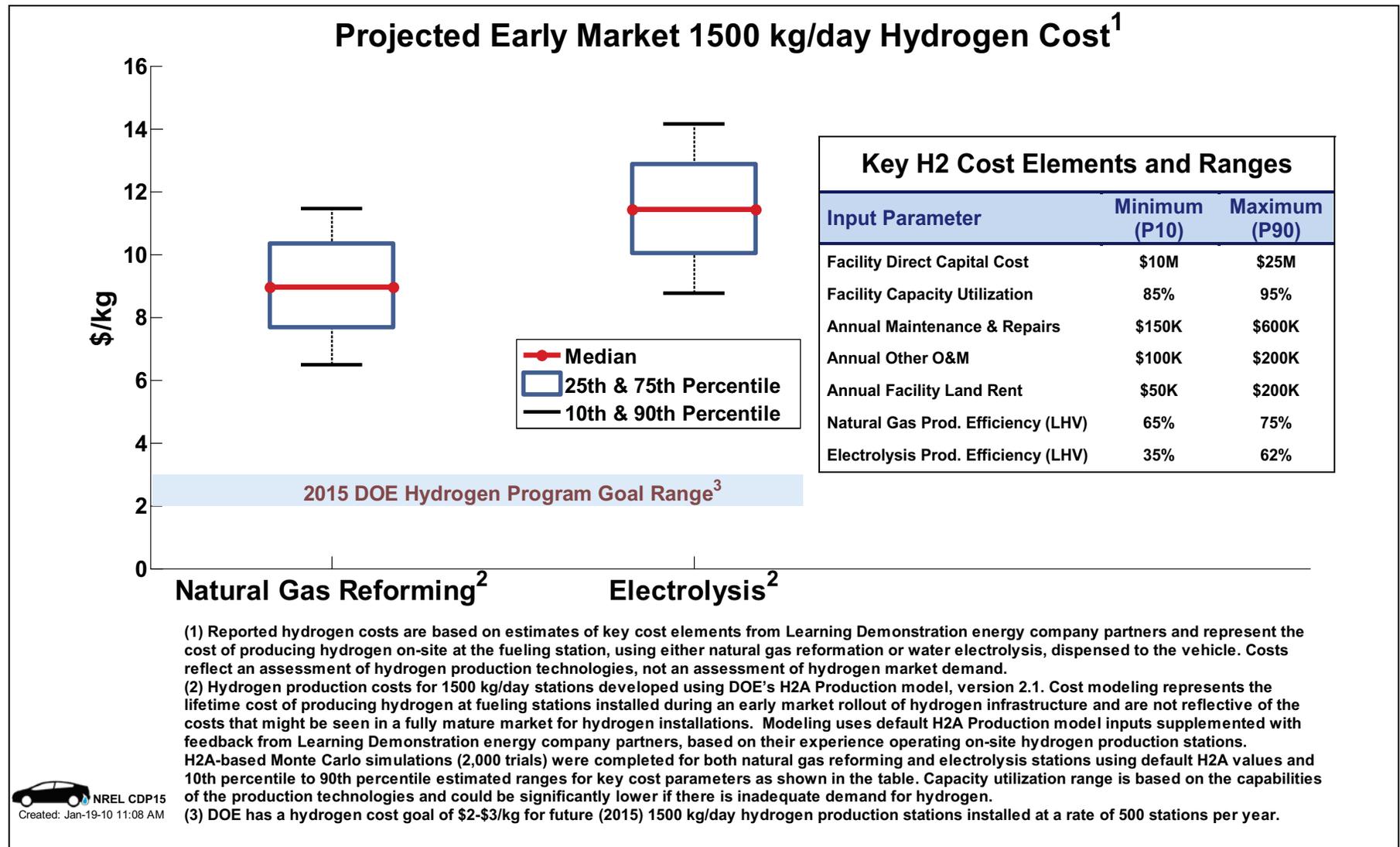
CDP#13: On-Site Hydrogen Production Efficiency



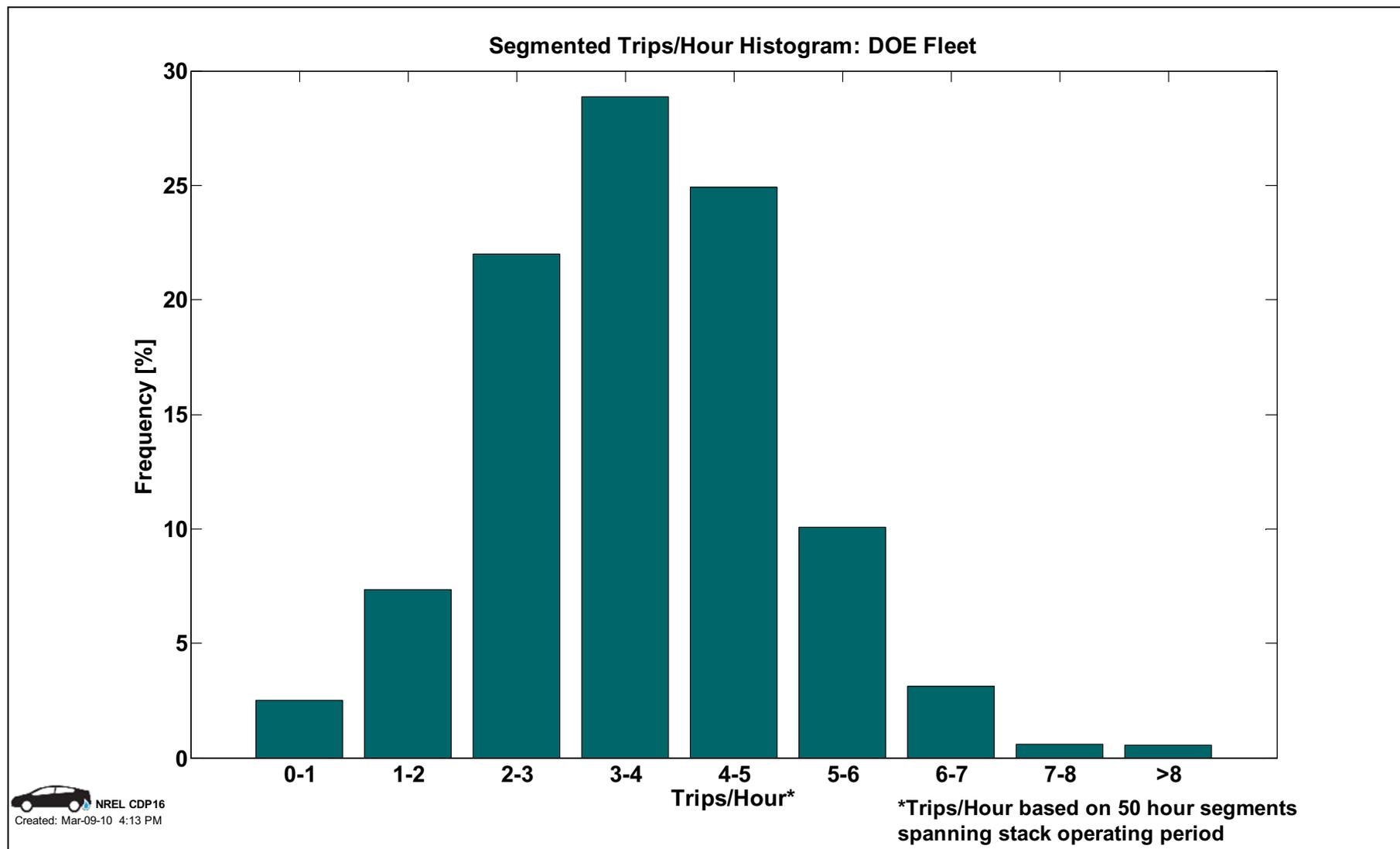
CDP#14: Fueling Rates – 350 and 700 bar



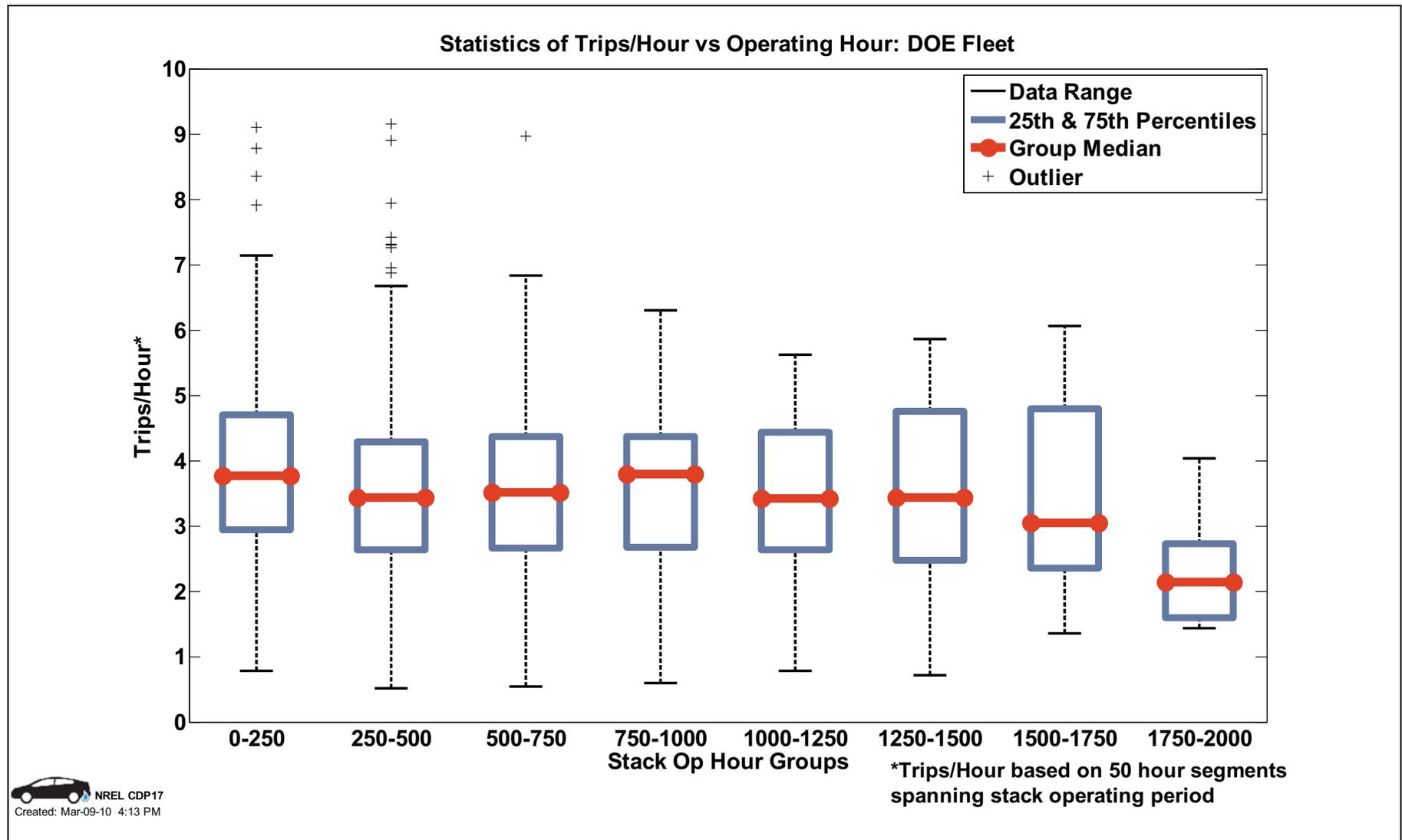
CDP#15: H2 Production Cost vs. Process



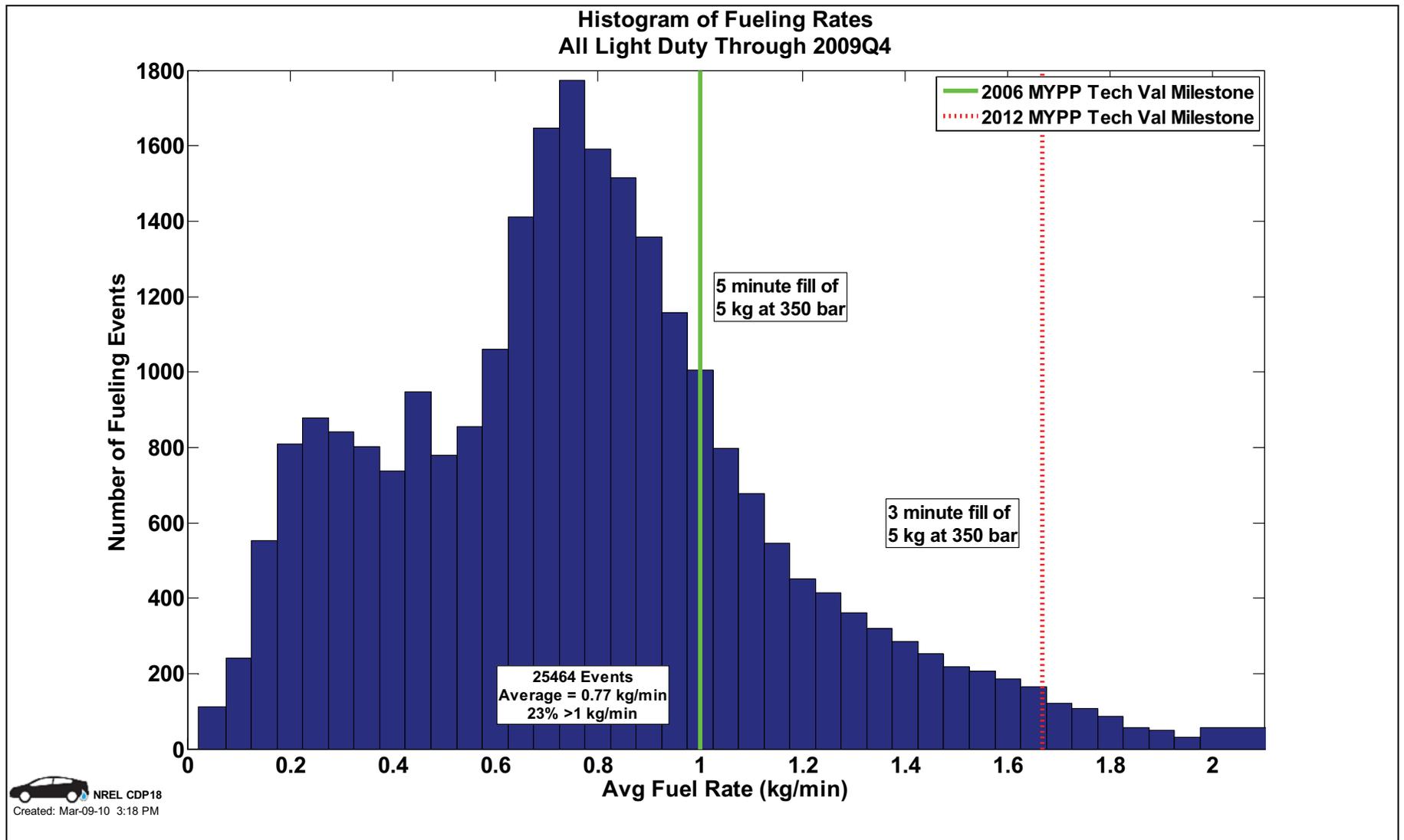
CDP#16: Fuel Cell Stack Trips Per Hour Histogram



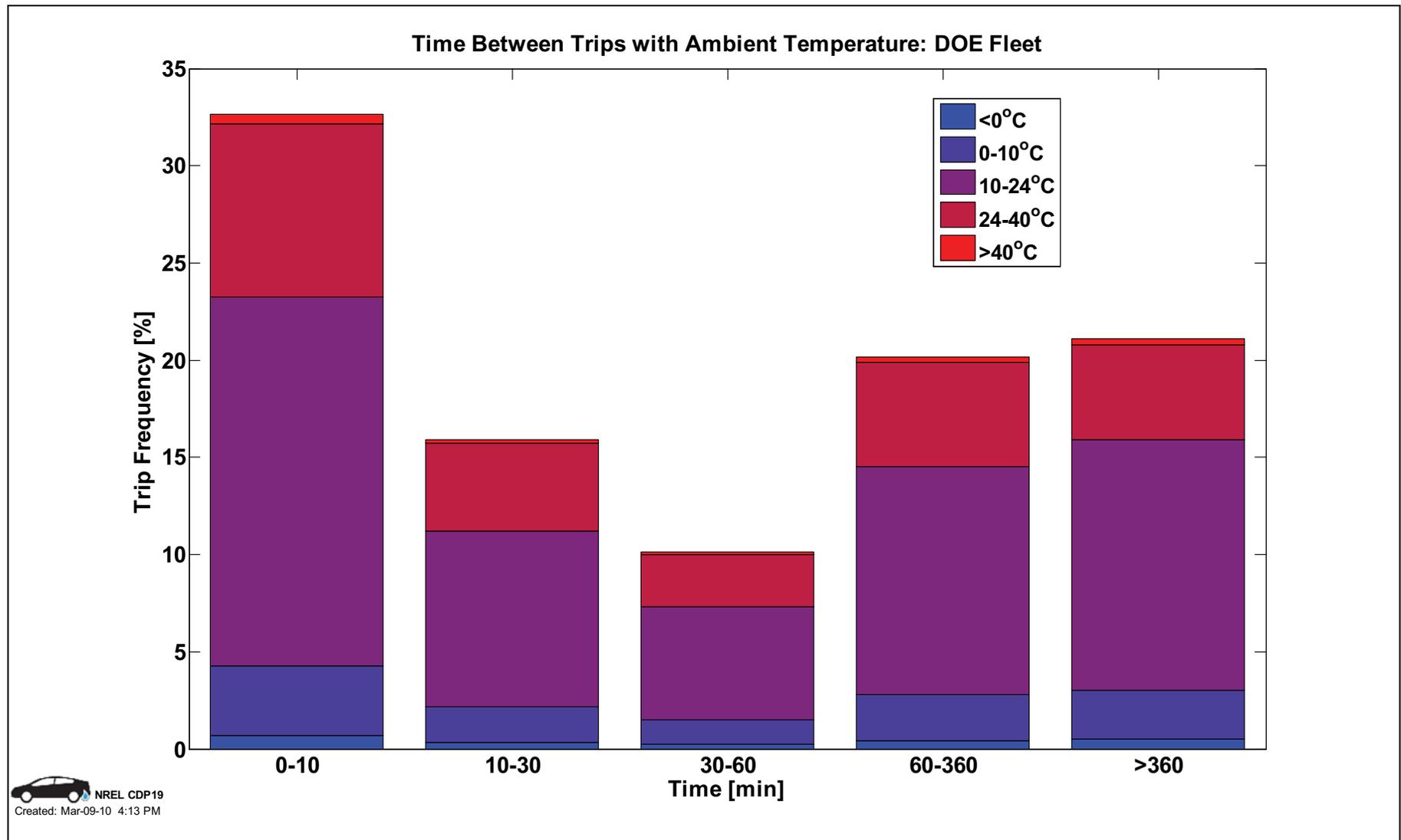
CDP#17: Statistics of Trips/Hour vs. Operating Hour



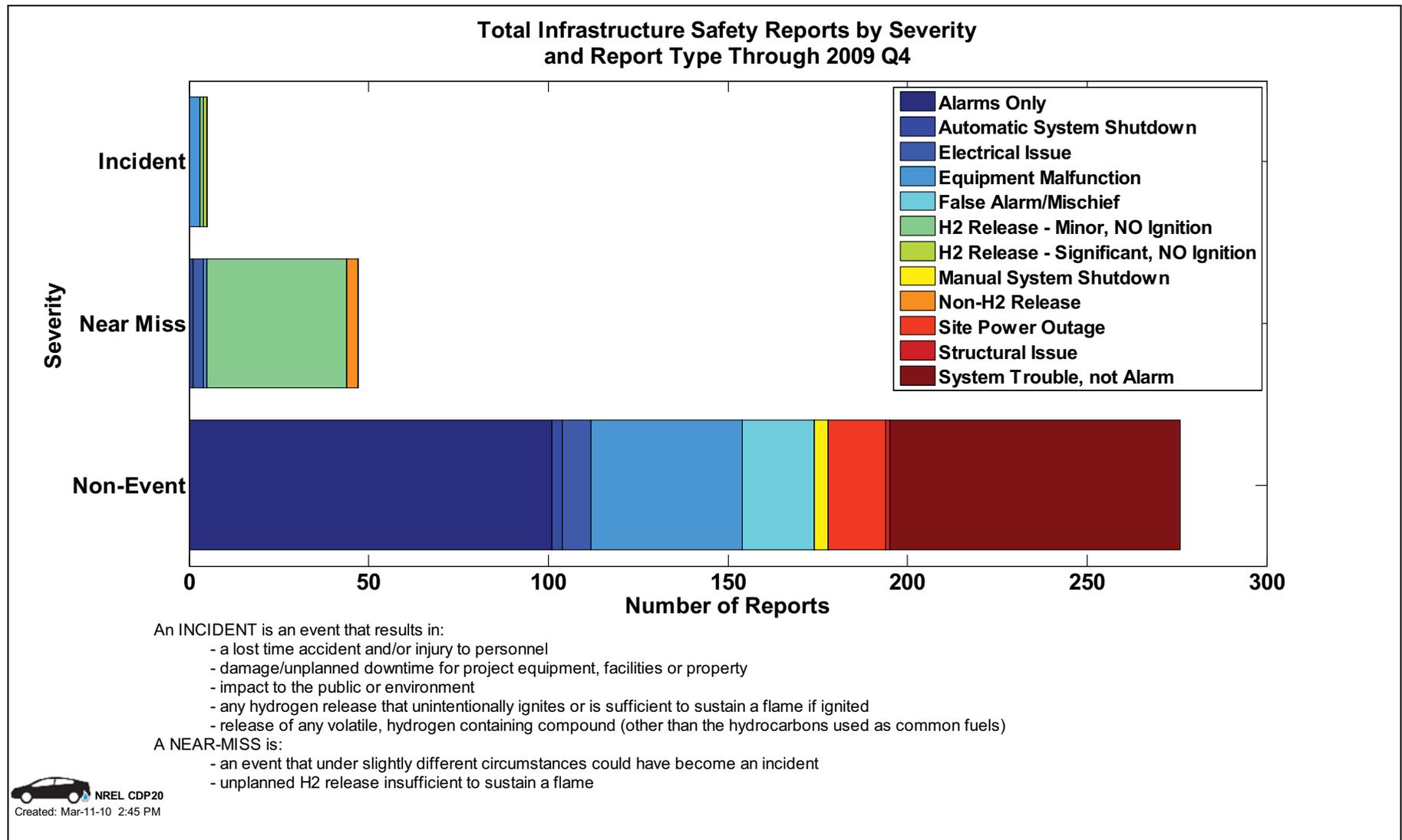
CDP#18: Refueling Rates



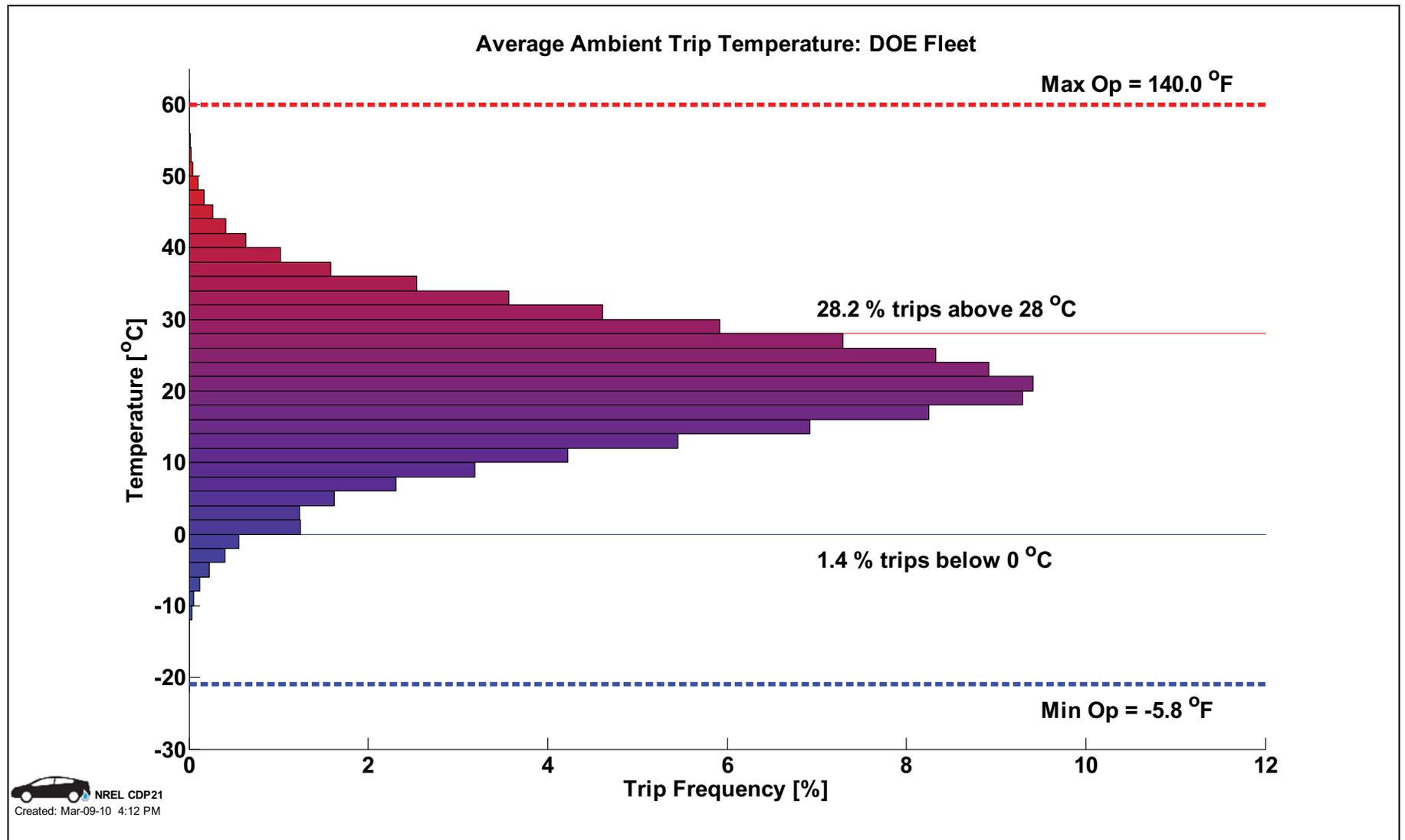
CDP#19: Time Between Trips & Ambient Temperature



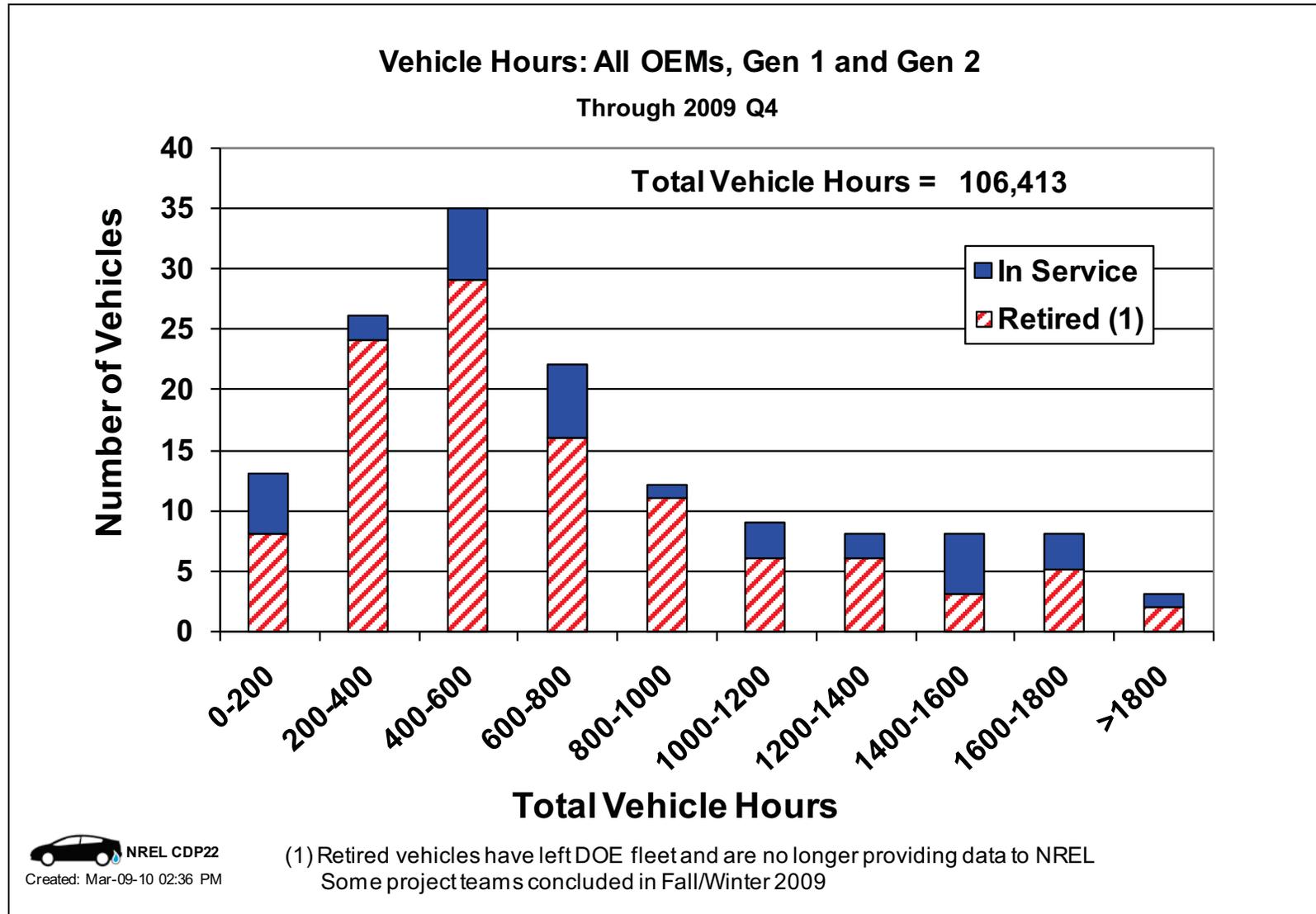
CDP#20: Safety Reports – Infrastructure



CDP#21: Range of Ambient Temperature During Vehicle Operation

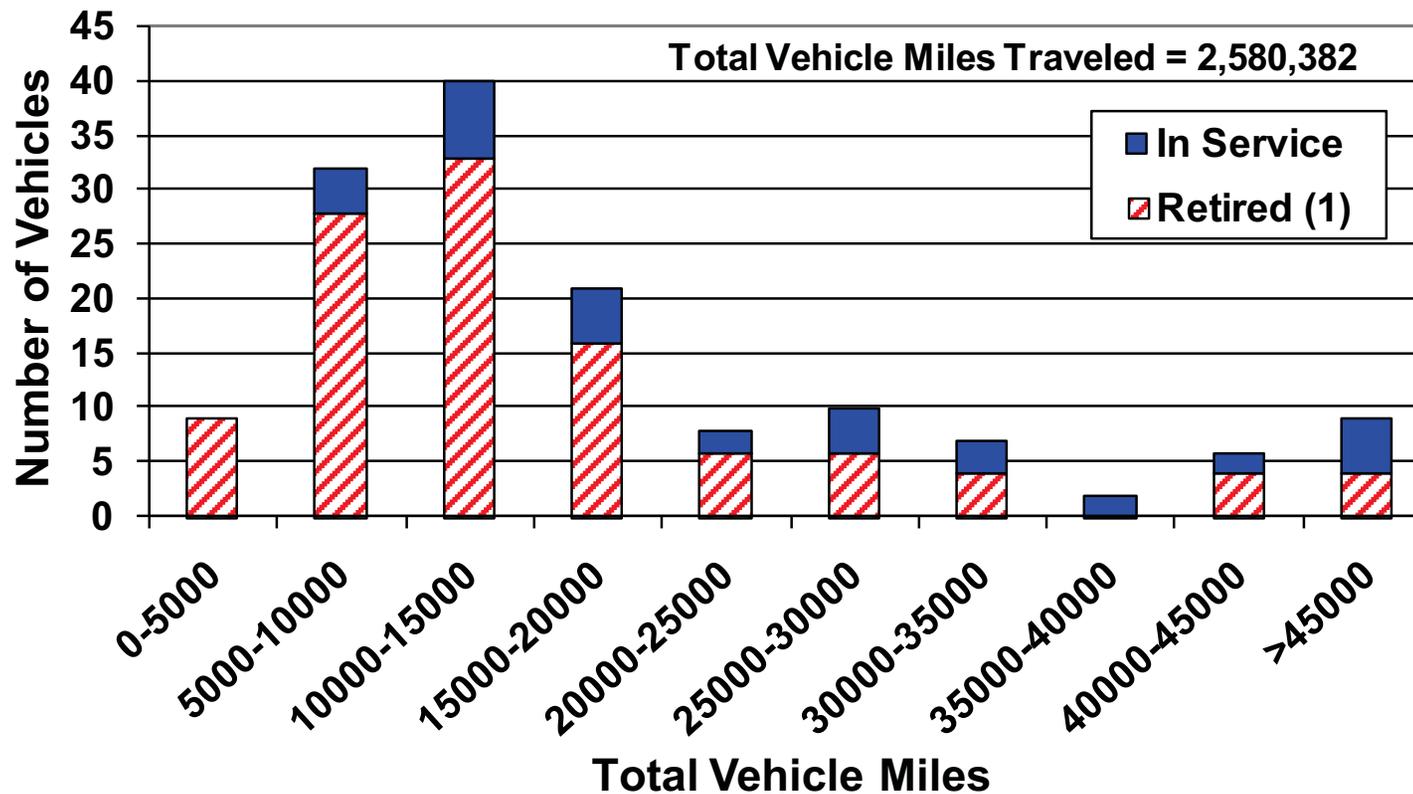


CDP#22: Vehicle Operating Hours



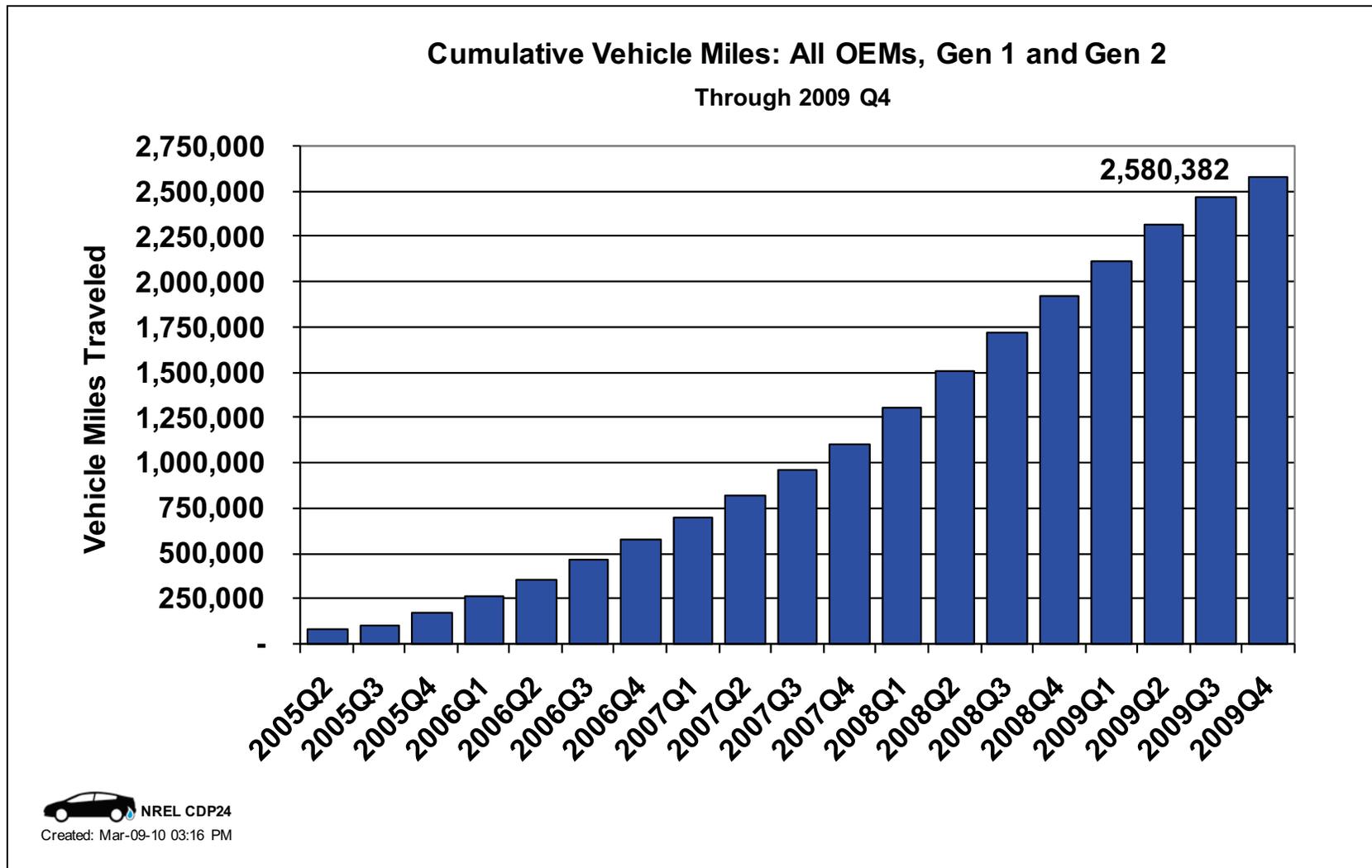
CDP#23: Vehicles vs. Miles Traveled

Vehicle Miles: All OEMs, Gen 1 and 2
Through 2009 Q4

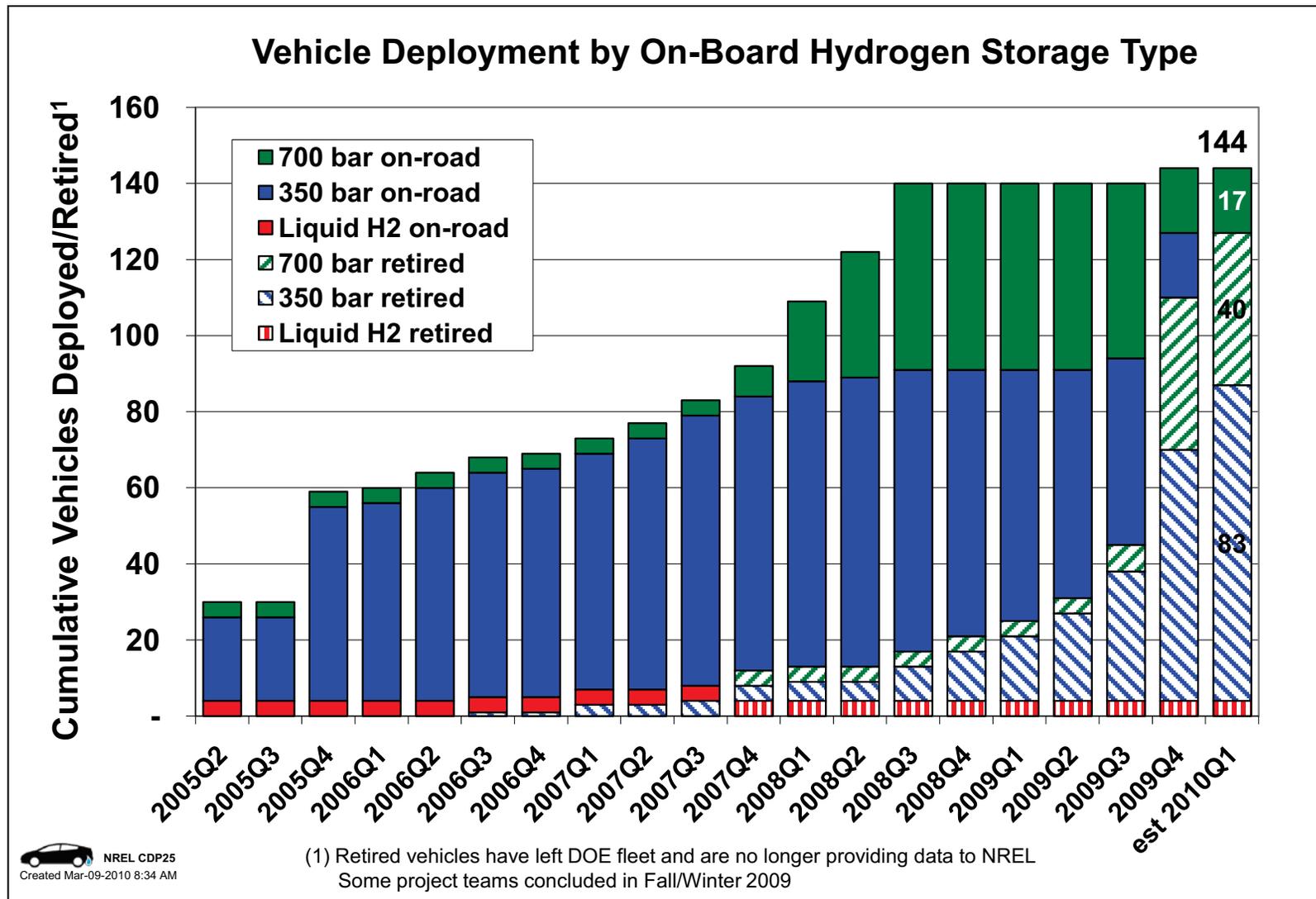


(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
Some project teams concluded in Fall/Winter 2009

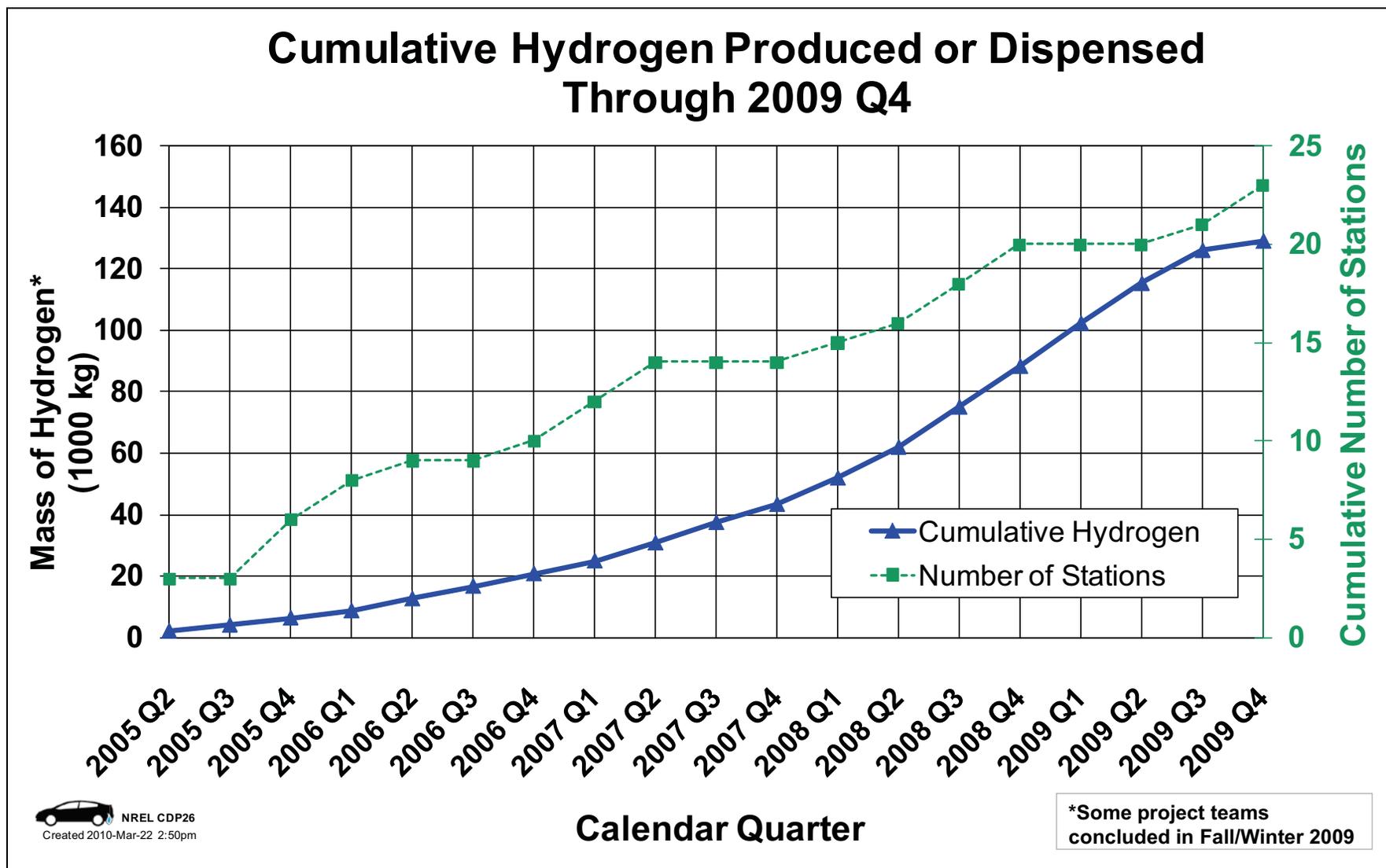
CDP#24: Cumulative Vehicle Miles Traveled



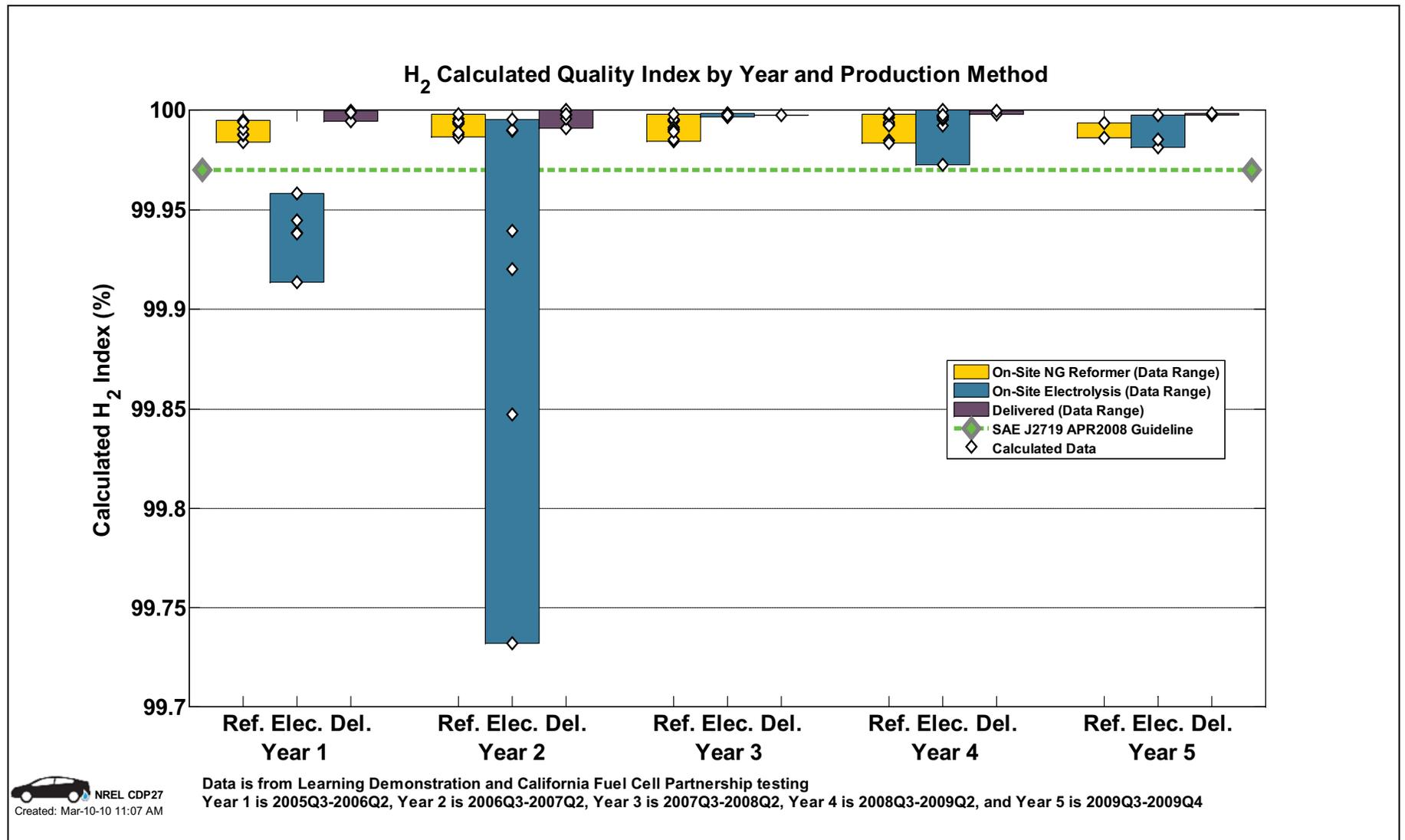
CDP#25: Vehicle H2 Storage Technologies



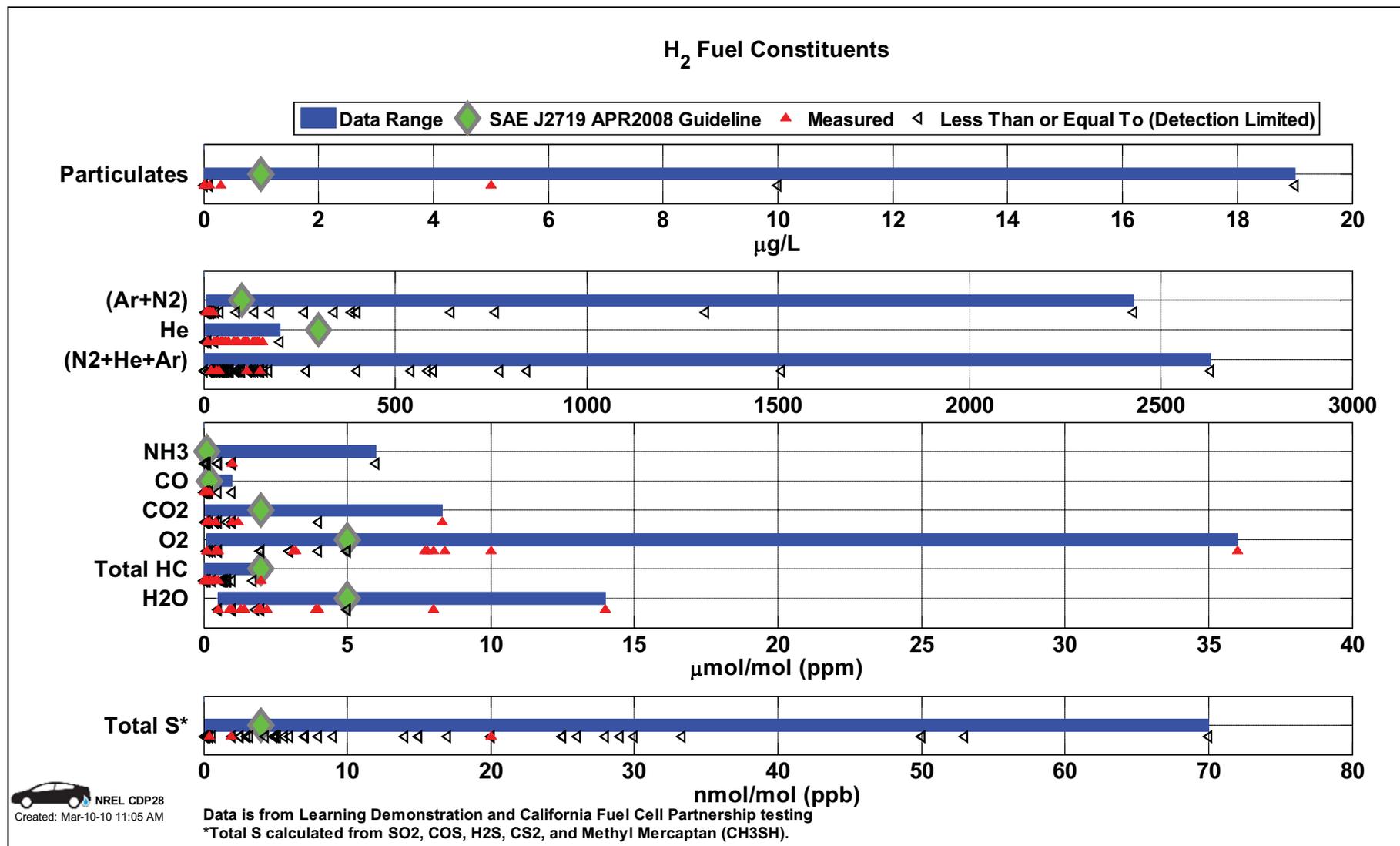
CDP#26: Cumulative H2 Produced or Dispensed



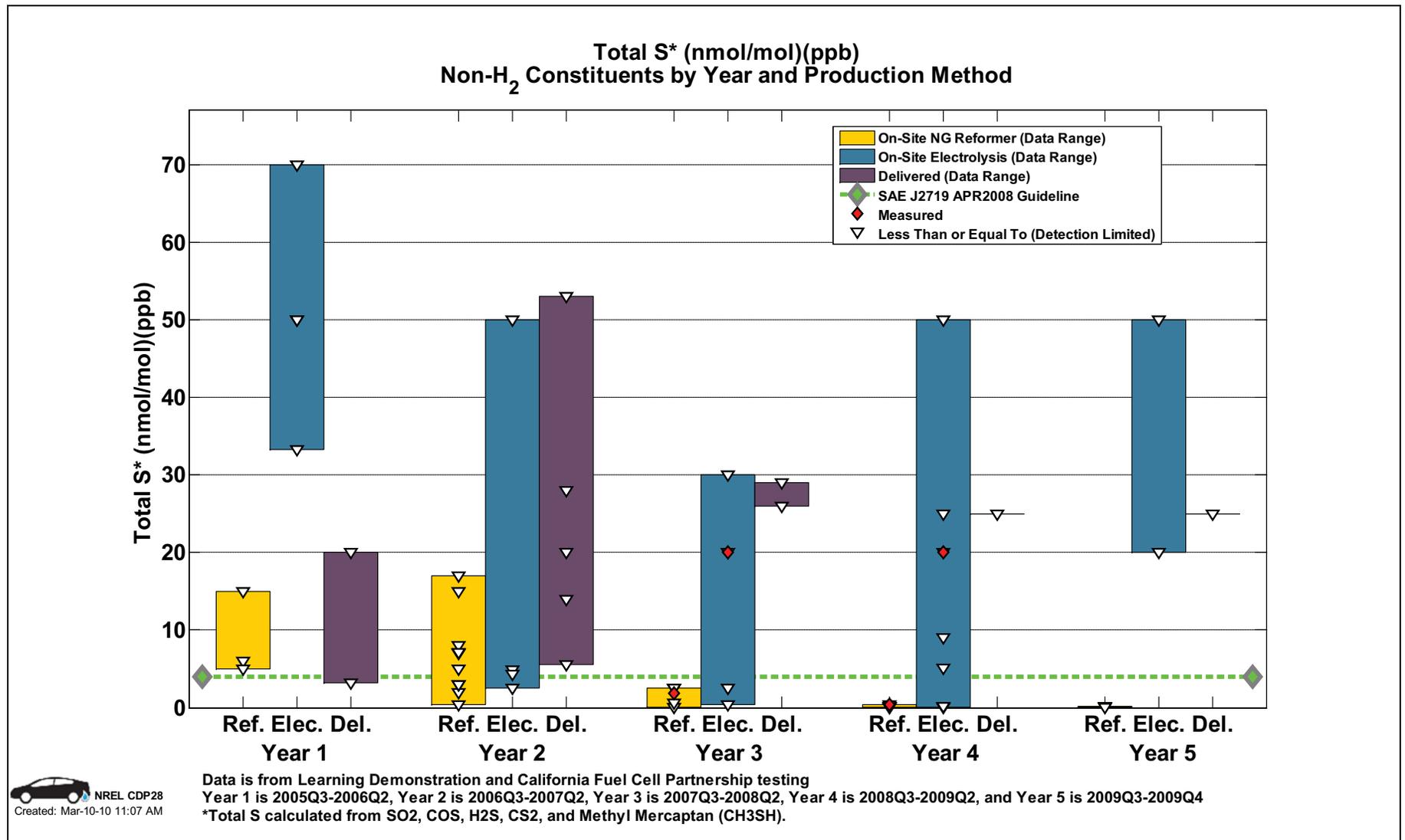
CDP#27: Hydrogen Quality Index



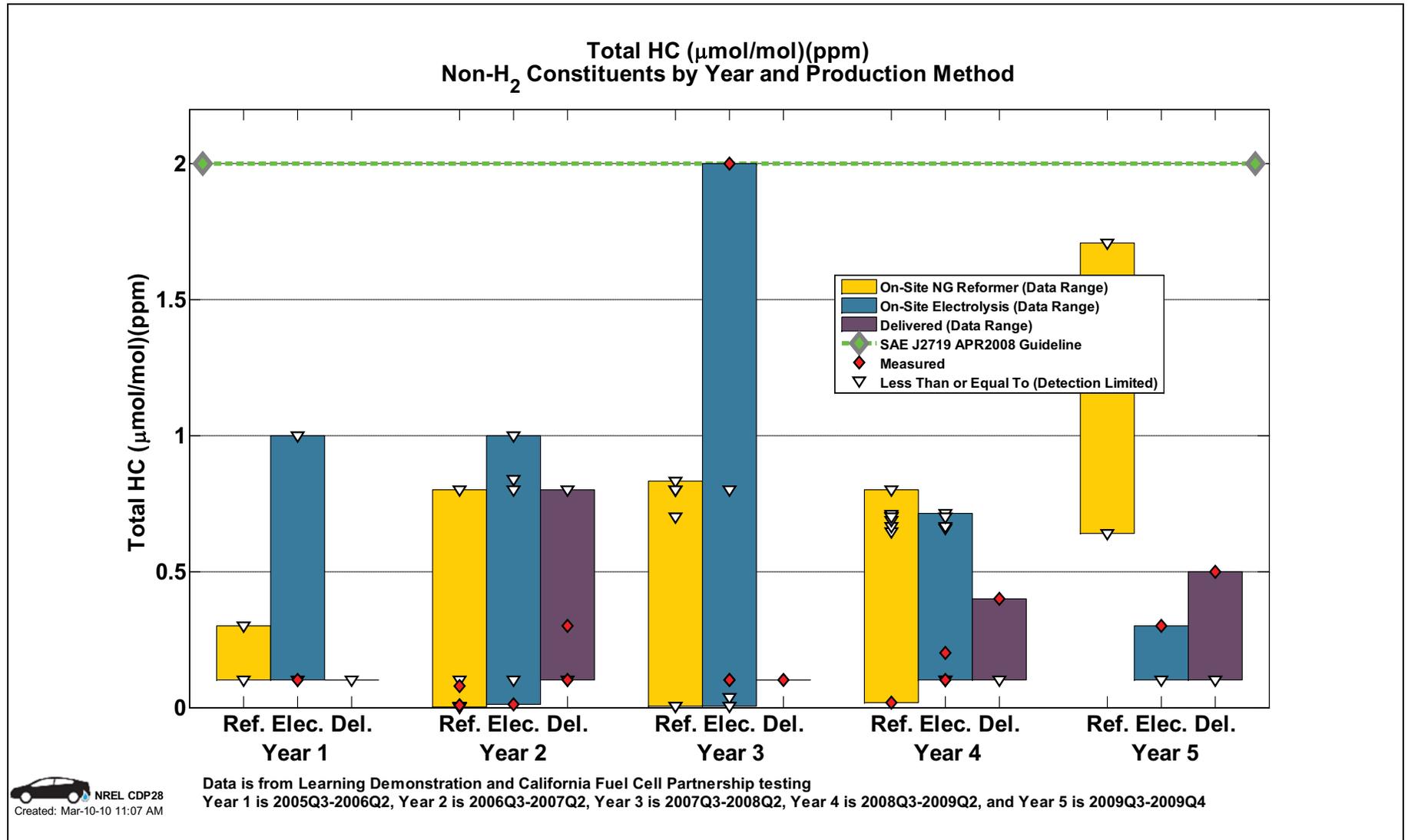
CDP#28: Hydrogen Fuel Constituents



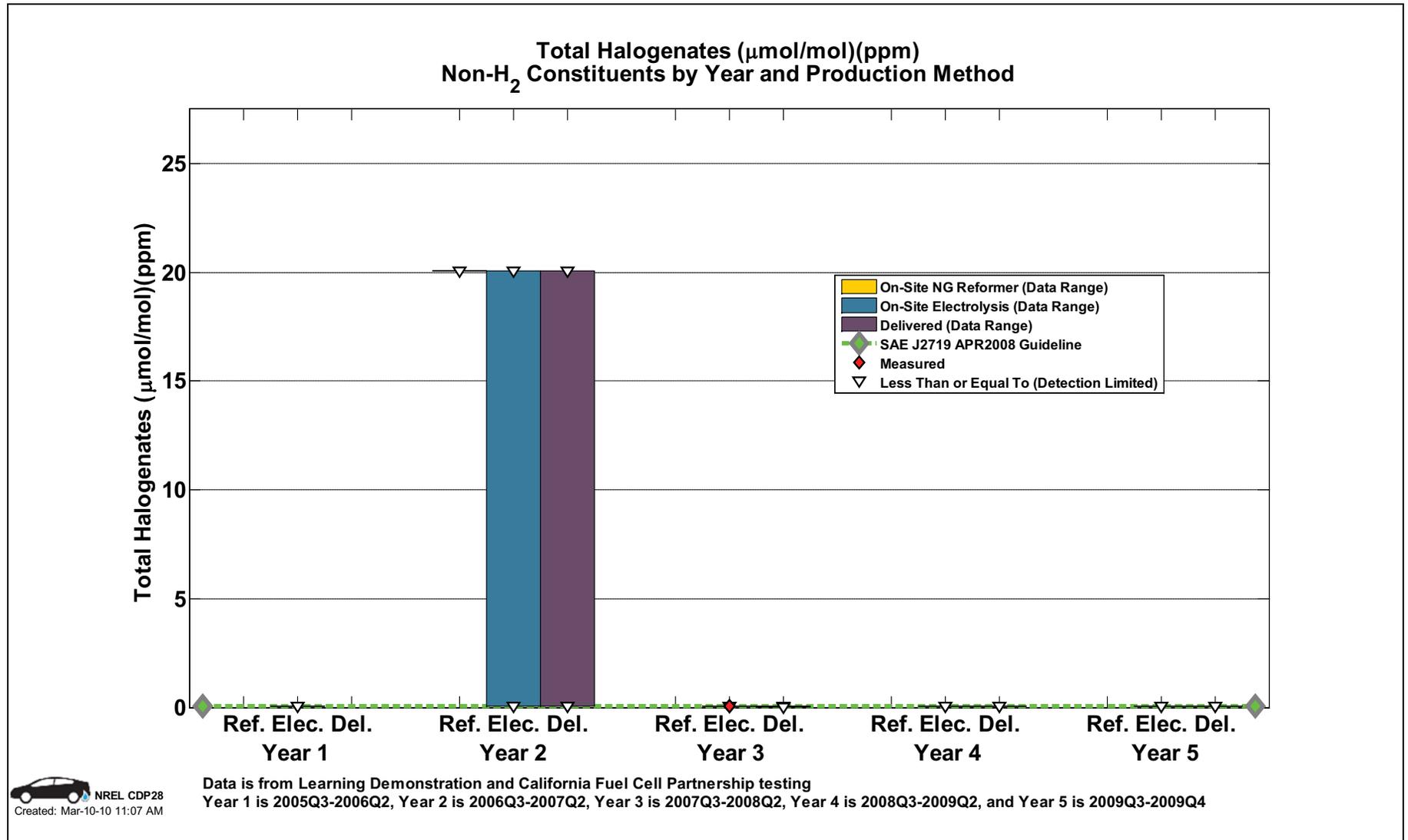
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



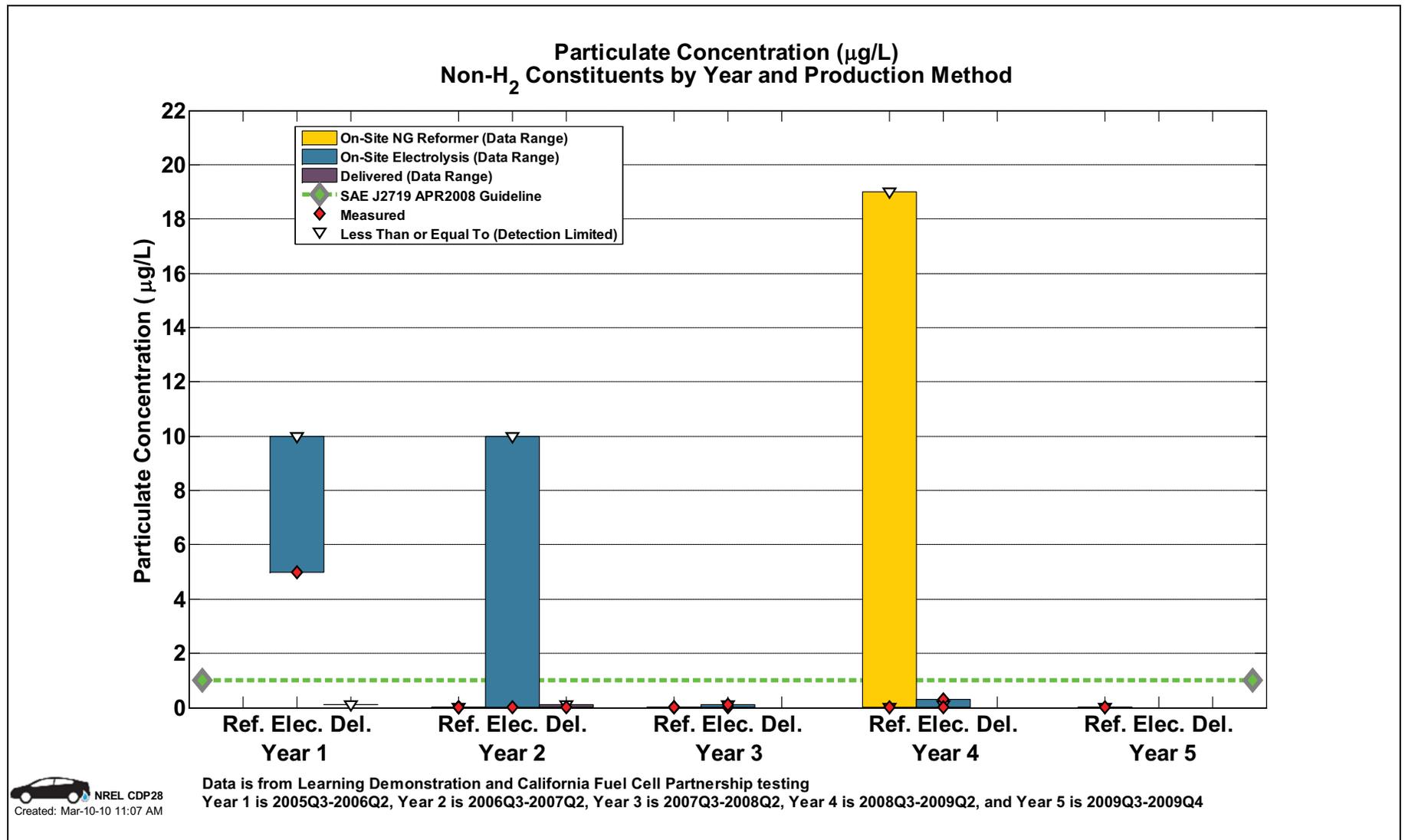
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



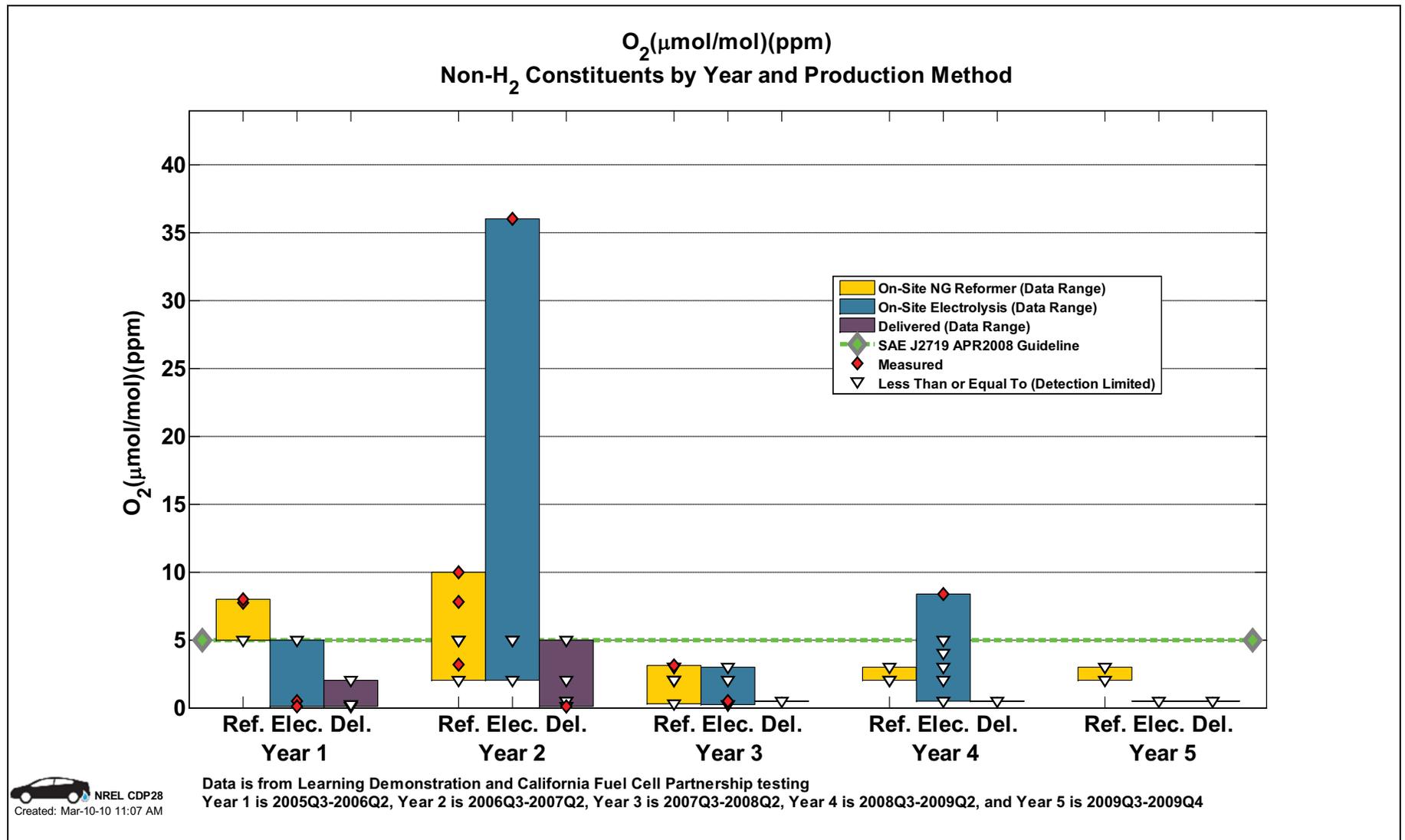
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



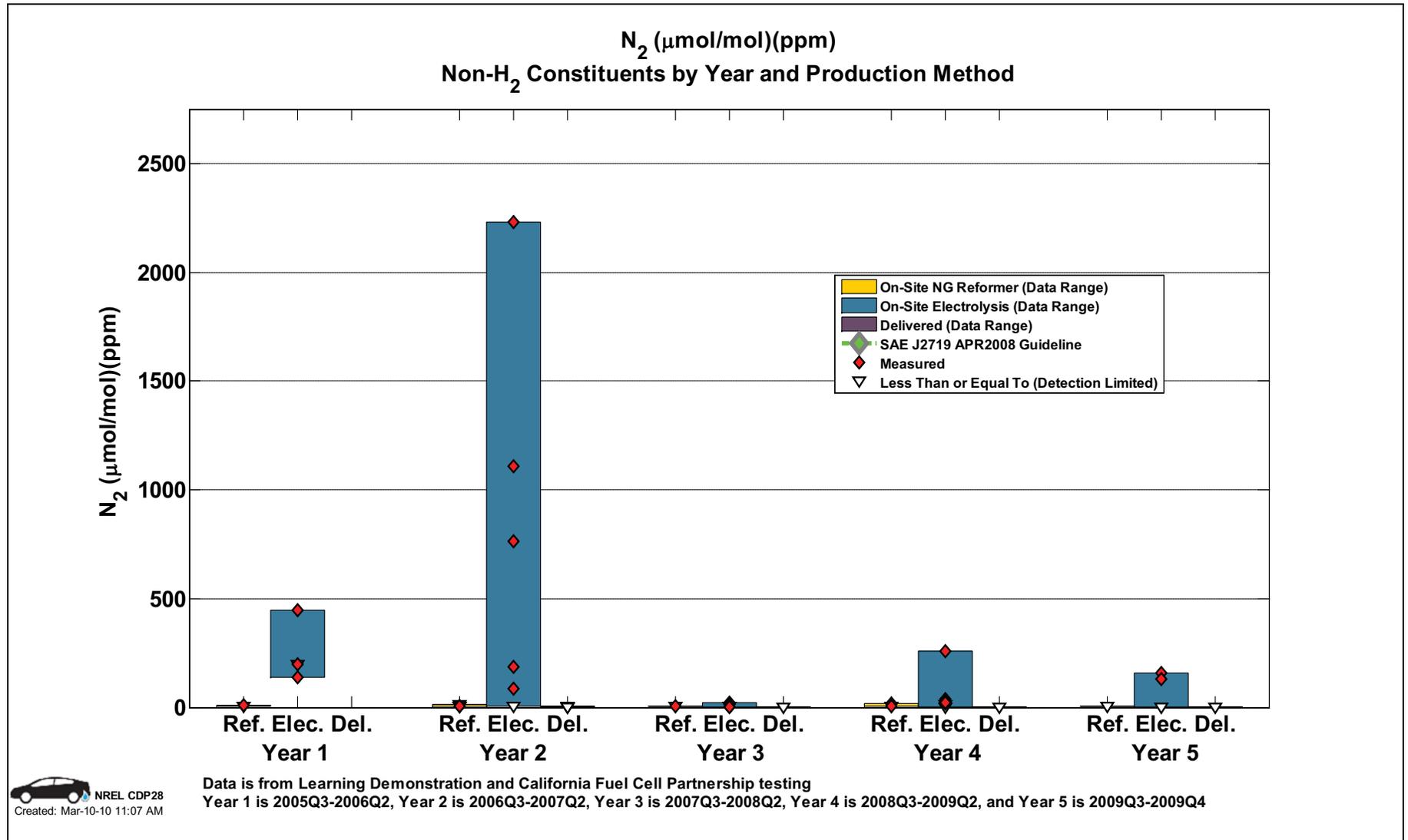
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



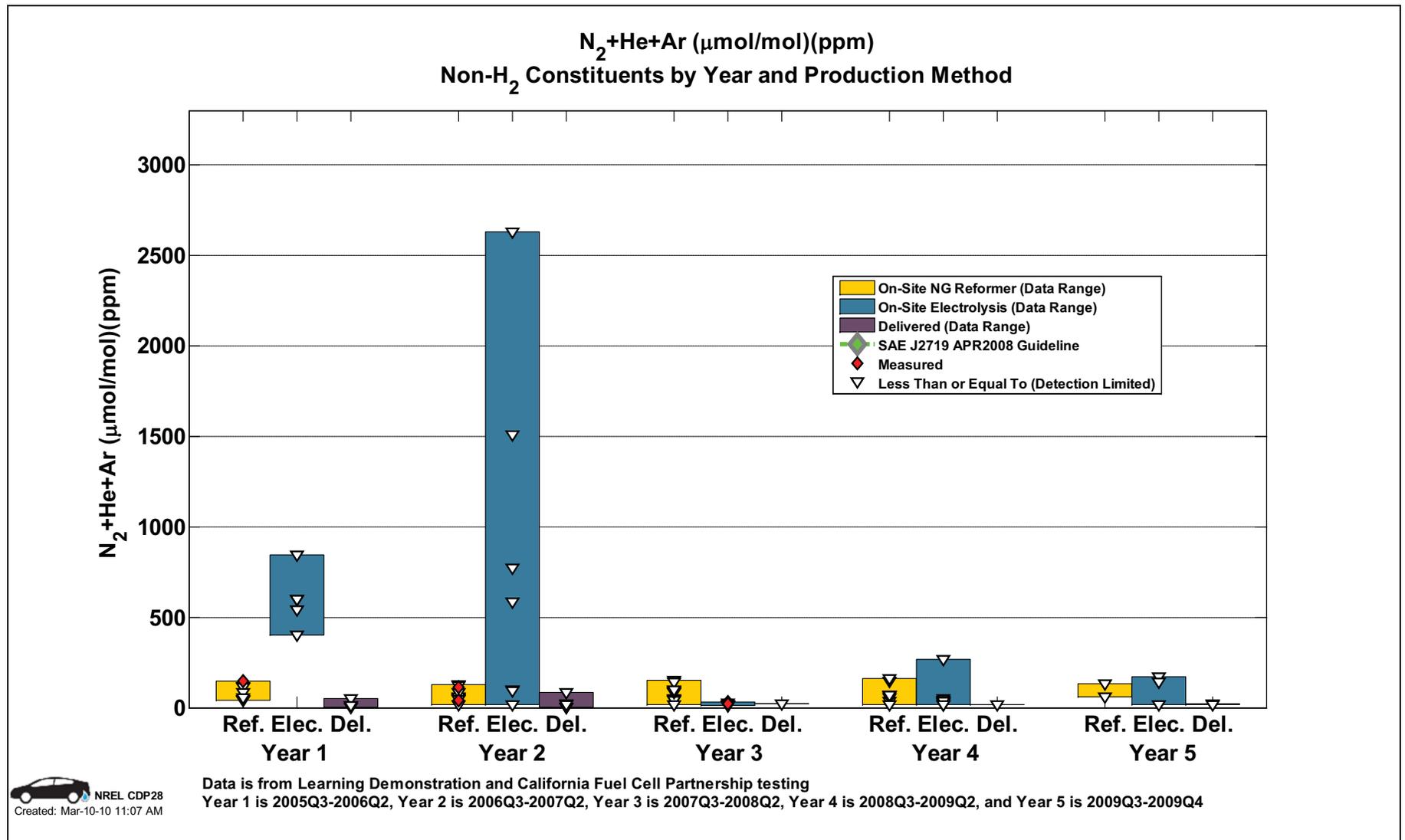
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



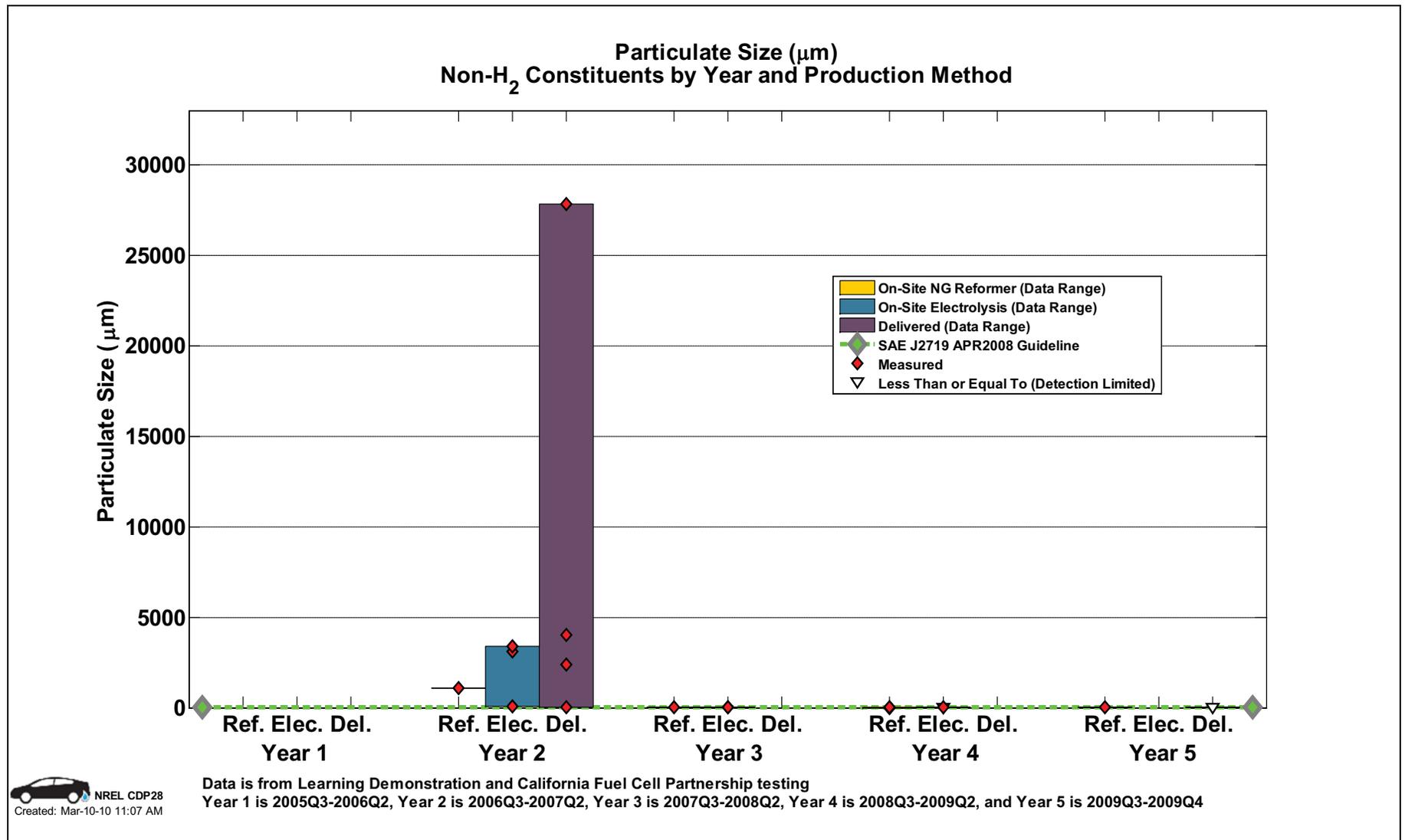
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



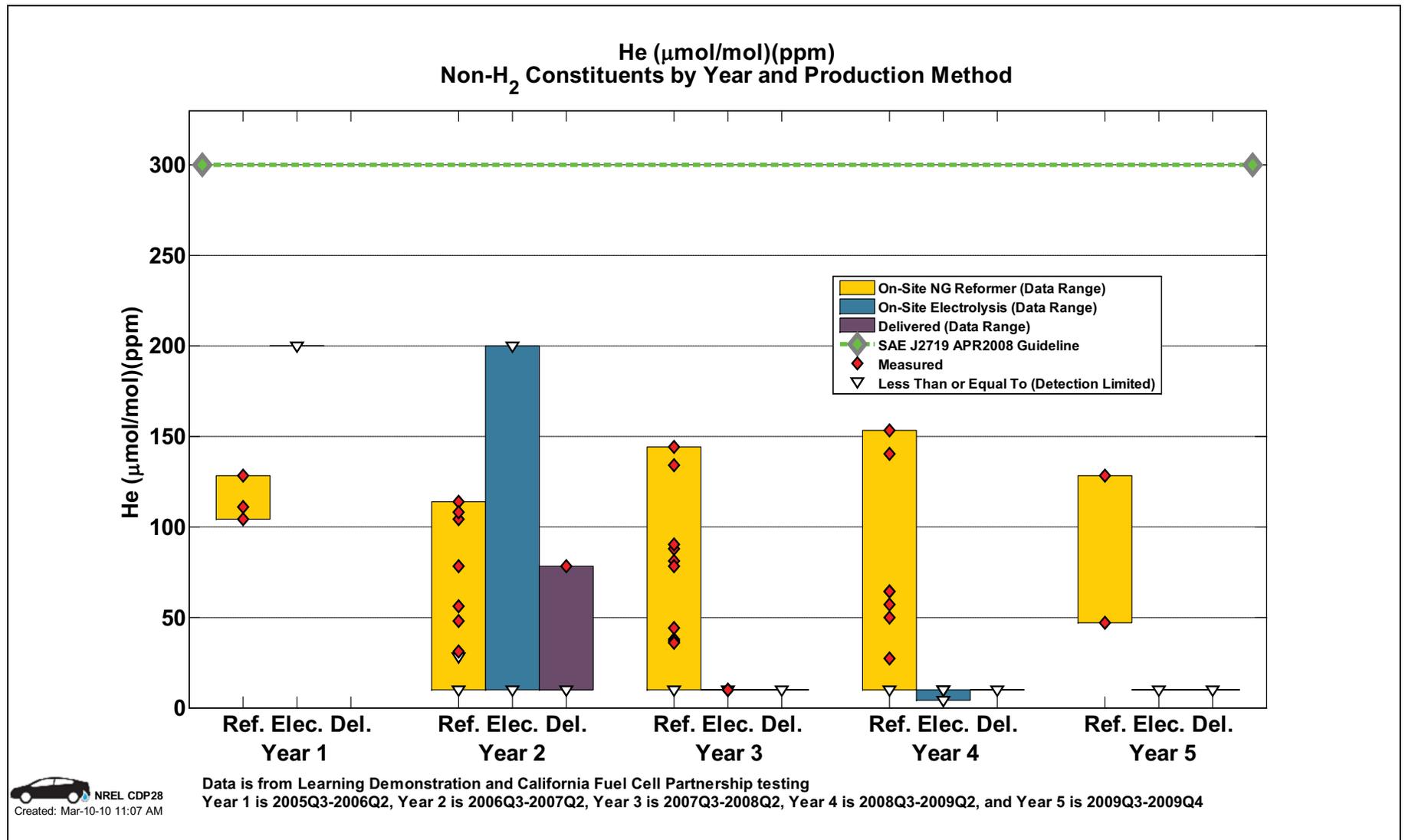
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



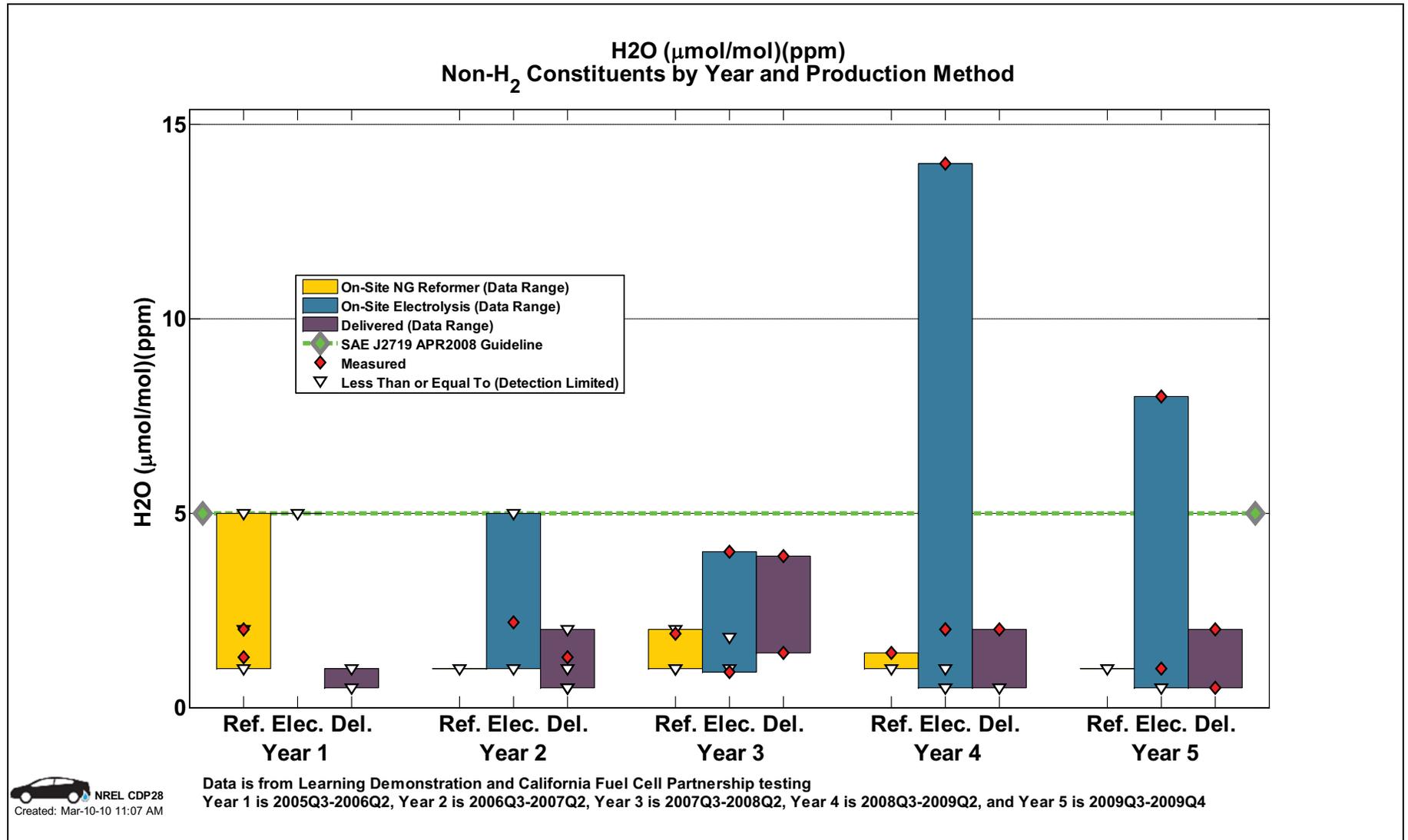
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



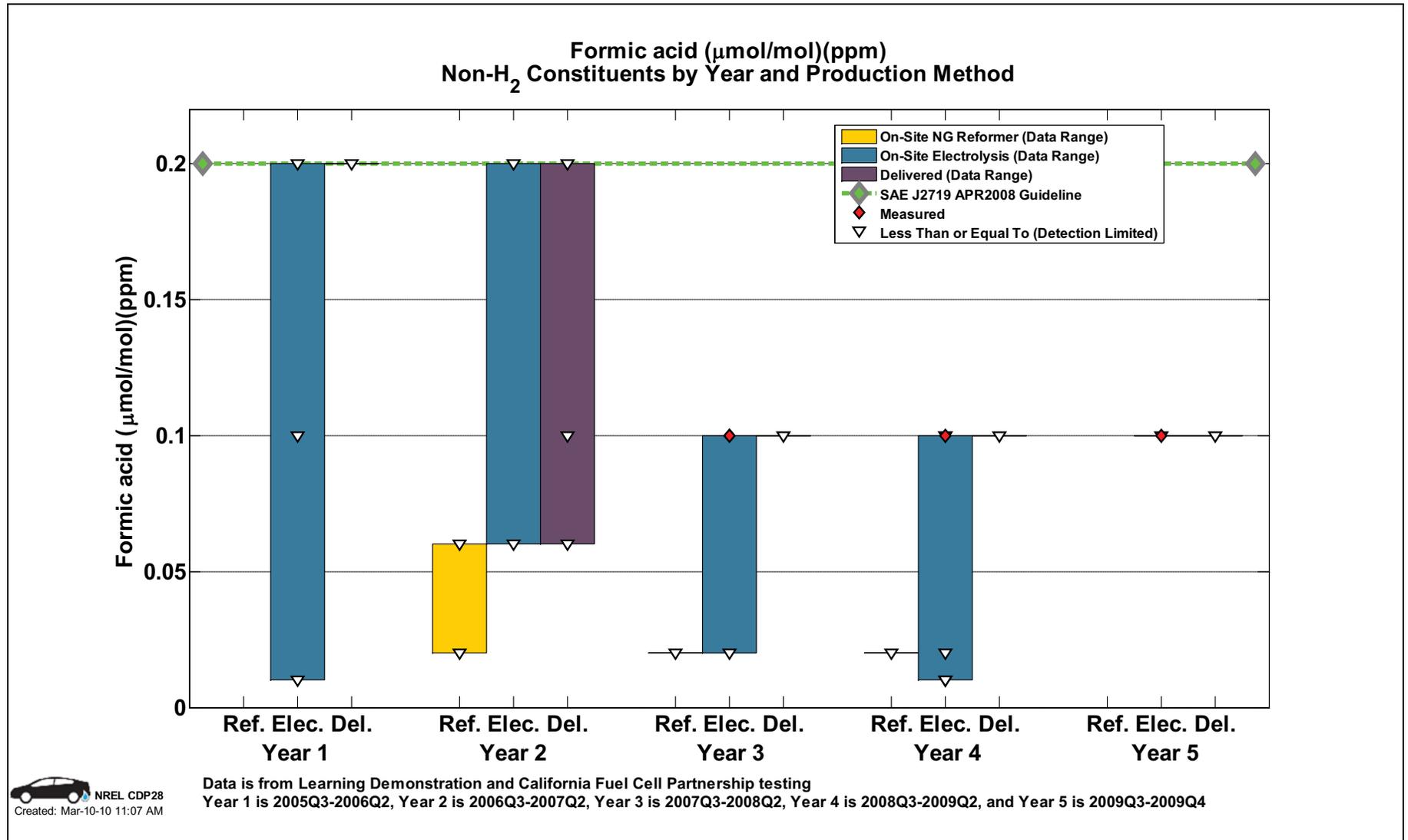
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



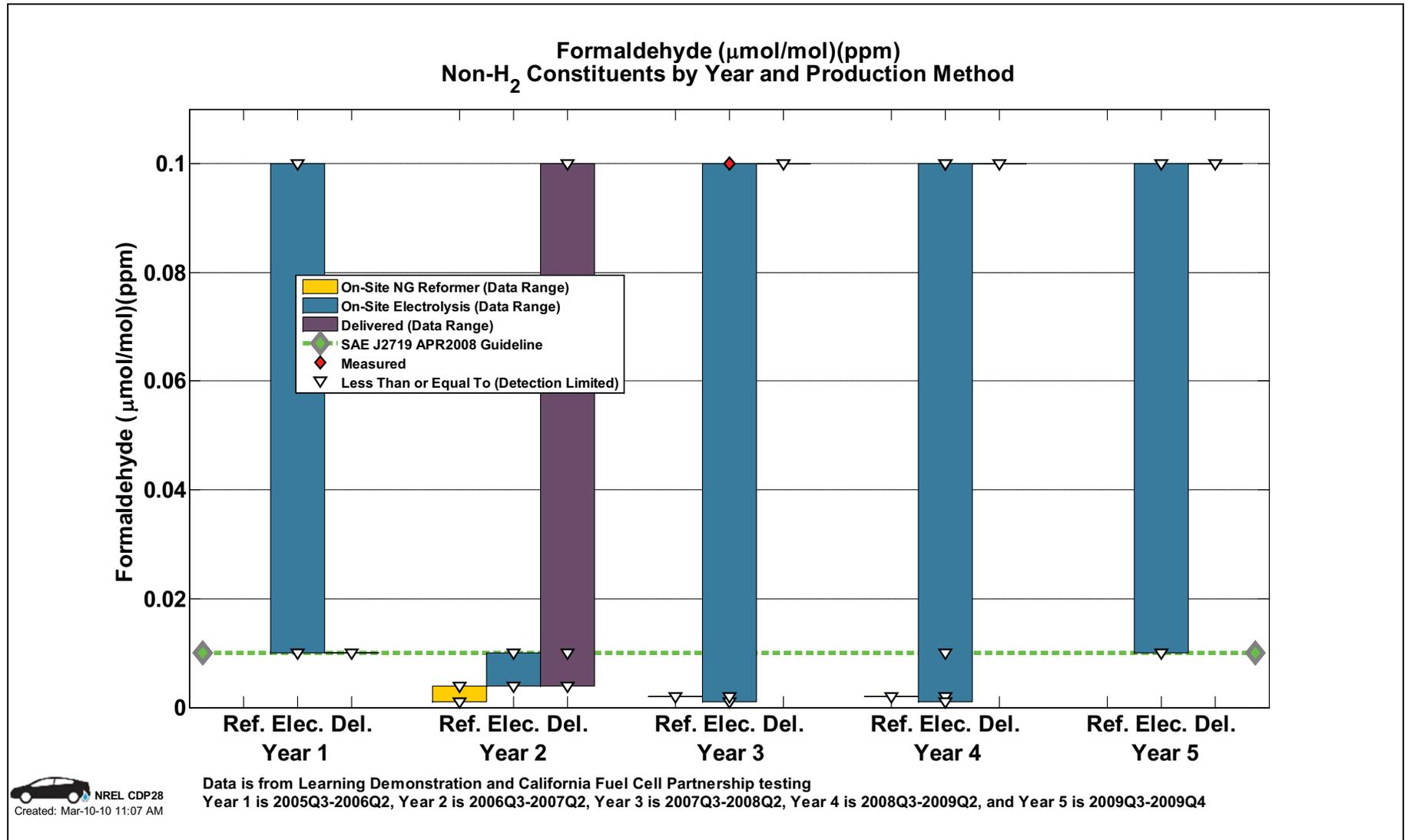
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



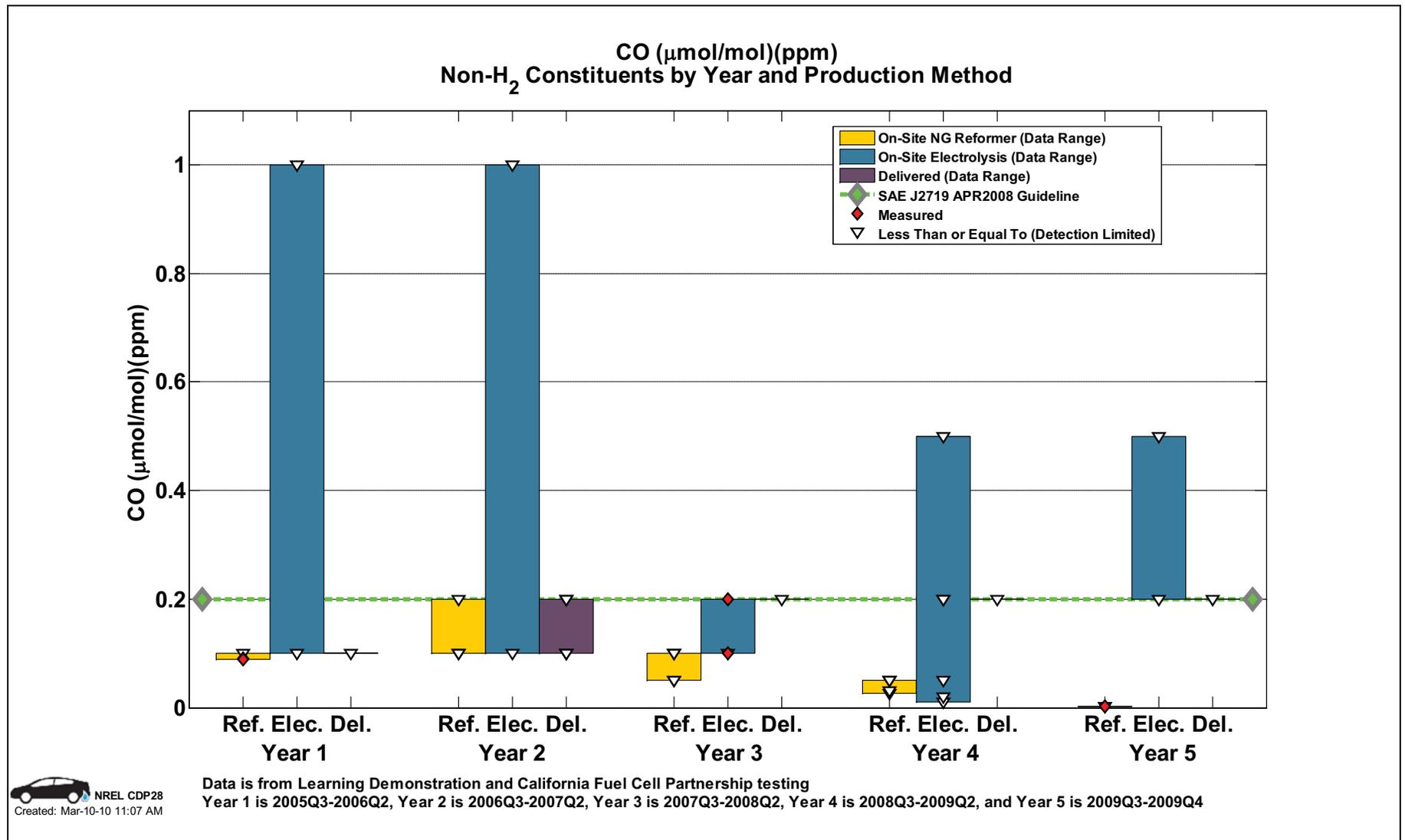
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



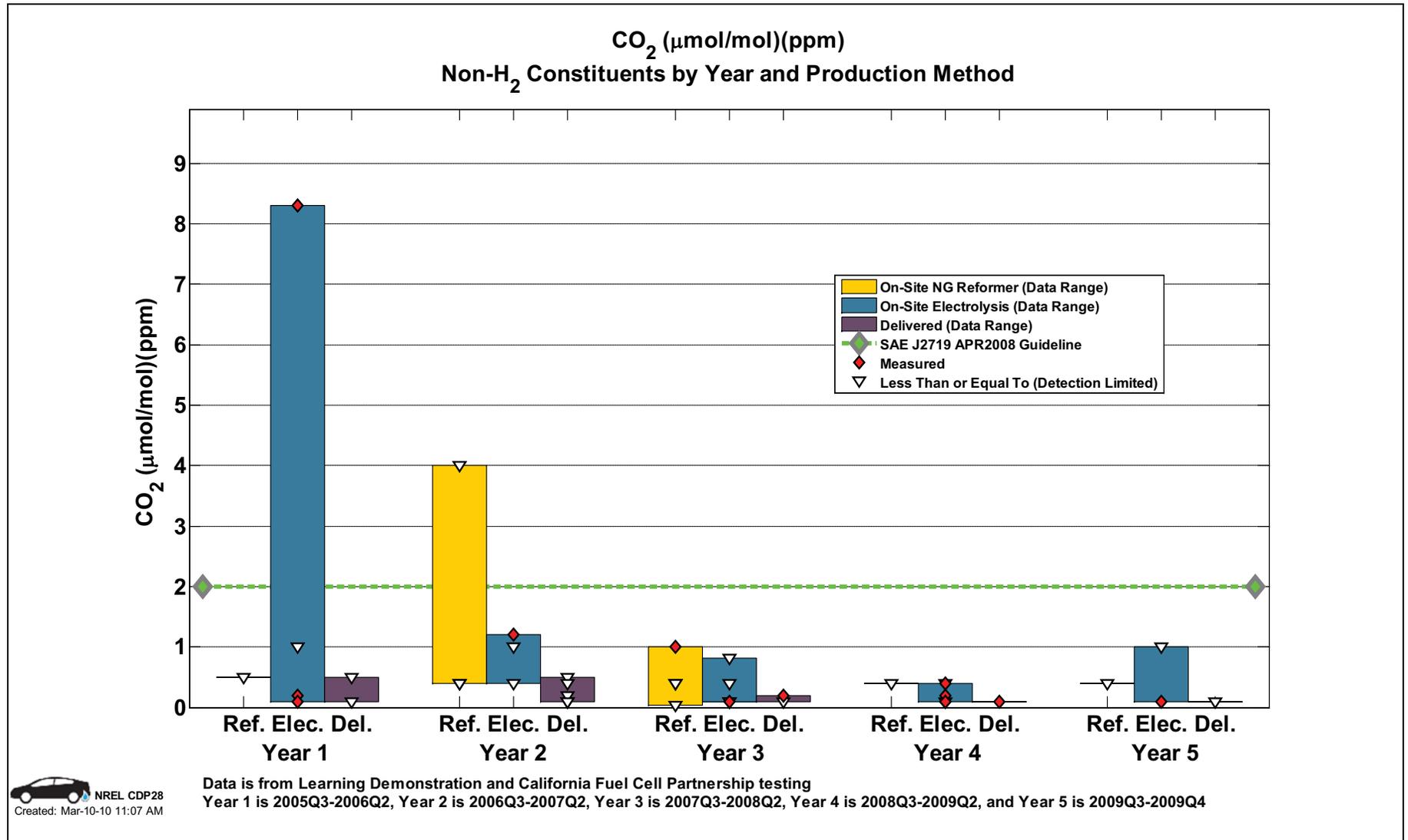
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



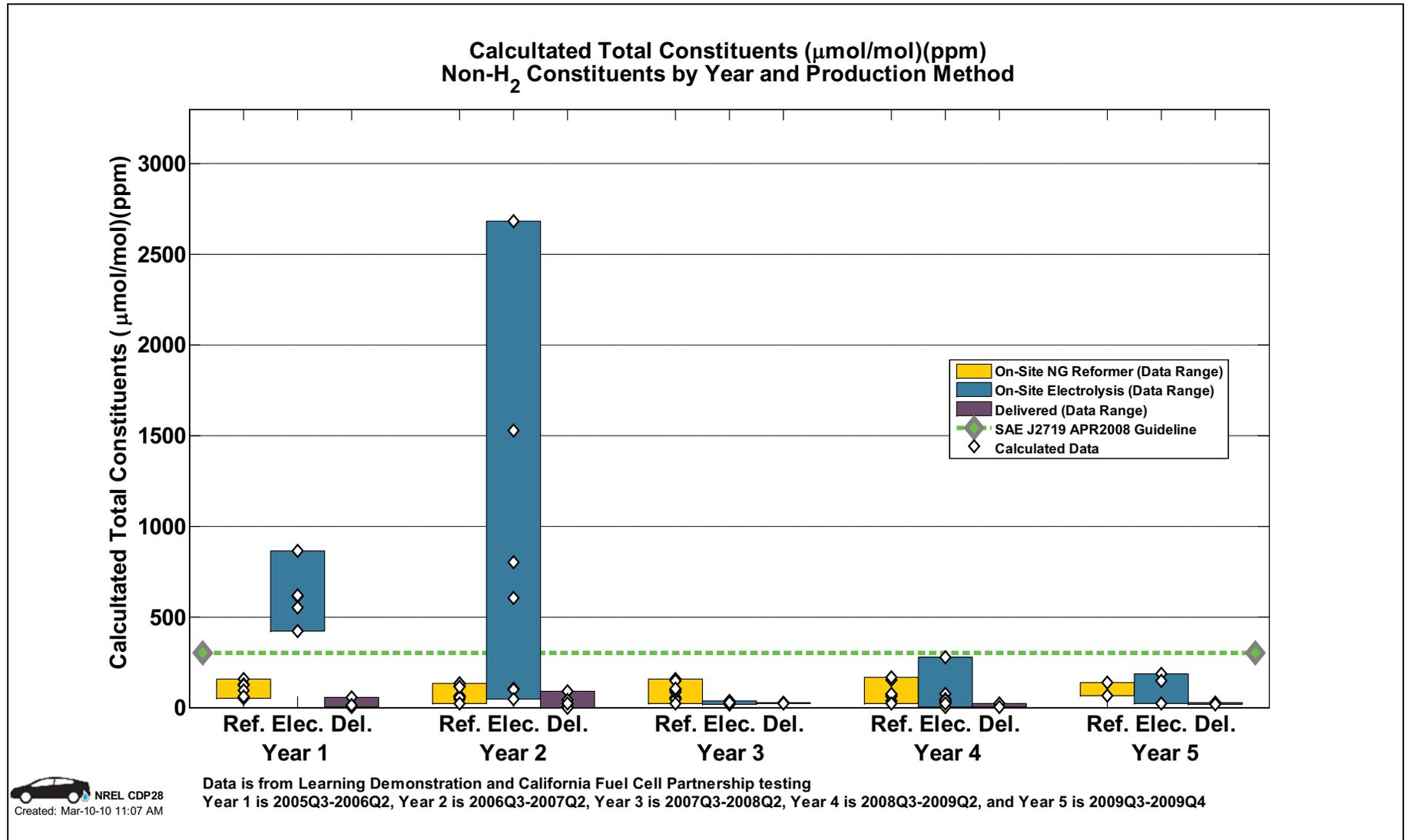
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



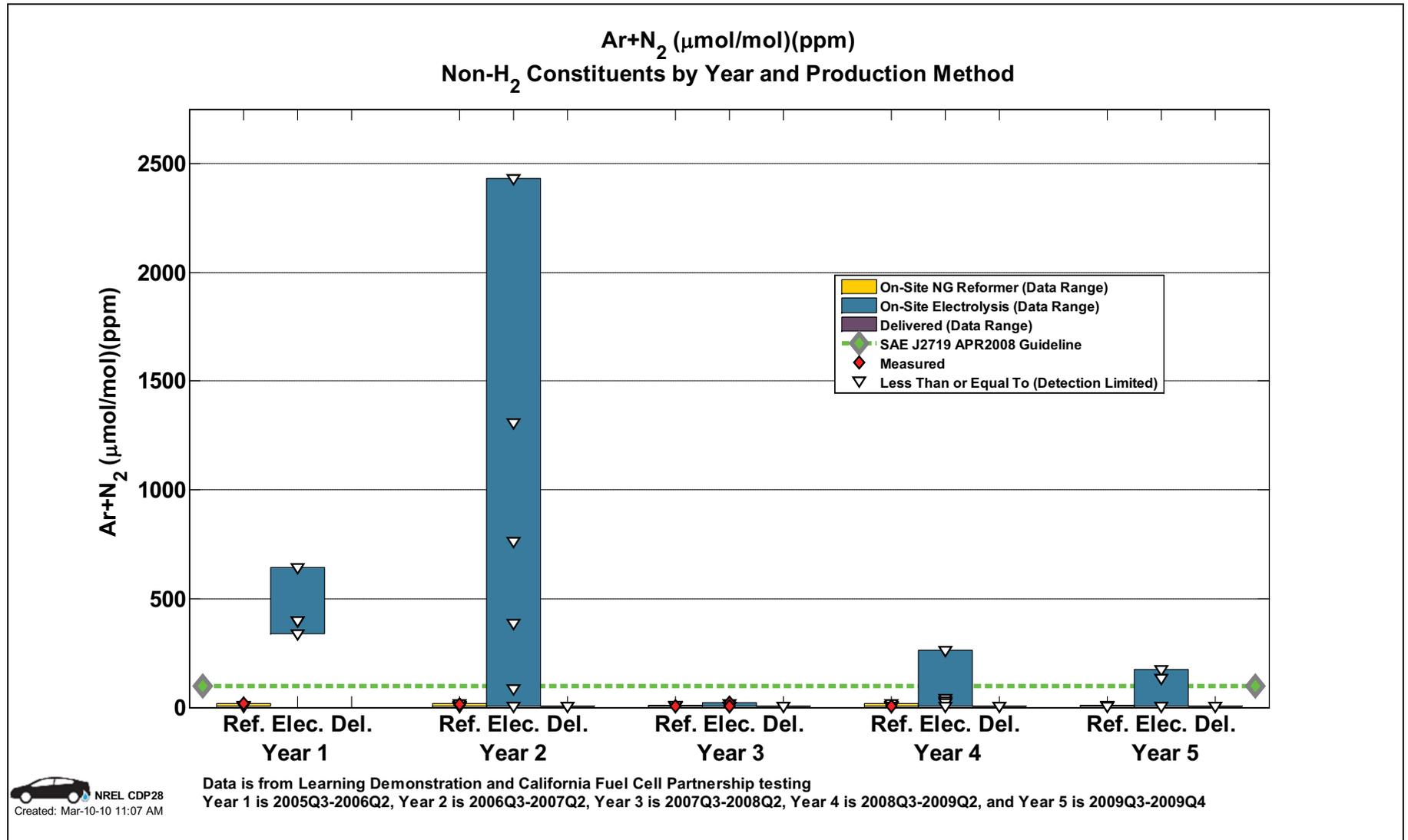
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



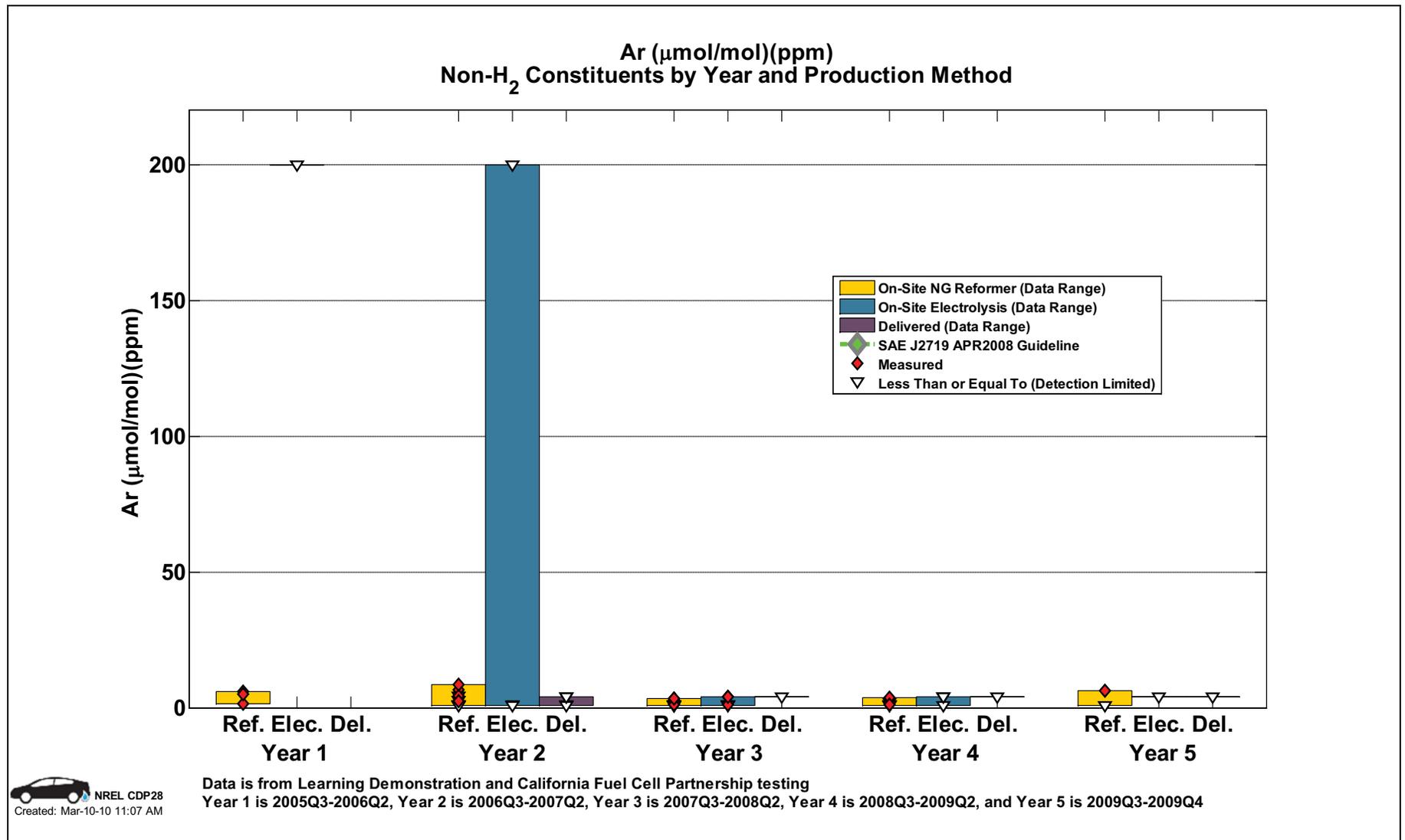
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



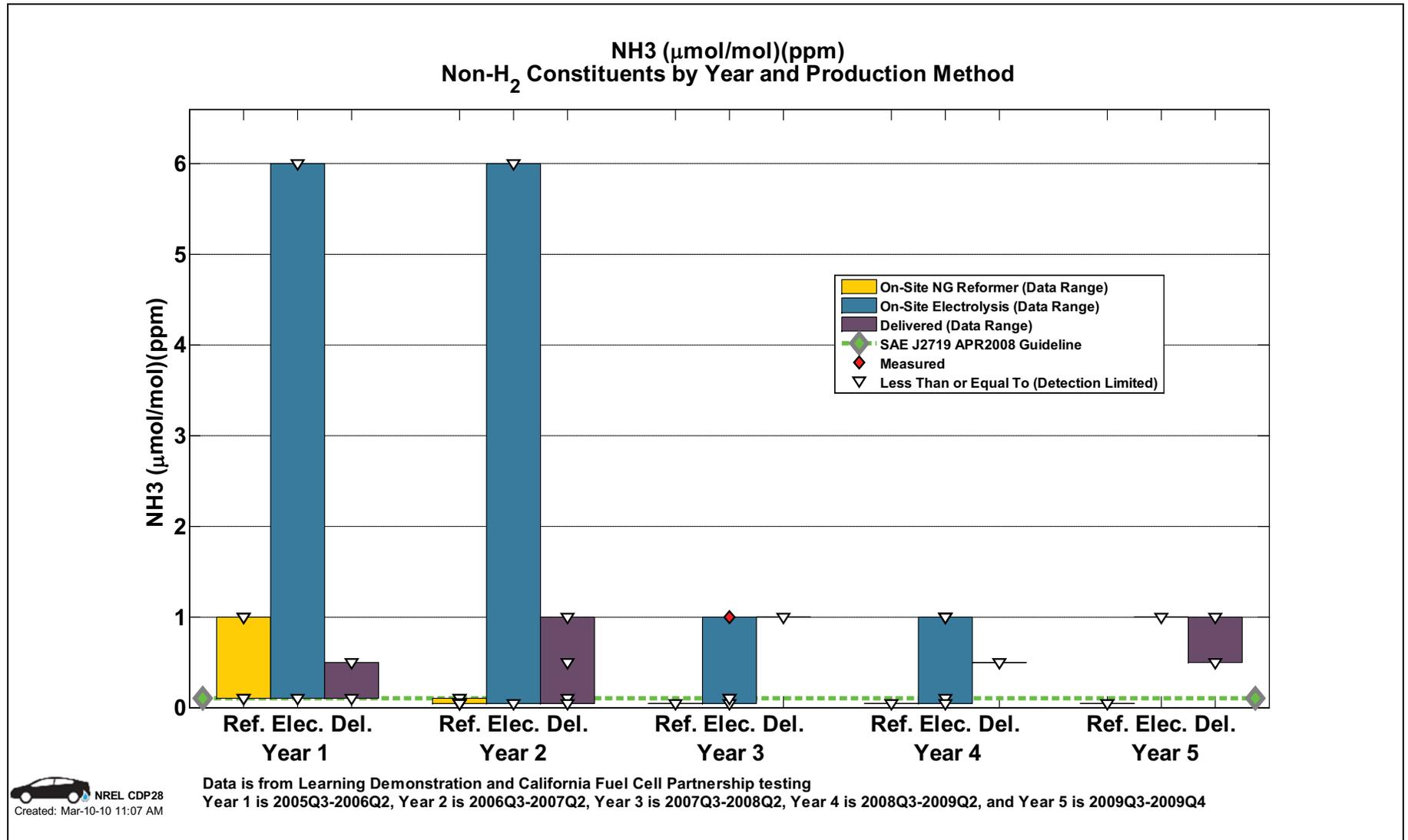
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



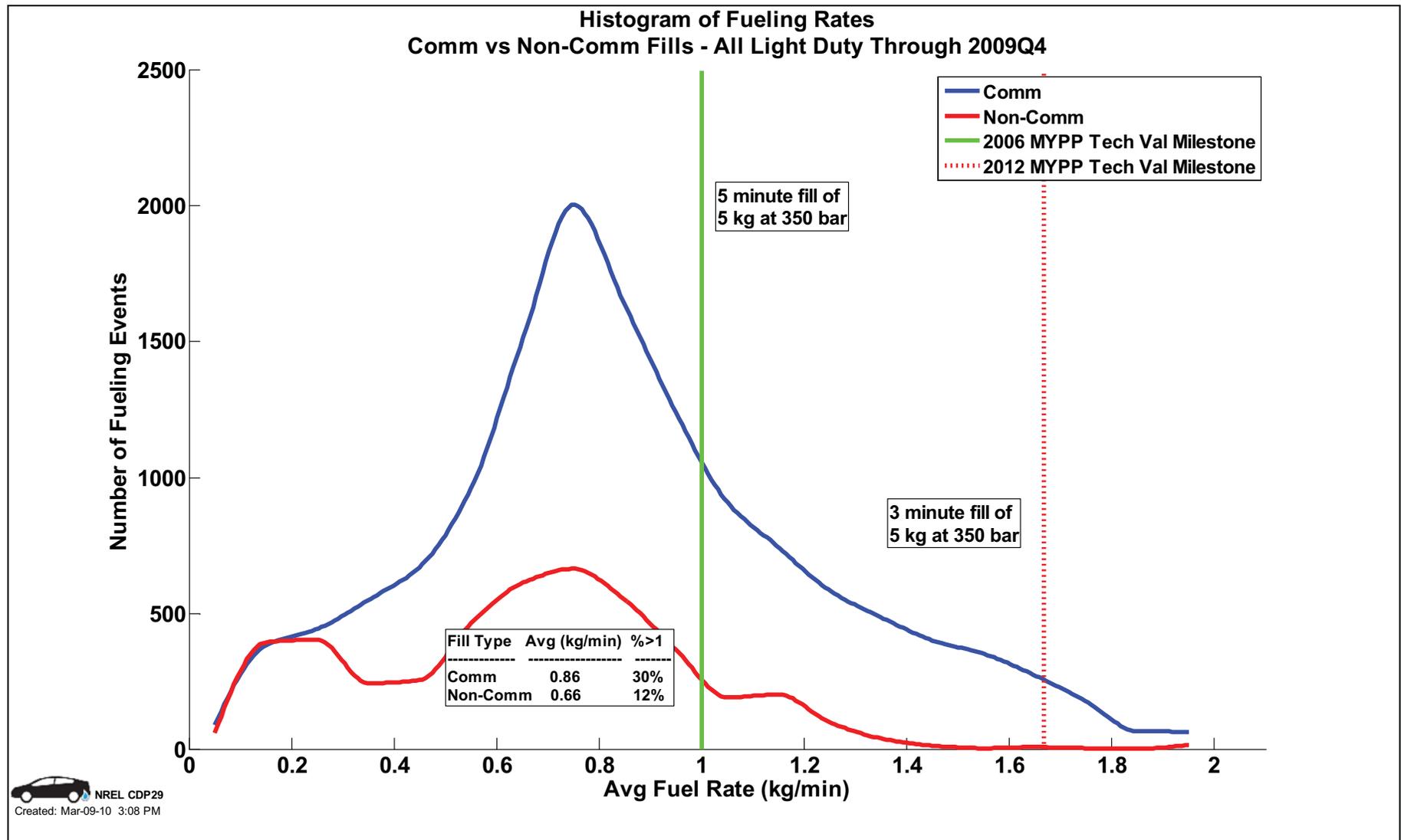
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



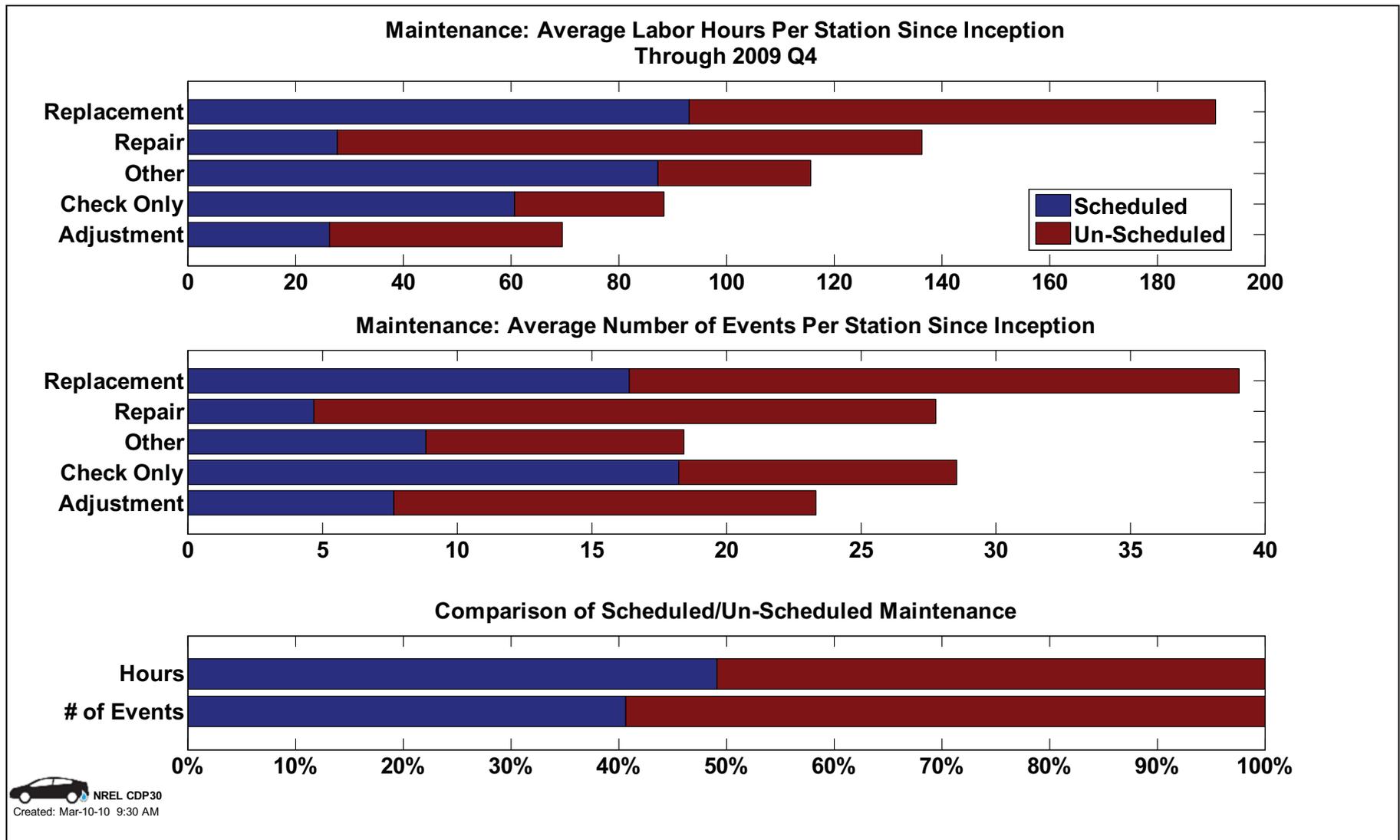
CDP#28 Supplemental: Hydrogen Constituents by Year and Production Method



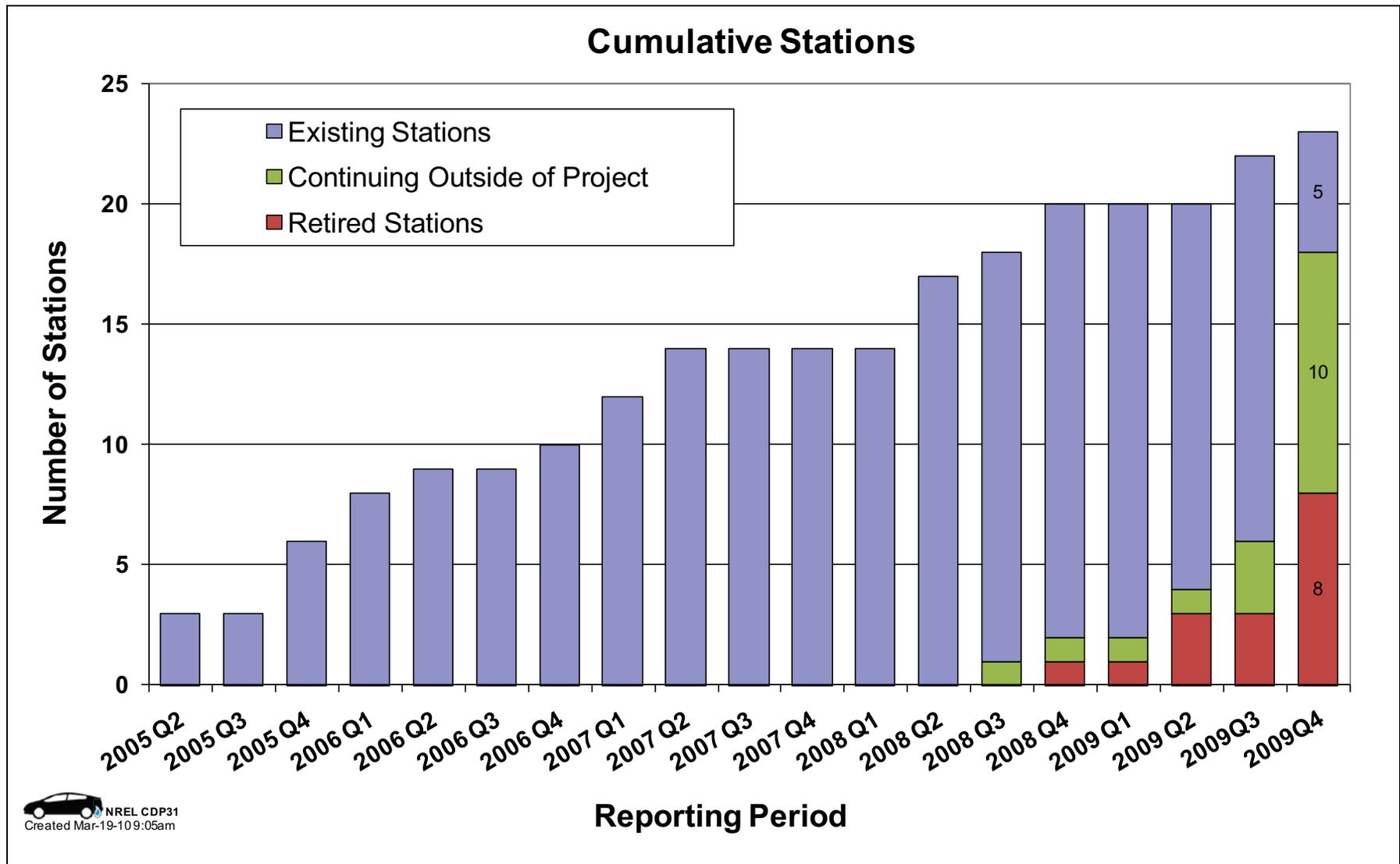
CDP#29: Fueling Rates Communication and Non-Communication Fills



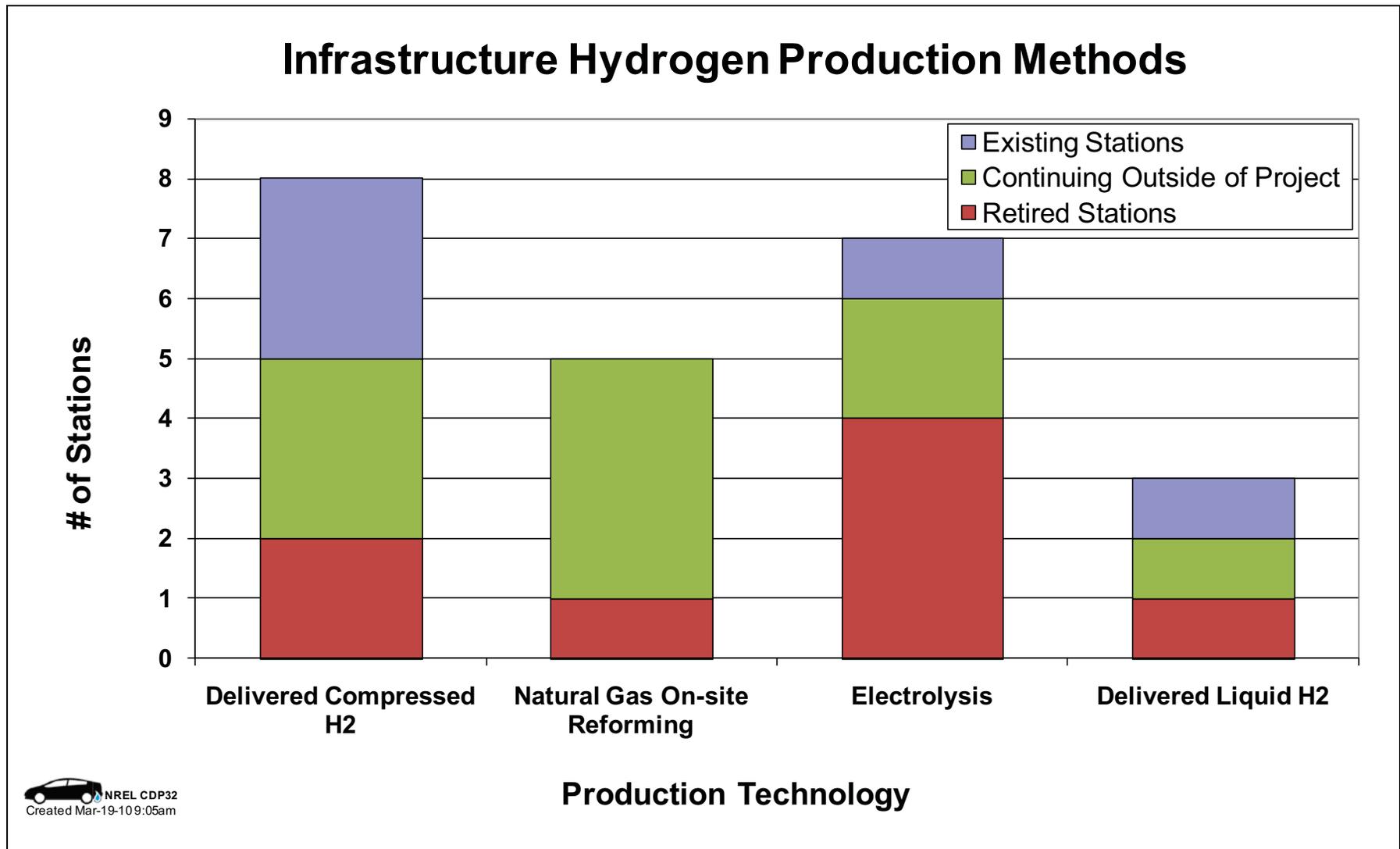
CDP#30: Infrastructure Maintenance



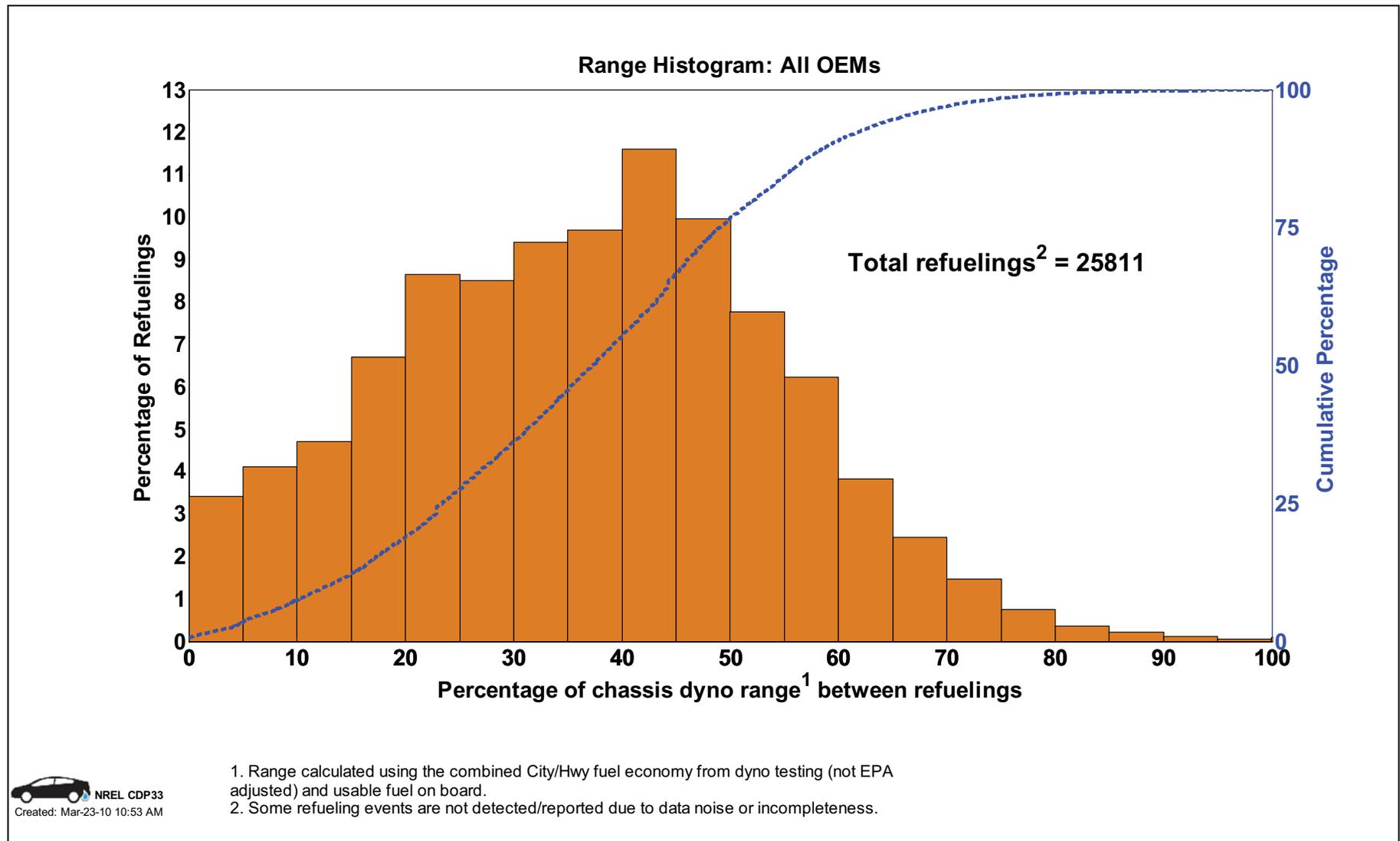
CDP#31: Number of Online Stations



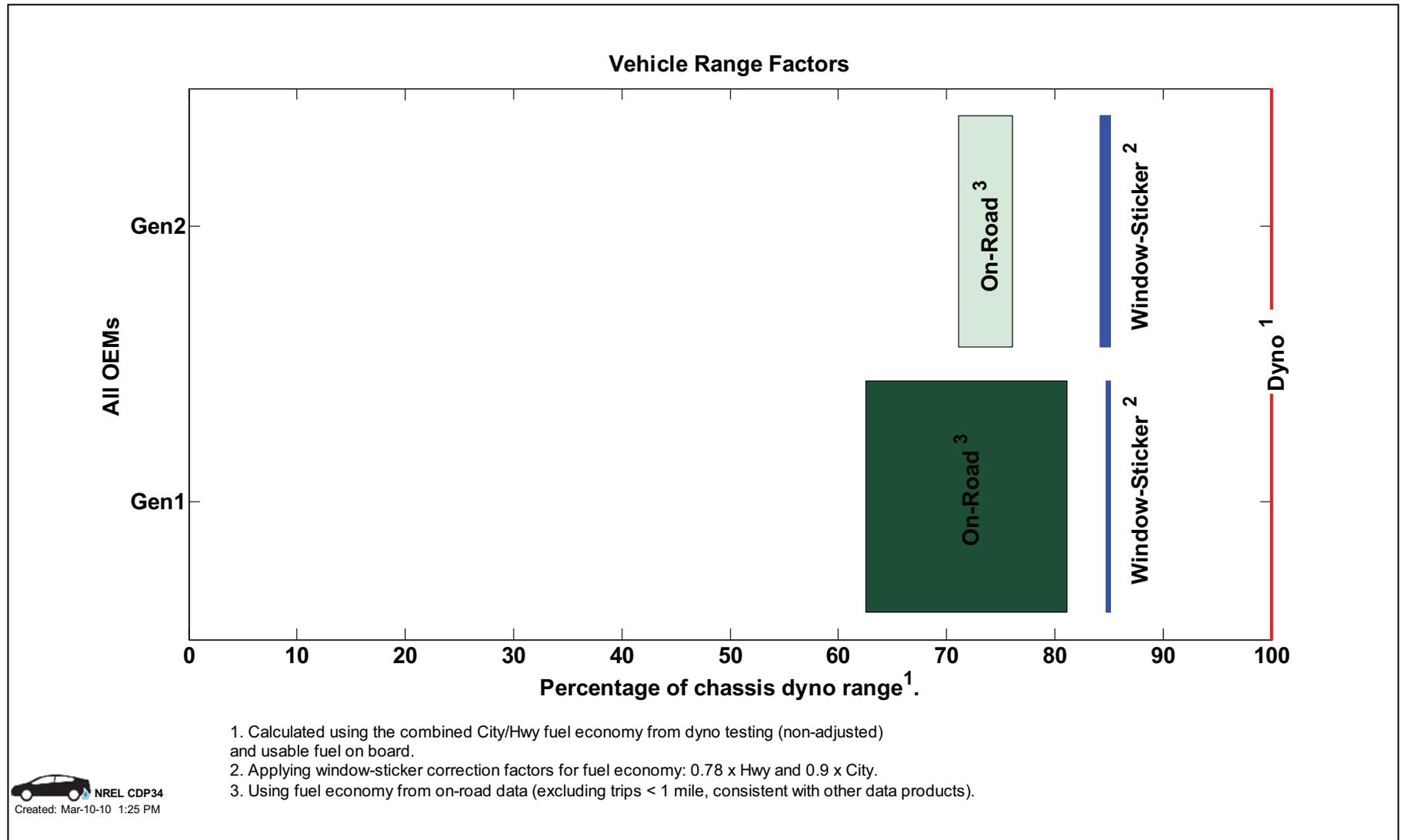
CDP#32: Infrastructure Hydrogen Production Methods



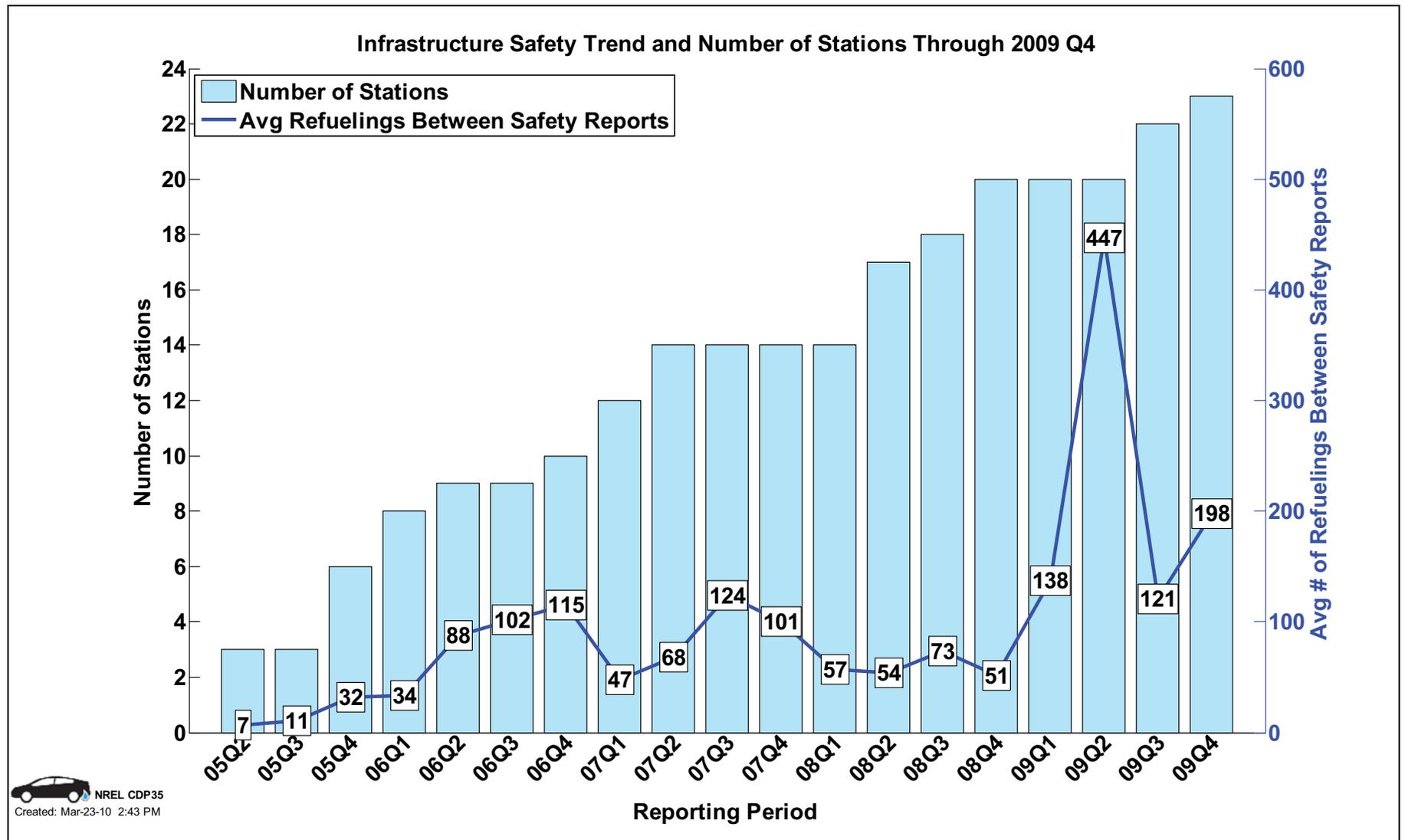
CDP#33: Percentage of Theoretical Range Traveled Between Refuelings



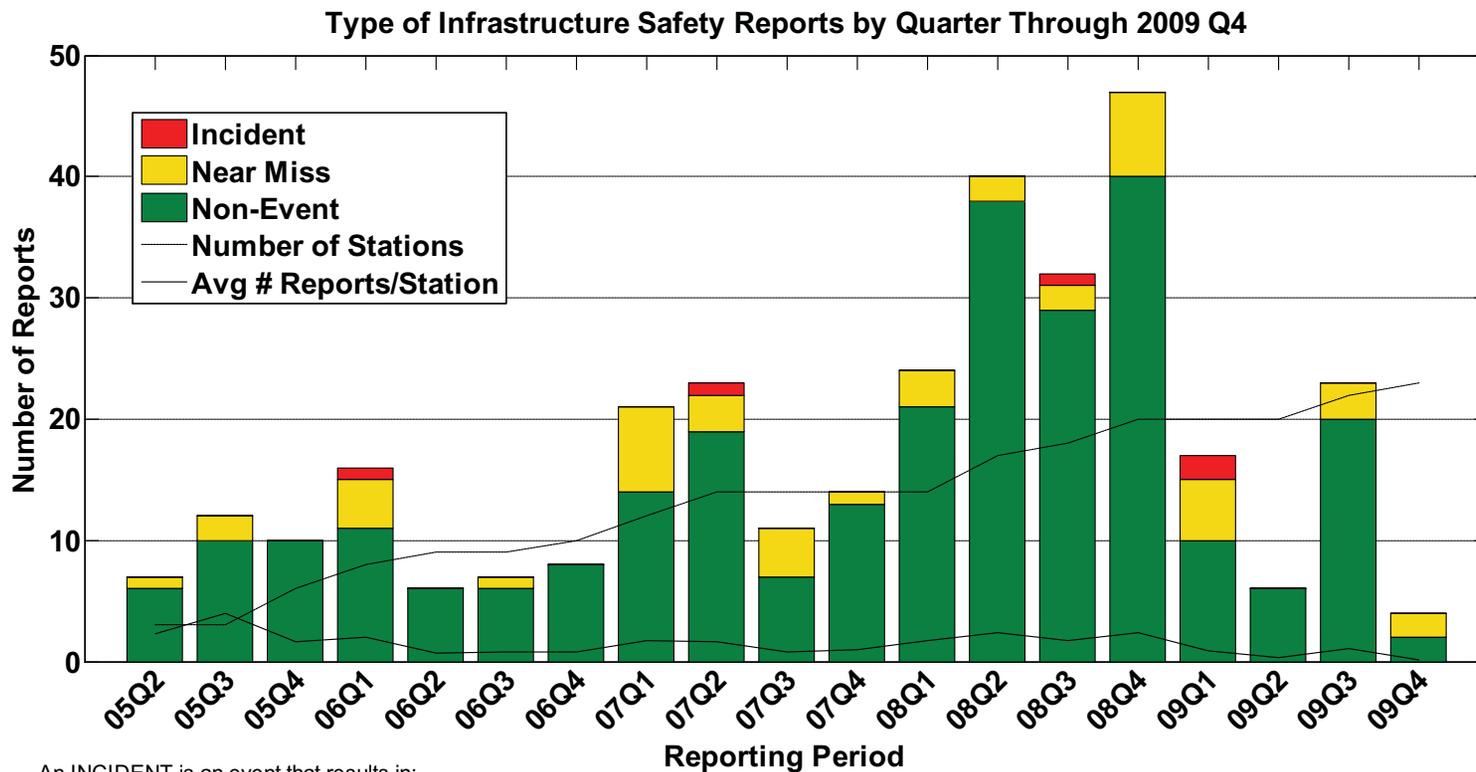
CDP#34: Effective Vehicle Range



CDP#35: Average Refuelings Between Infrastructure Safety Reports



CDP#36: Type of Infrastructure Safety Report By Quarter



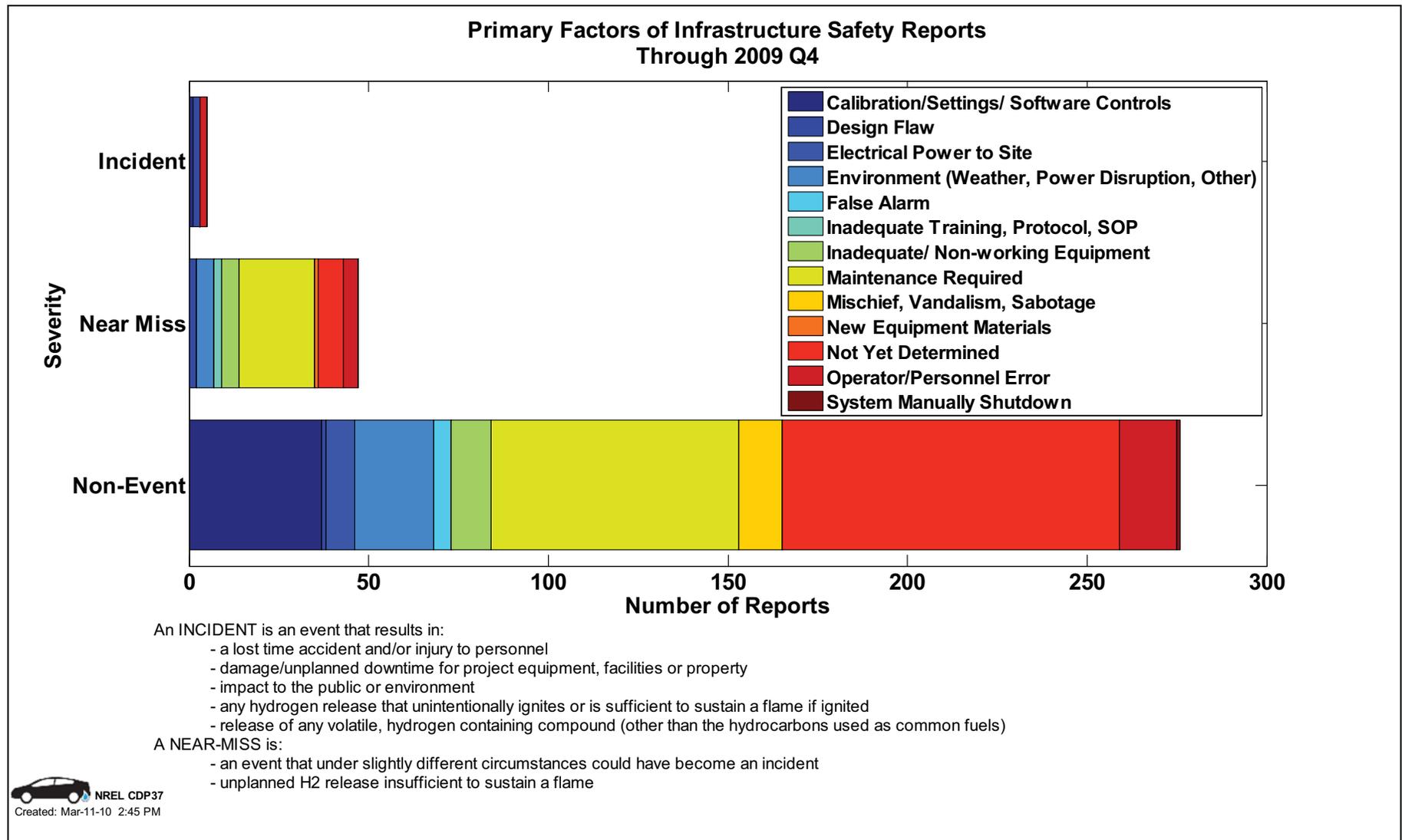
An INCIDENT is an event that results in:

- 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)

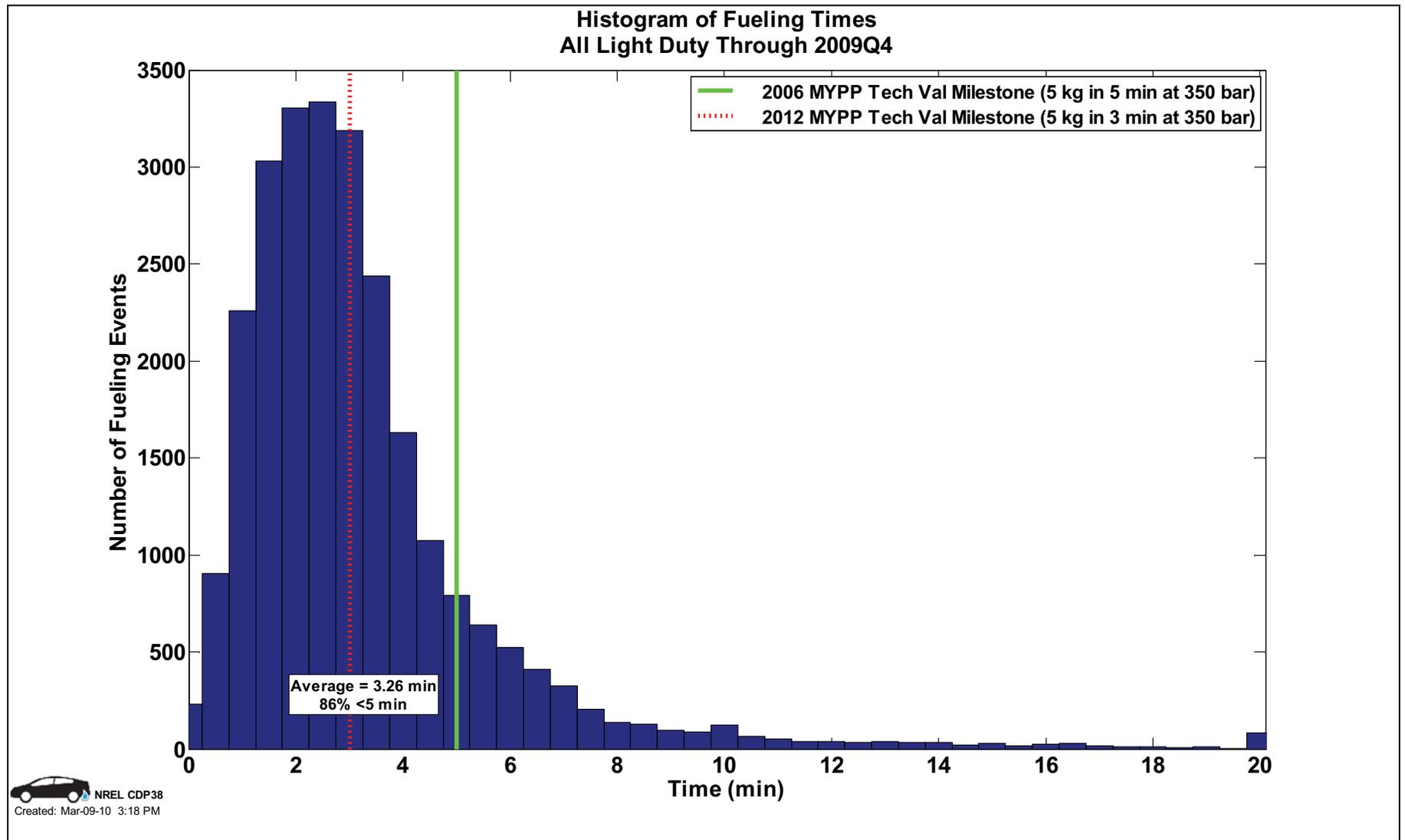
A NEAR-MISS is:

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

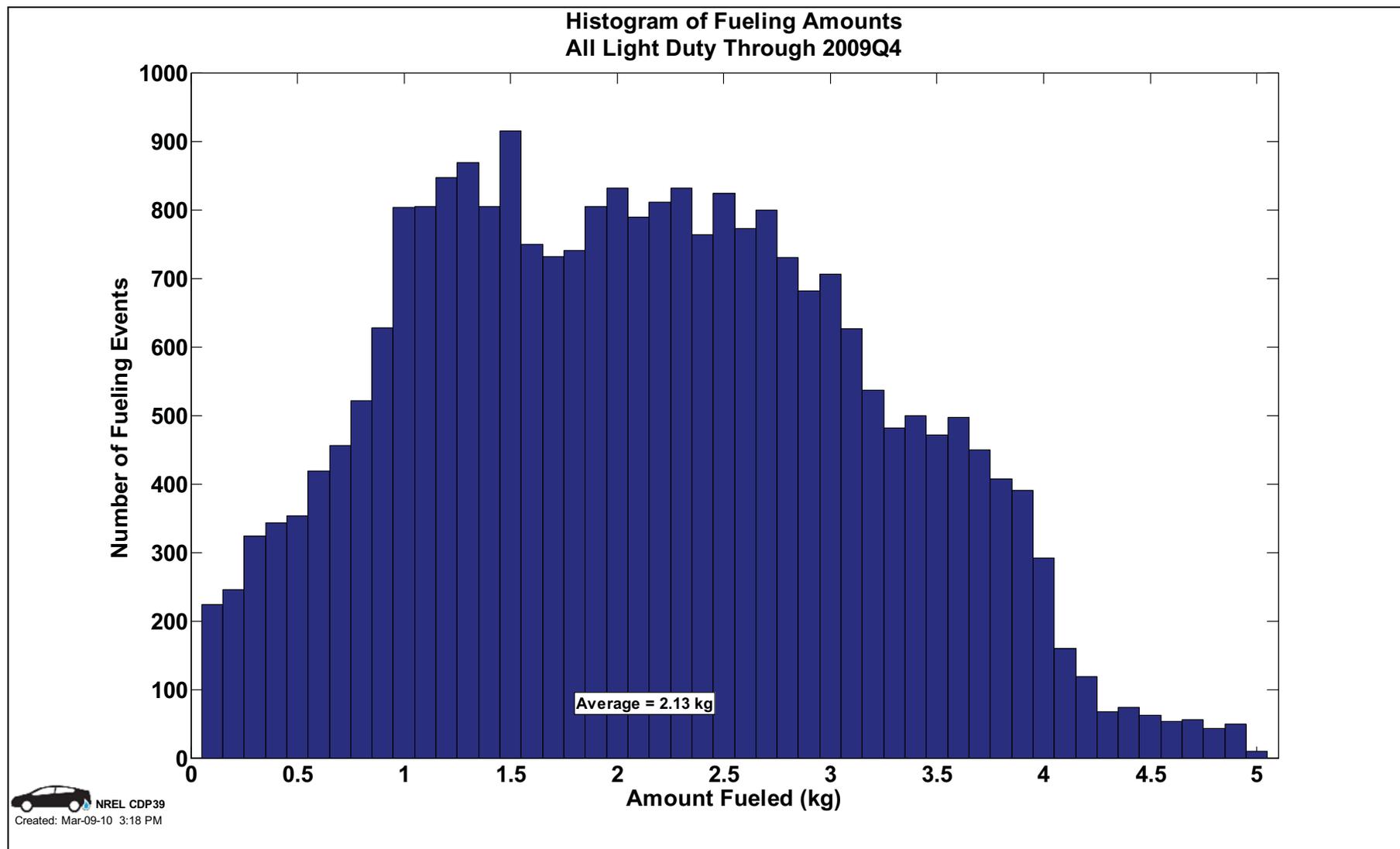
CDP#37: Primary Factors of Infrastructure Safety Reports



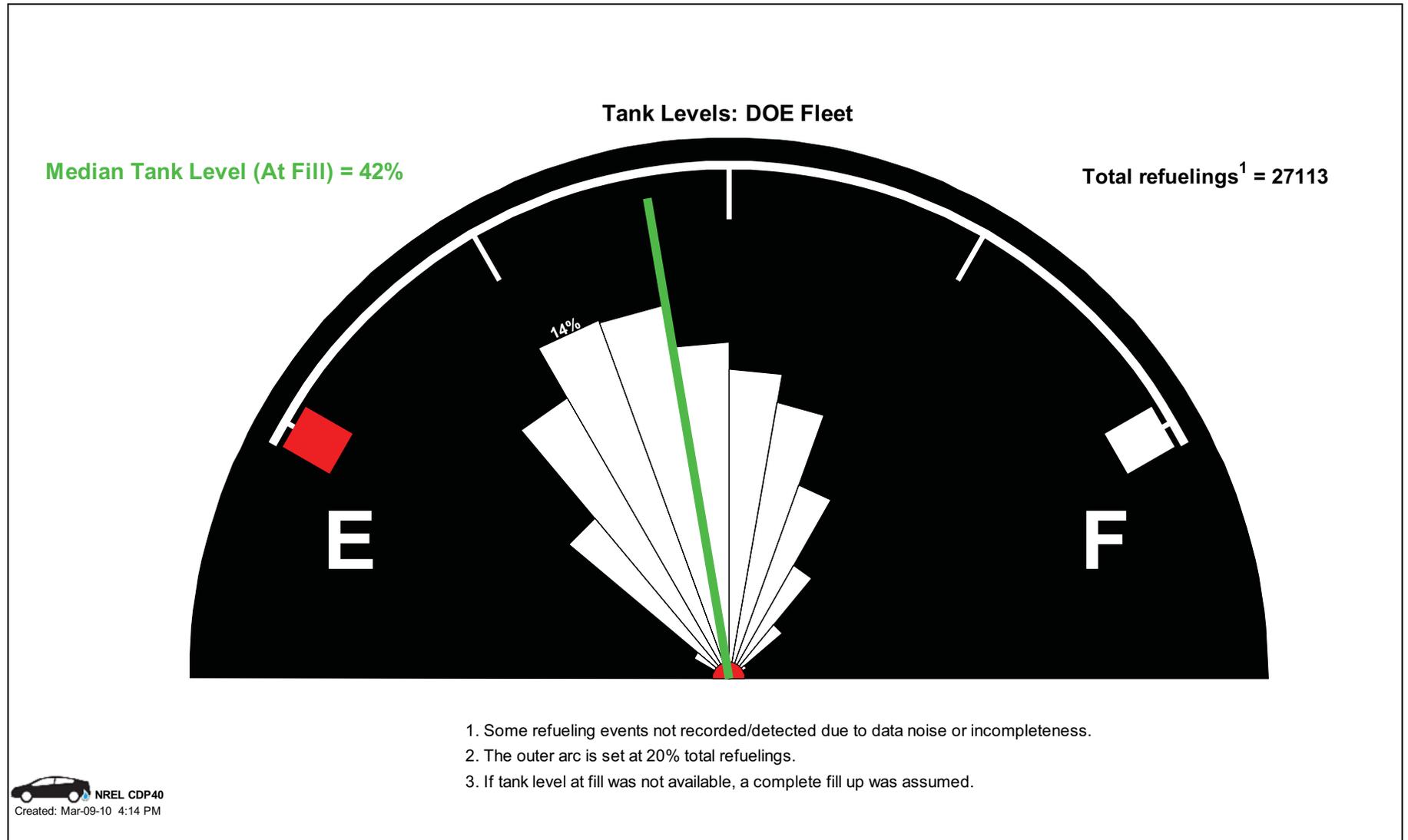
CDP#38: Refueling Times



CDP#39: Refueling Amounts



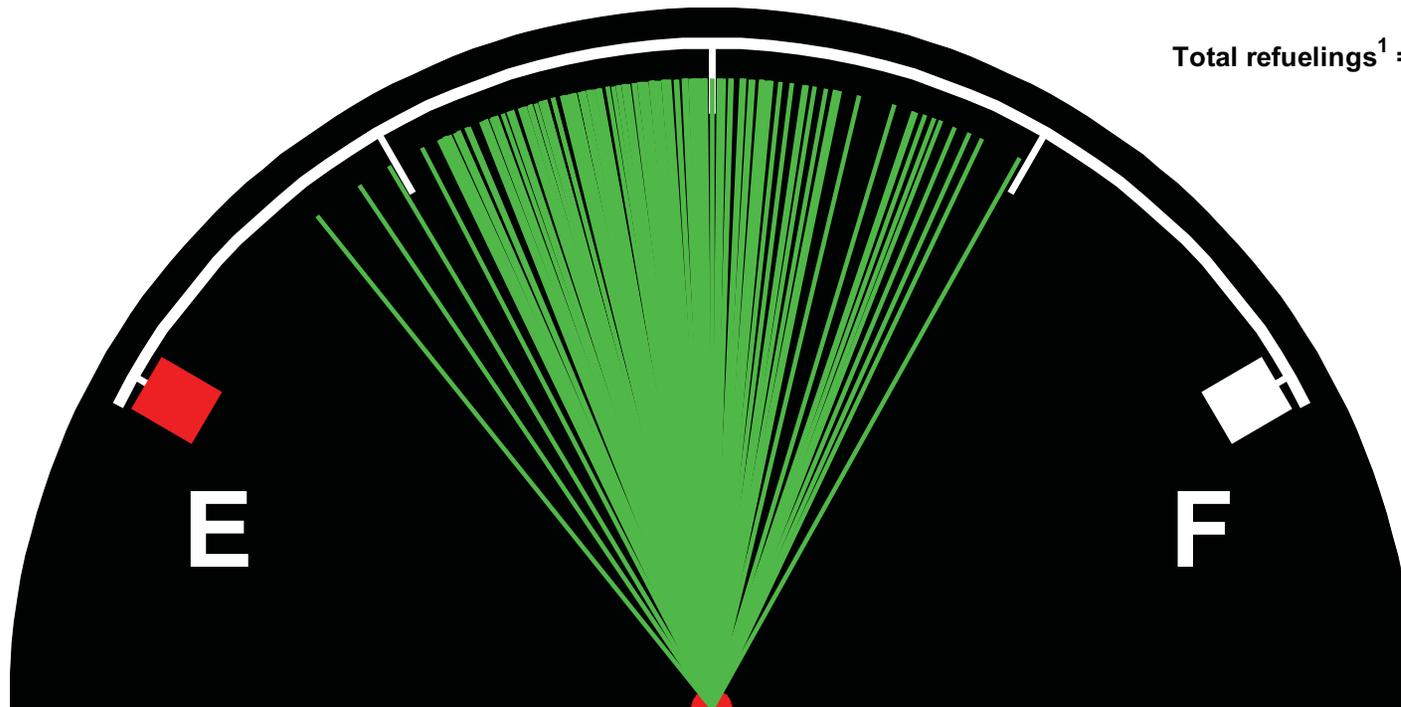
CDP#40: H2 Tank Level at Refueling



CDP#41: Refueling Tank Levels - Medians

Tank Level Medians (At Fill): DOE Fleet, All Vehicles

Total refuelings¹ = 27113



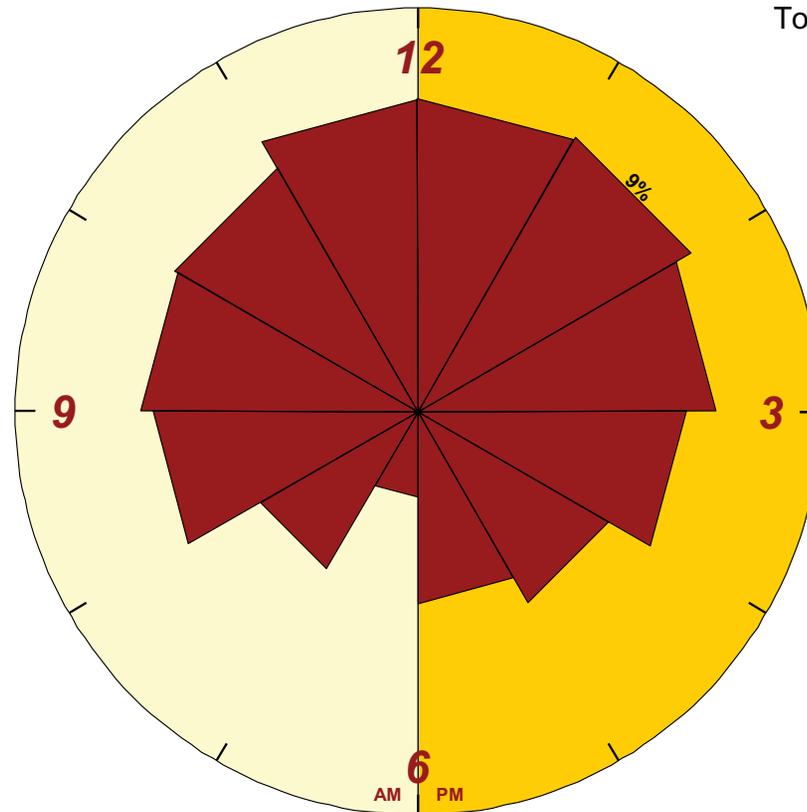
1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. If tank level at fill was not available, a complete fill up was assumed.

CDP#42: Refueling by Time of Day

Refueling by Time of Day: DOE Fleet

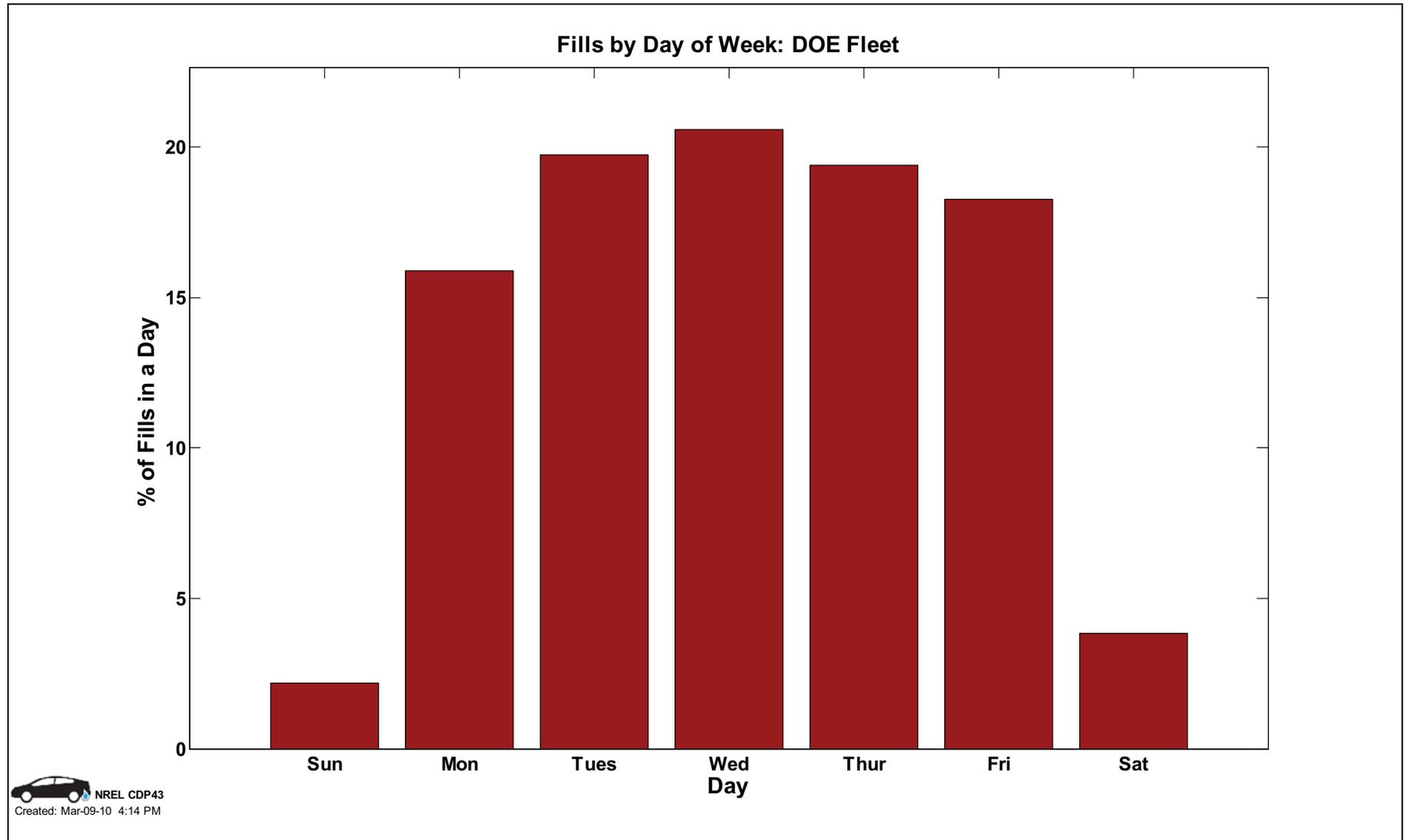
% of fills b/t 6 AM & 6 PM: 89.7%

Total Fill³ Events = 22657



1. Fills between 6 AM & 6 PM
2. The outer arc is set at 12 % total Fill.
3. Some events not recorded/detected due to data noise or incompleteness.

CDP#43: Refueling by Day of Week

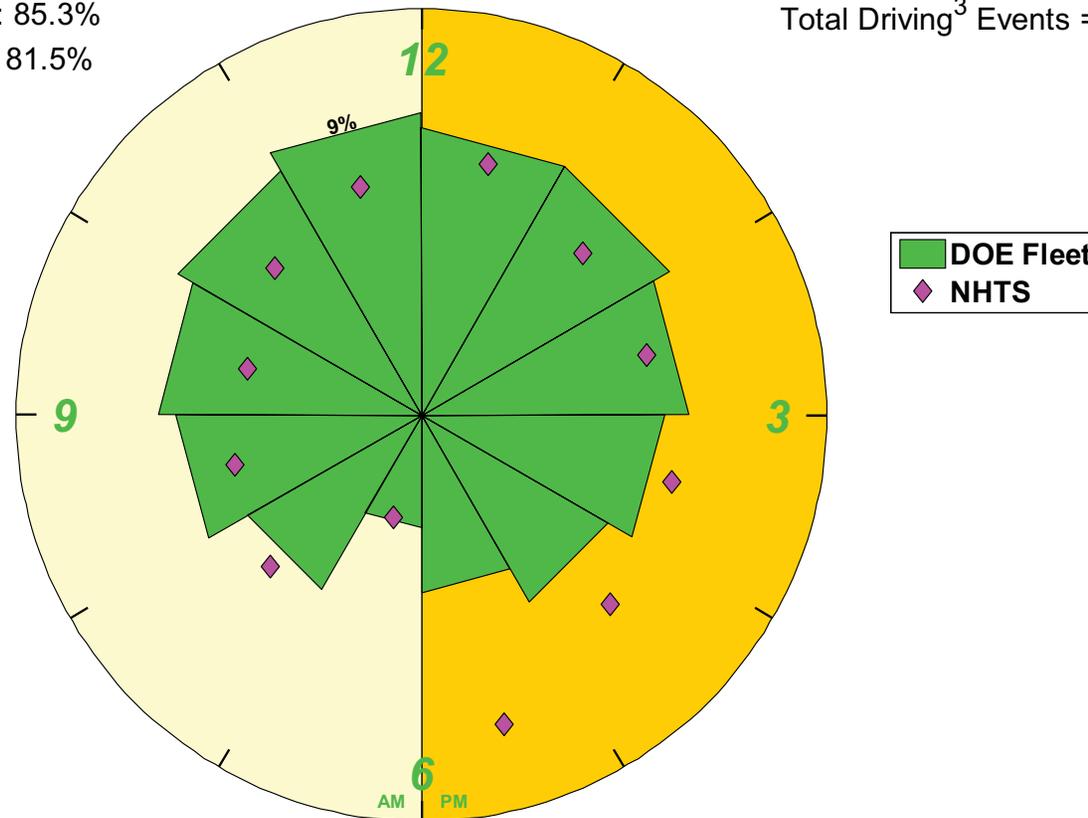


CDP#44: Driving Start Time – Day

Driving Start Time - Day: DOE Fleet

% of driving trips b/t 6 AM & 6 PM: 85.3%
 % of NHTS trips b/t 6 AM & 6 PM: 81.5%

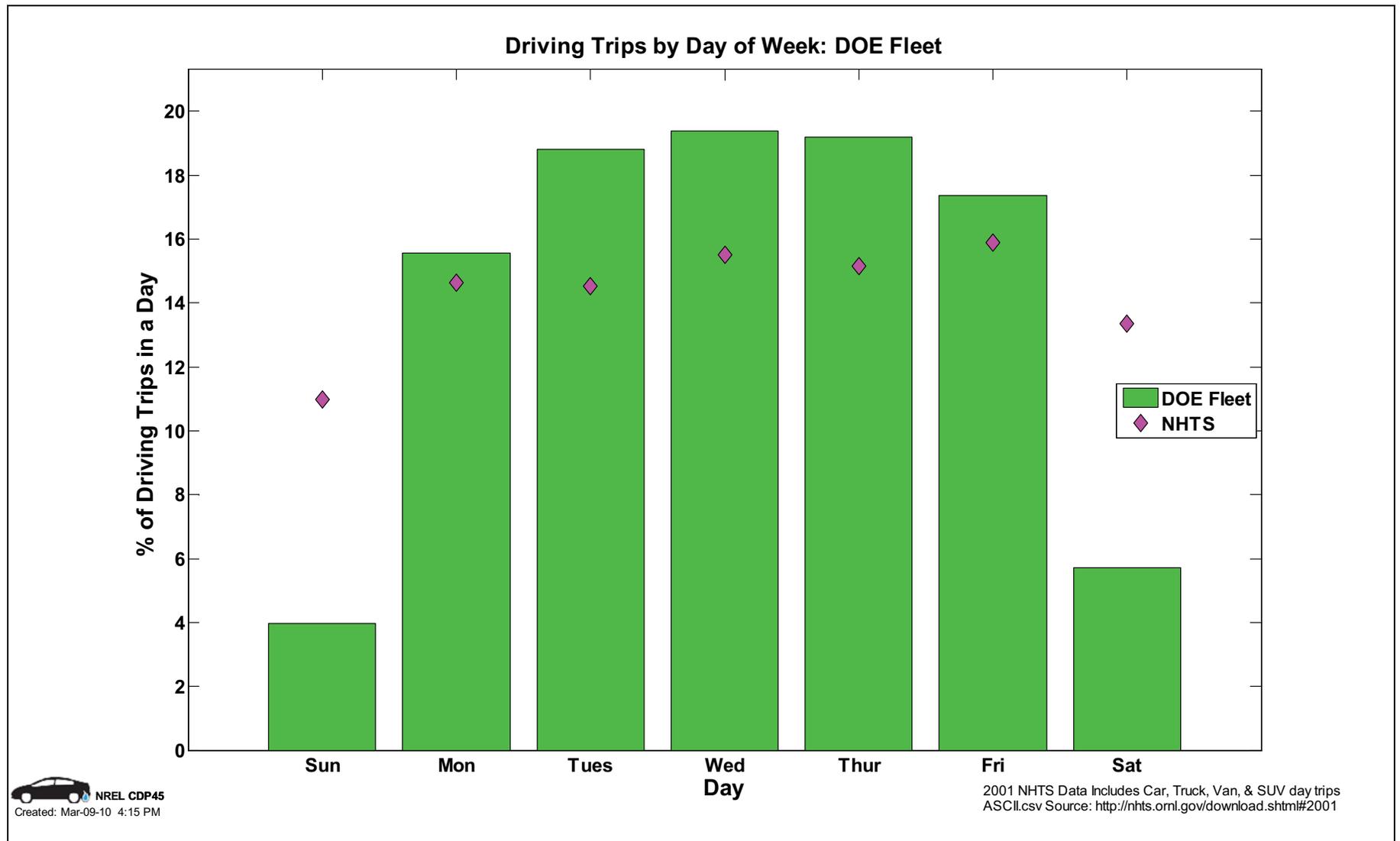
Total Driving³ Events = 295222



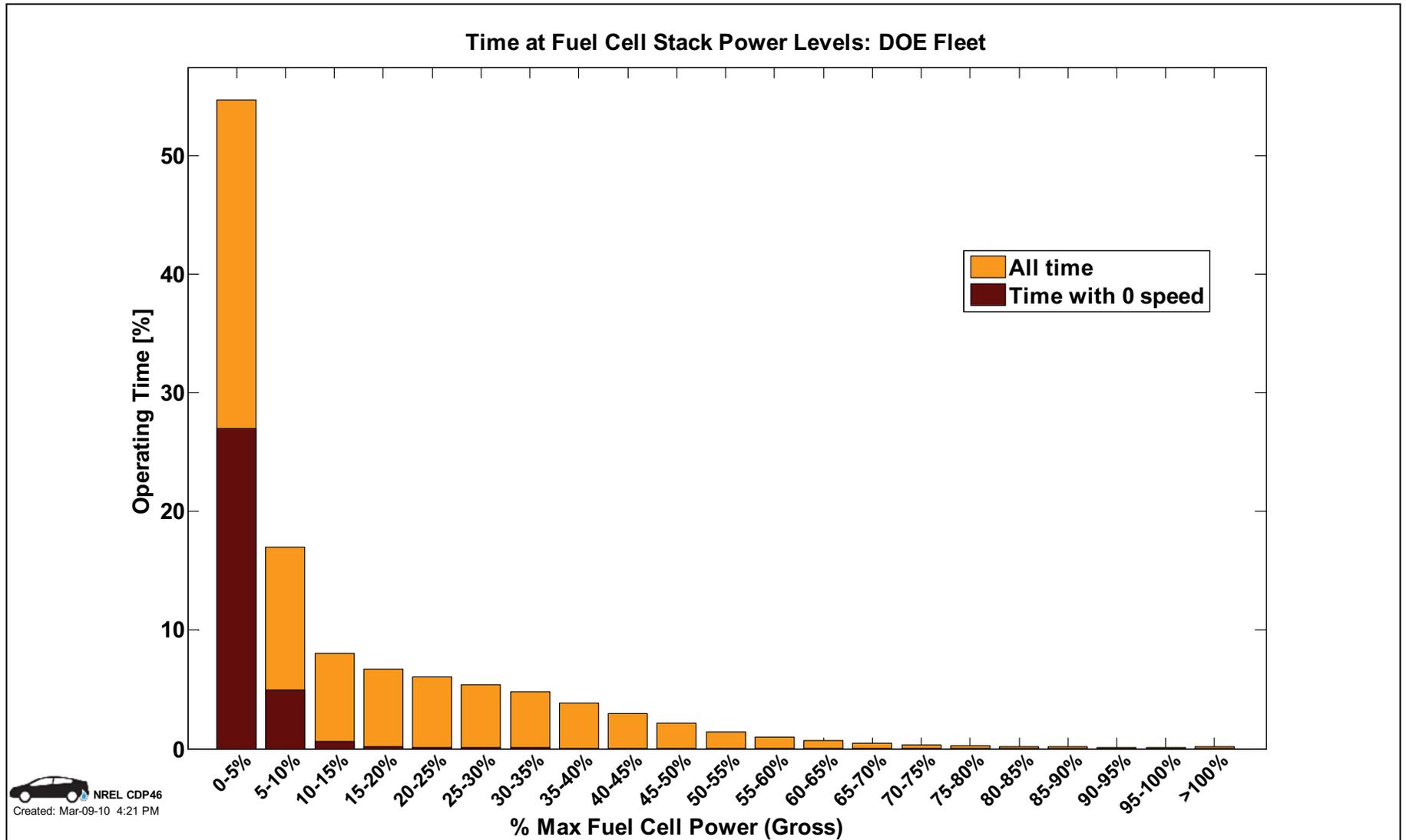
1. Driving trips between 6 AM & 6 PM
2. The outer arc is set at 12 % total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips
 ASCII.csv Source: <http://nhts.ornl.gov/download.shtml#2001>

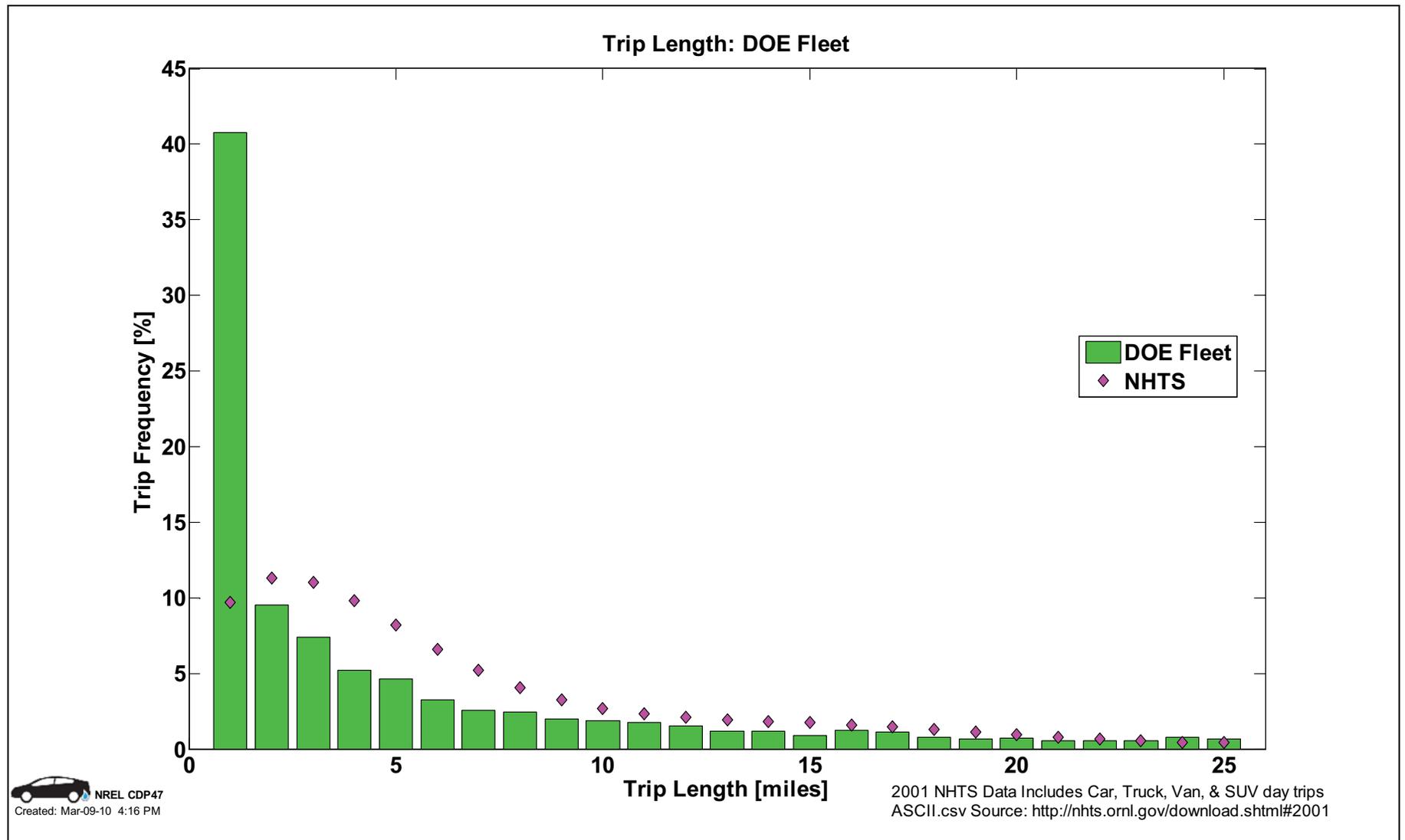
CDP#45: Driving by Day of Week



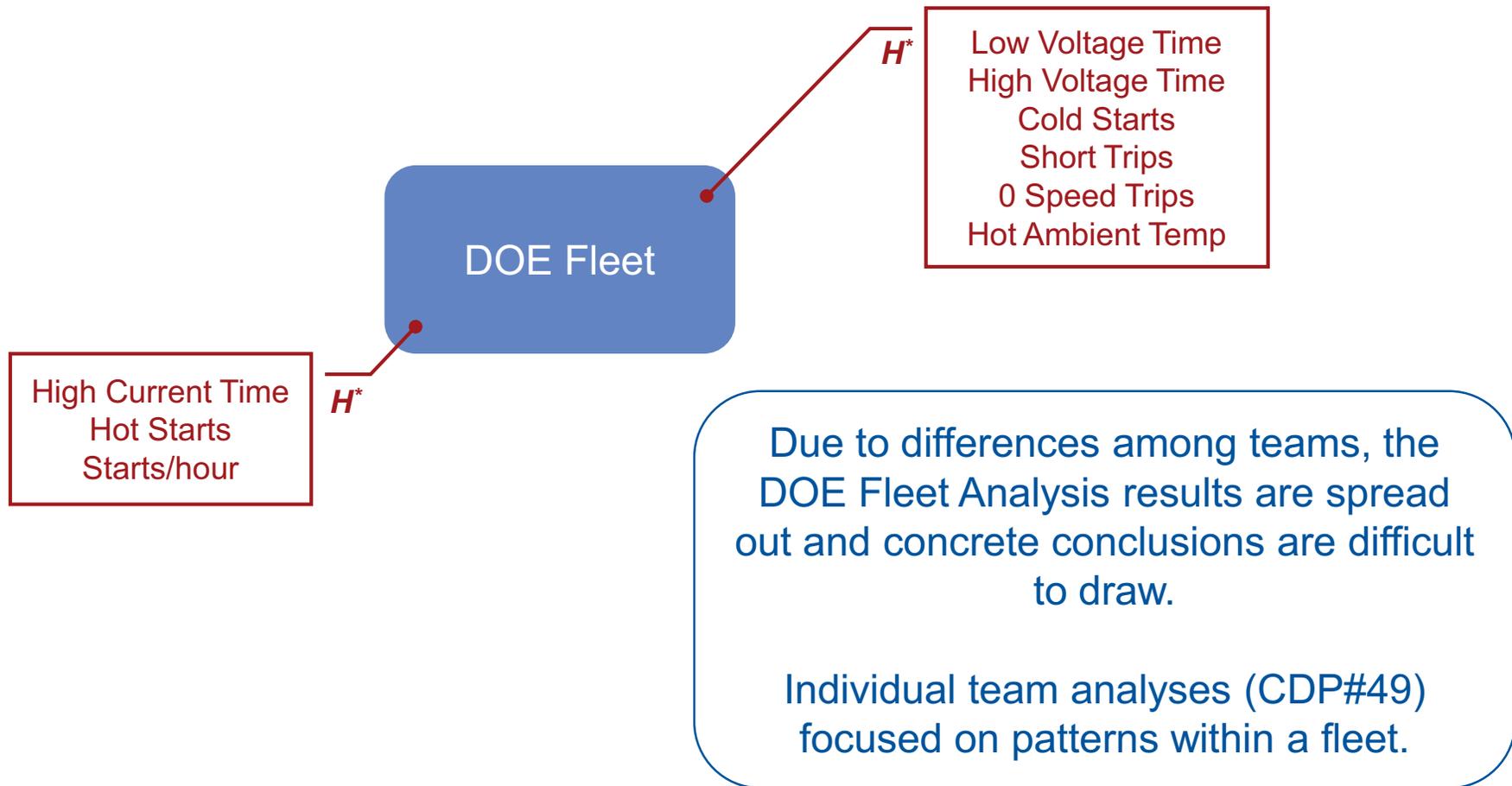
CDP#46: Fuel Cell System Operating Power



CDP#47: Trip Length



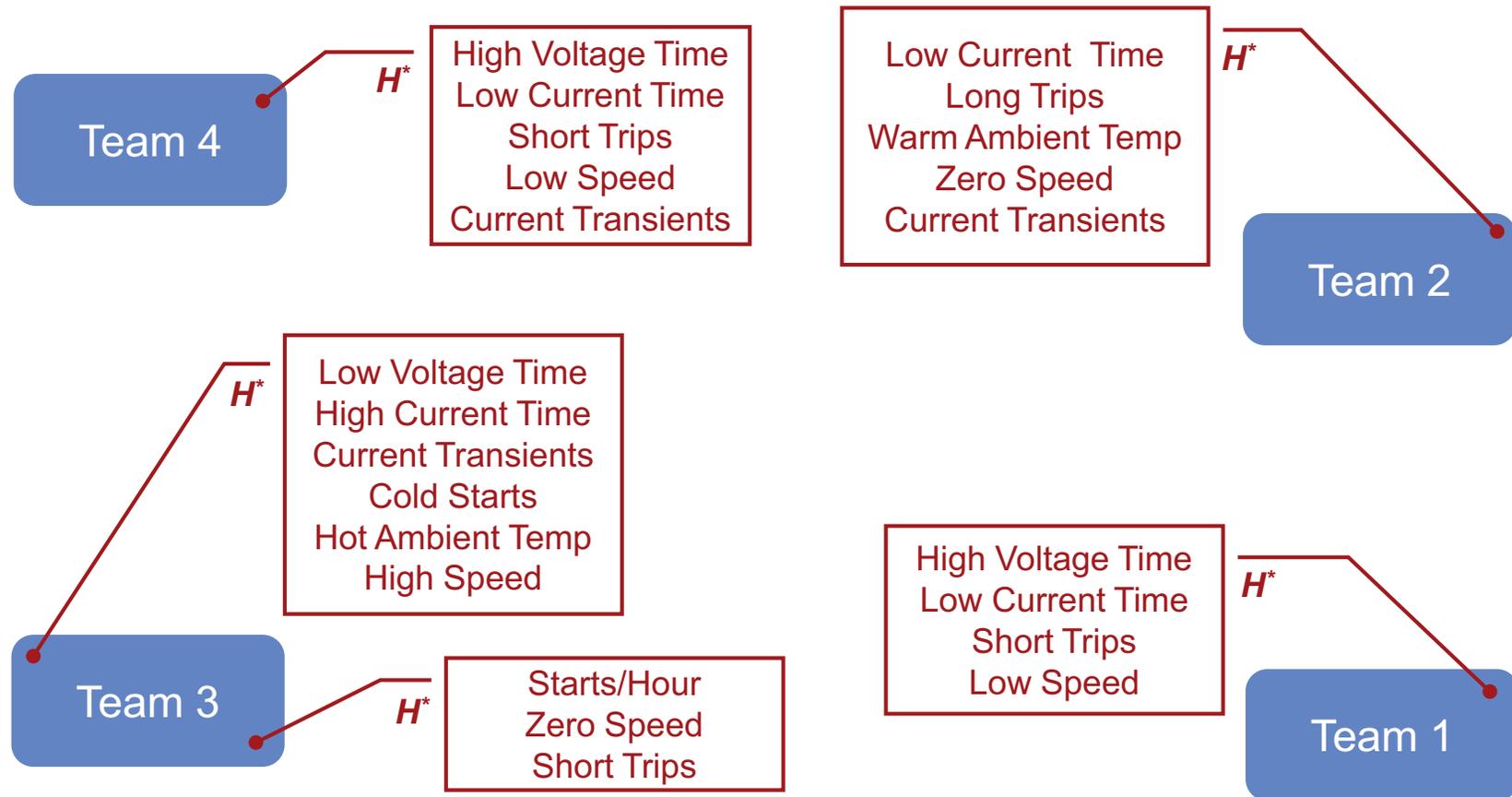
CDP#48: Primary Factors Affecting Learning Demo Fleet Fuel Cell Degradation



- 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

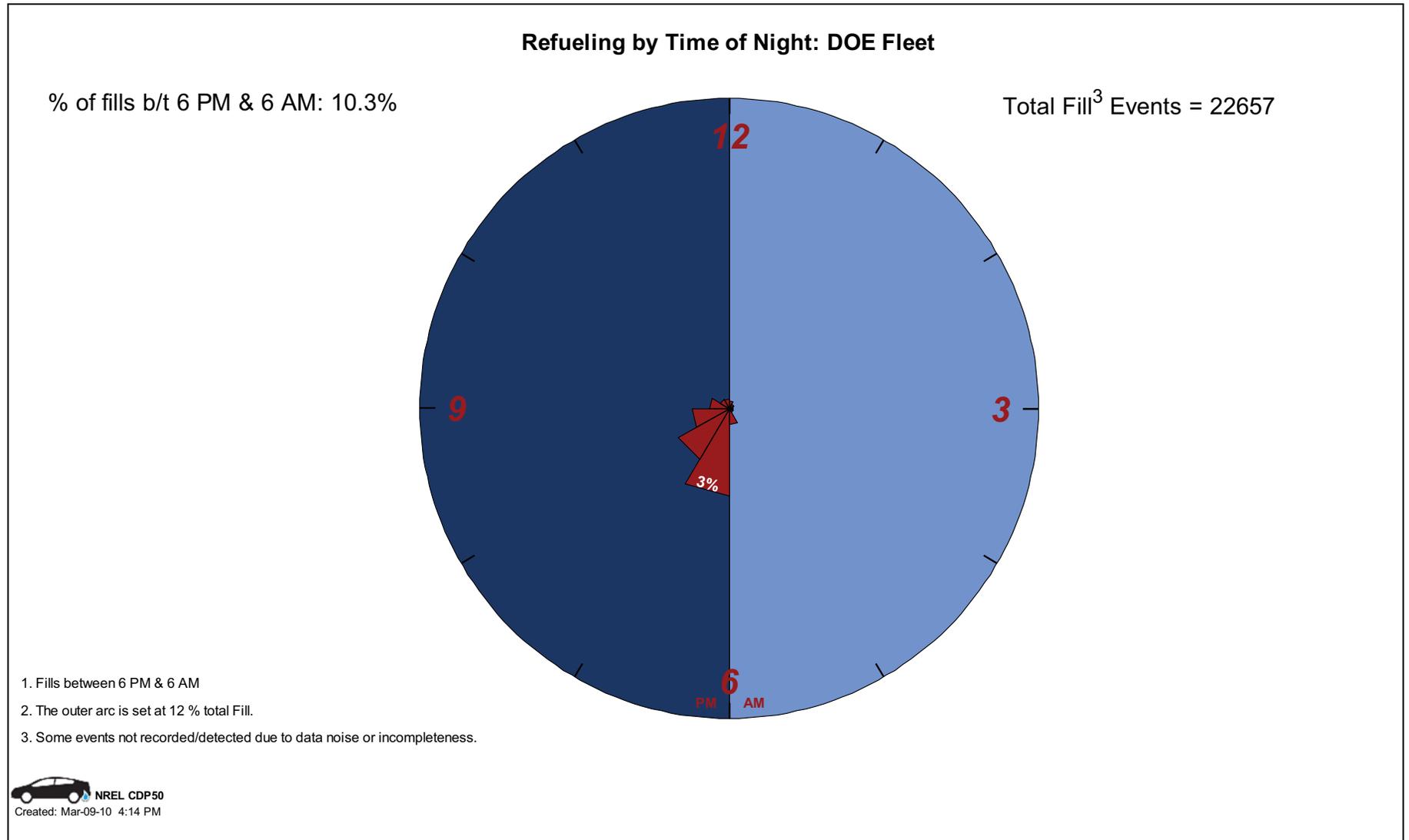
CDP#49: Primary Factors Affecting Learning Demo Team Fuel Cell Degradation



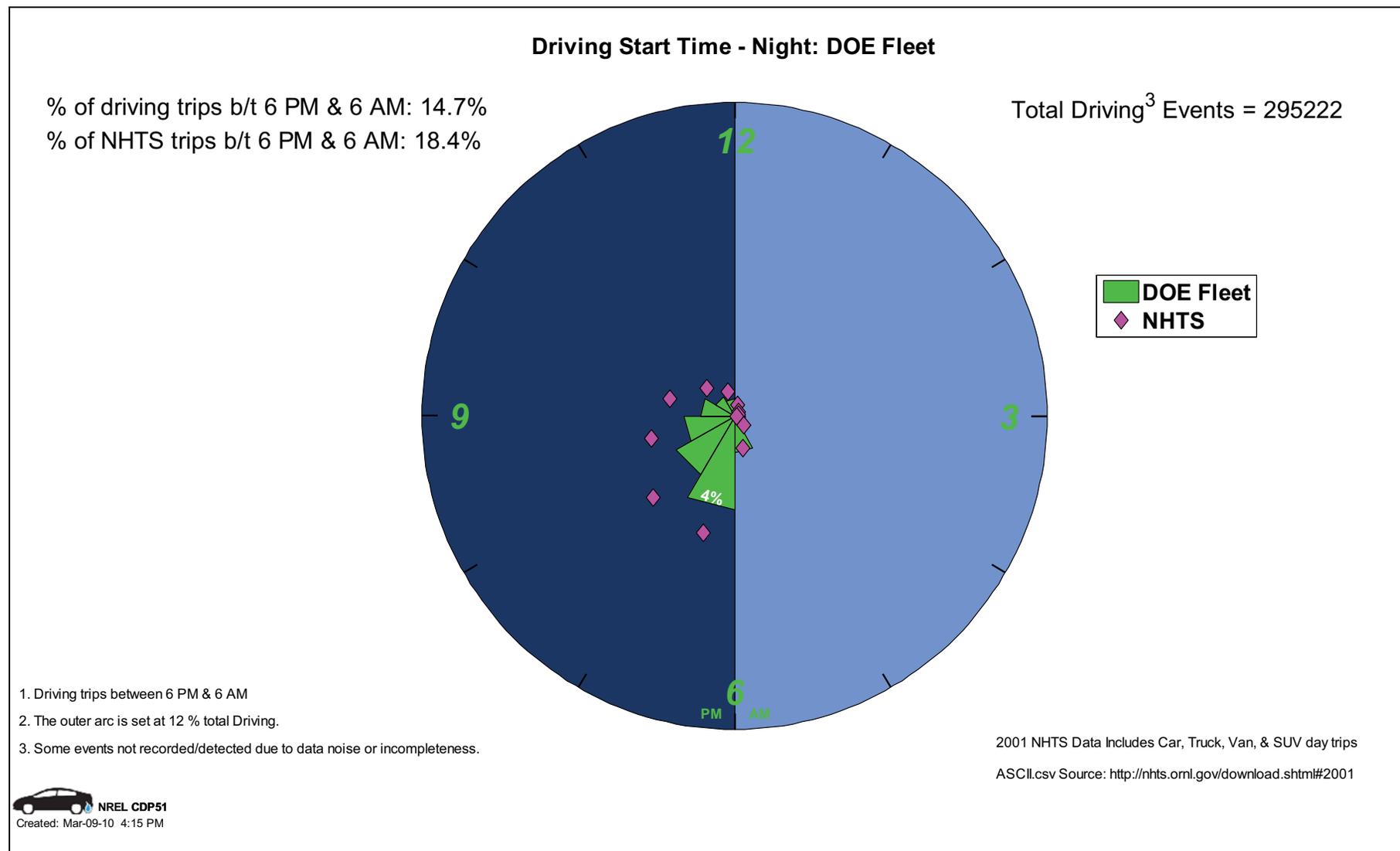
- 1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team's Gen 1 fleet.
- 2) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.
- 3) Factor groups associated with stacks that are opposite to the identified groups here are not specified.

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

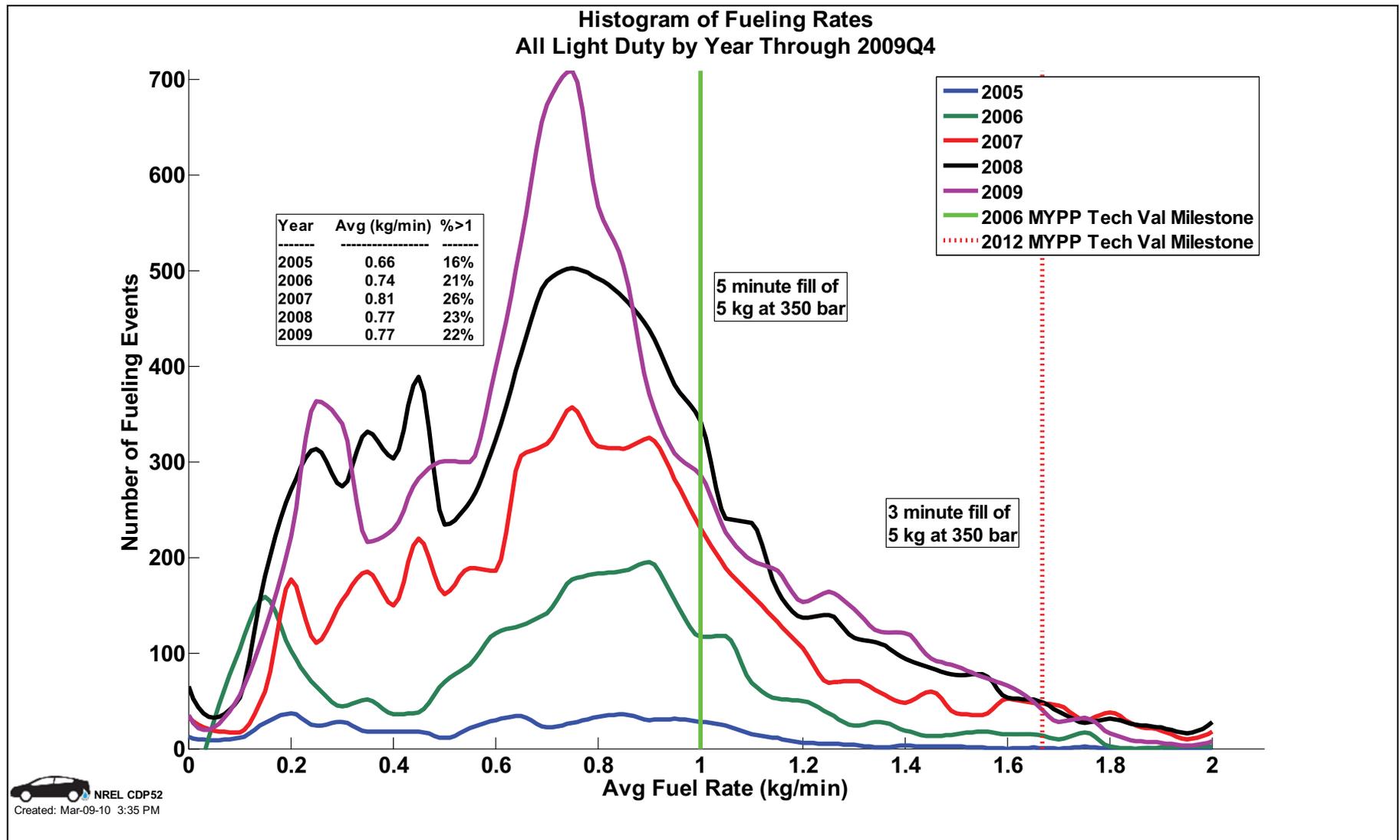
CDP#50: Refueling by Time of Night



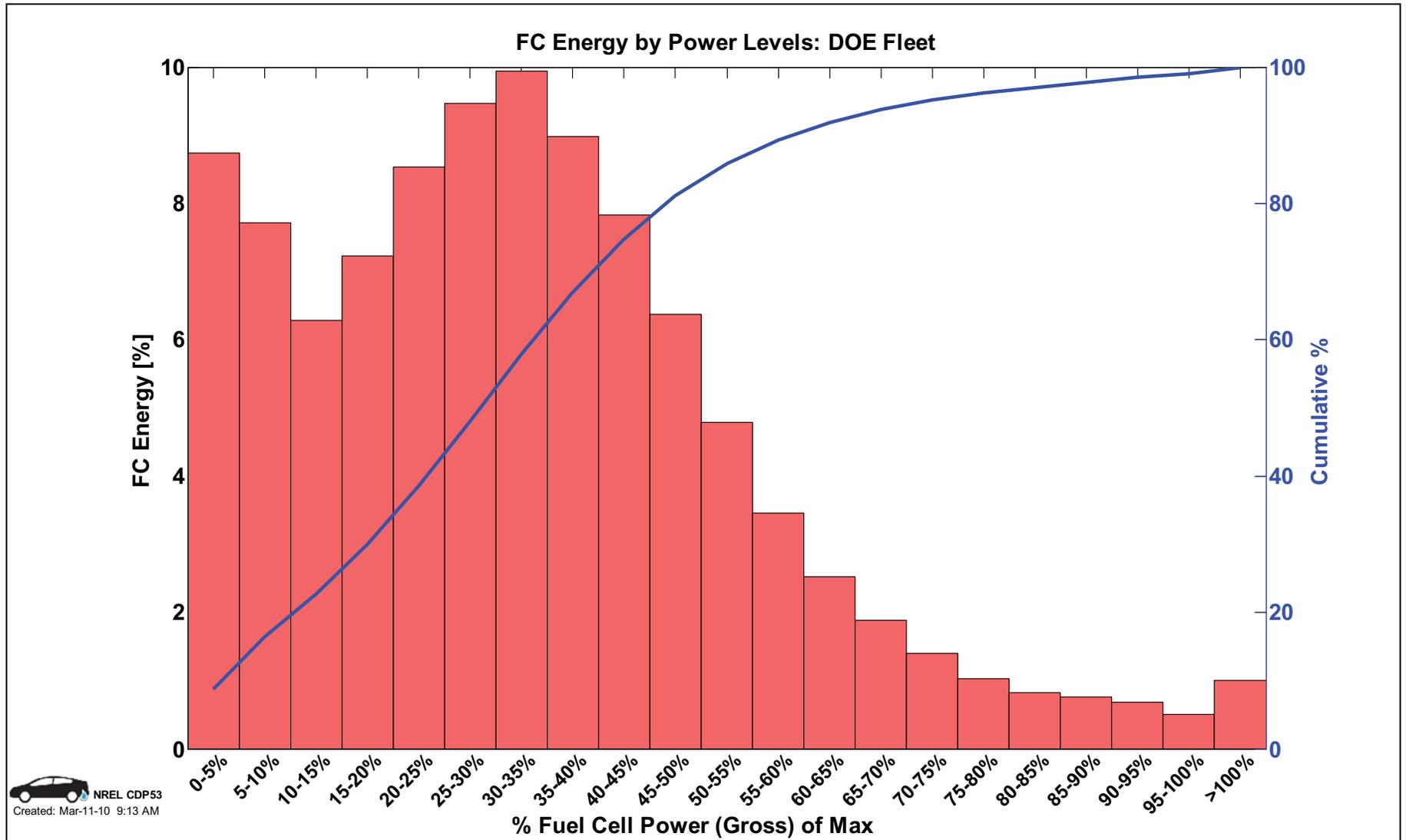
CDP#51: Driving Start Time – Night



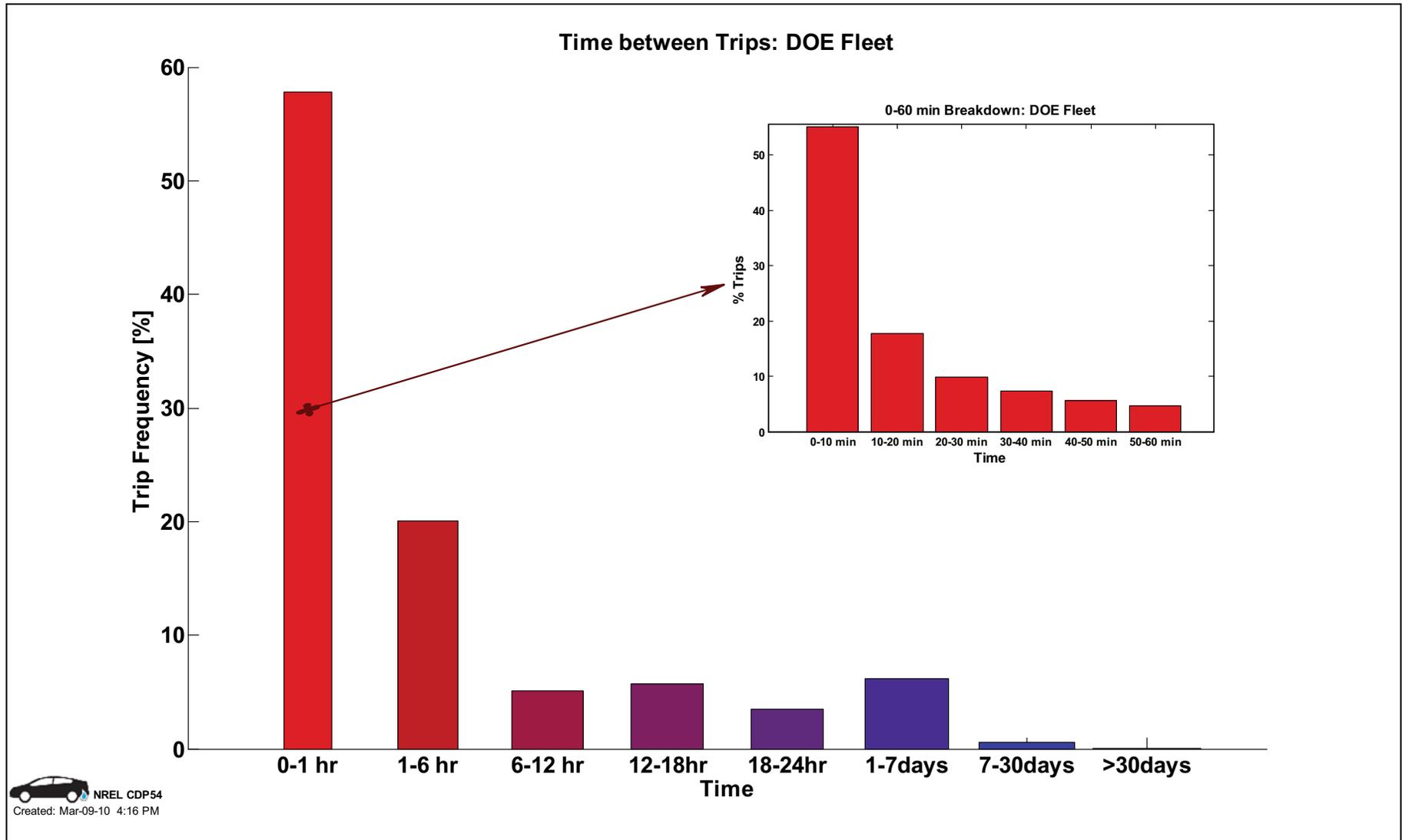
CDP#52: Refueling Data by Year



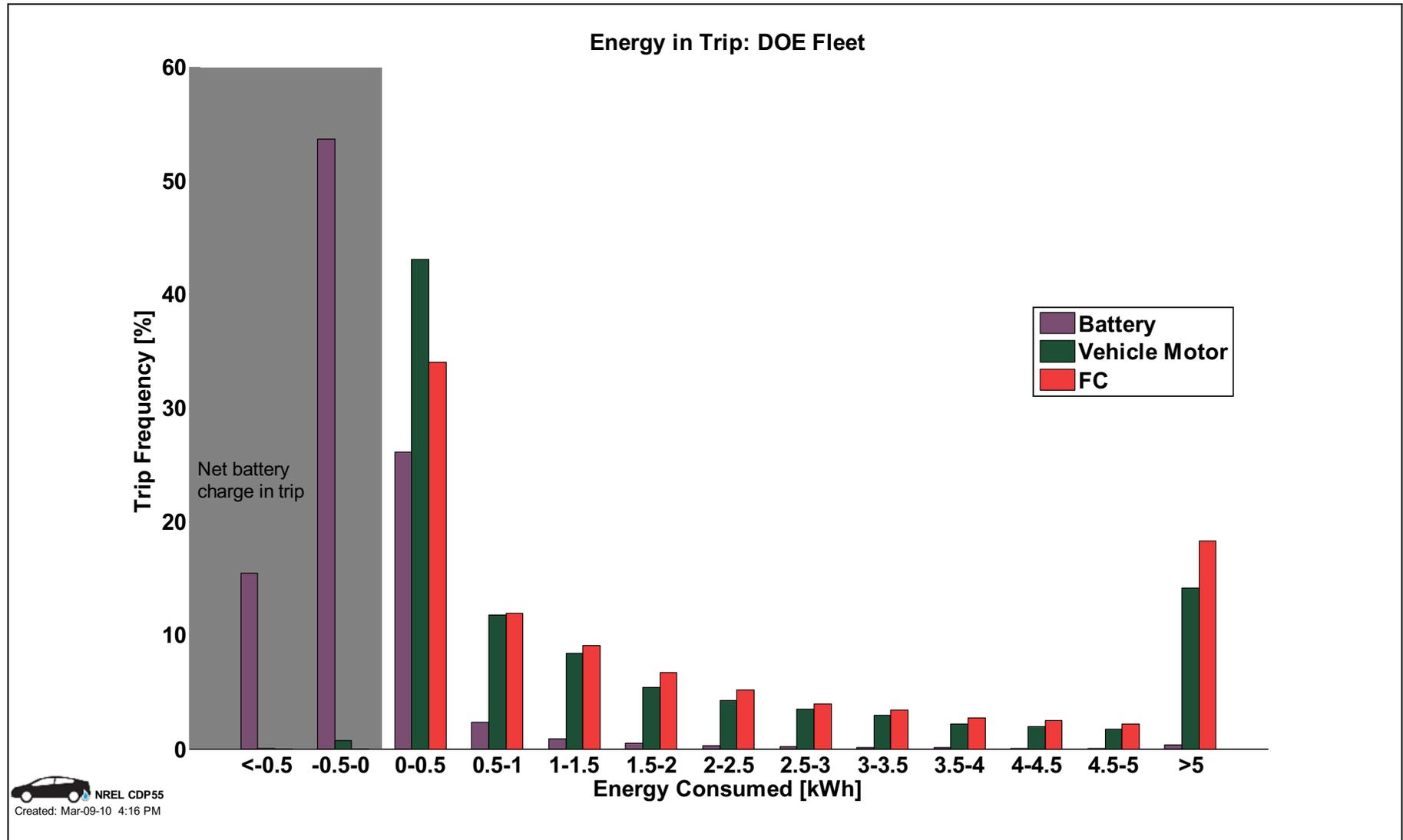
CDP#53: Fuel Cell System Energy within Power Levels



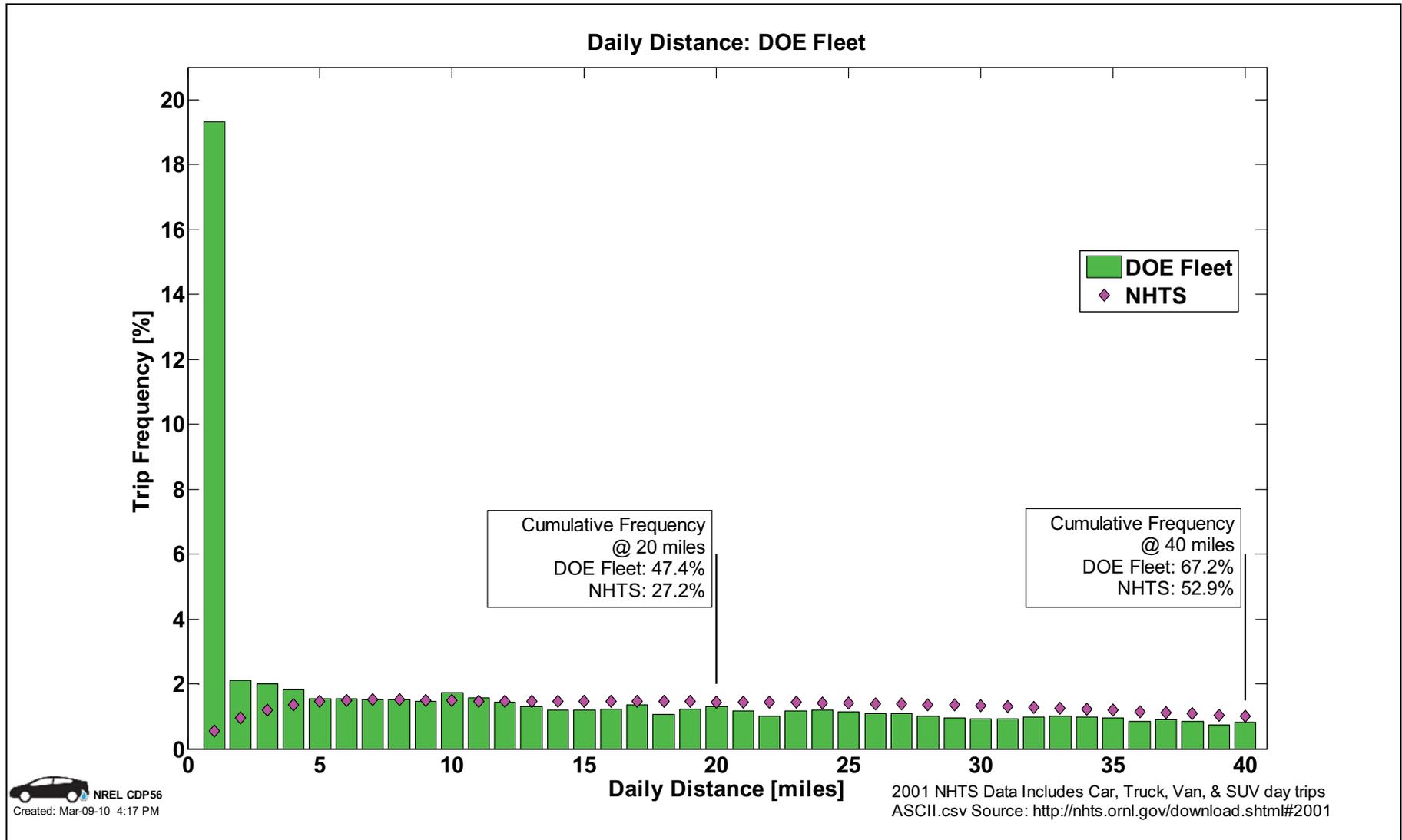
CDP#54: Time Between Trips



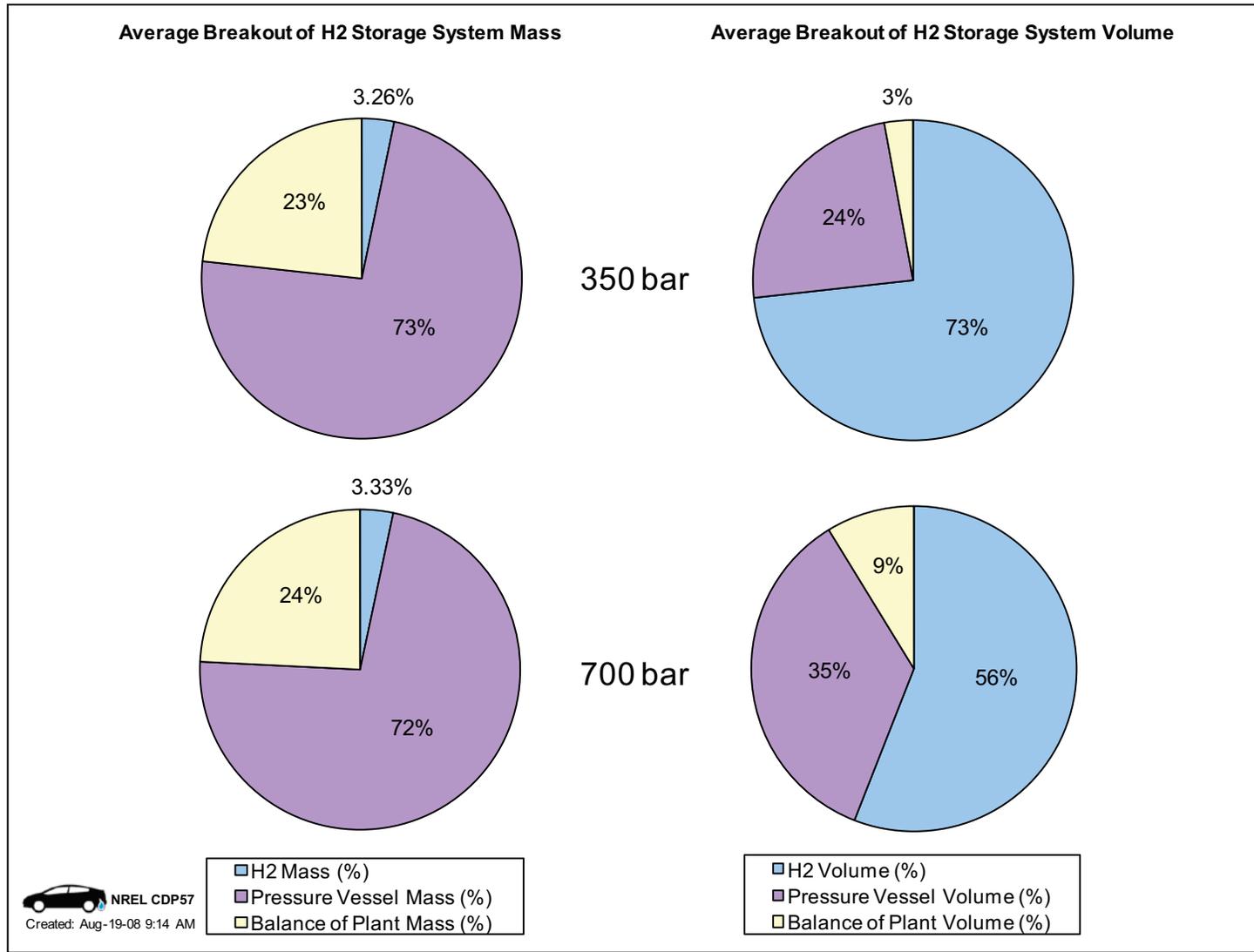
CDP#55: Fuel Cell System Energy



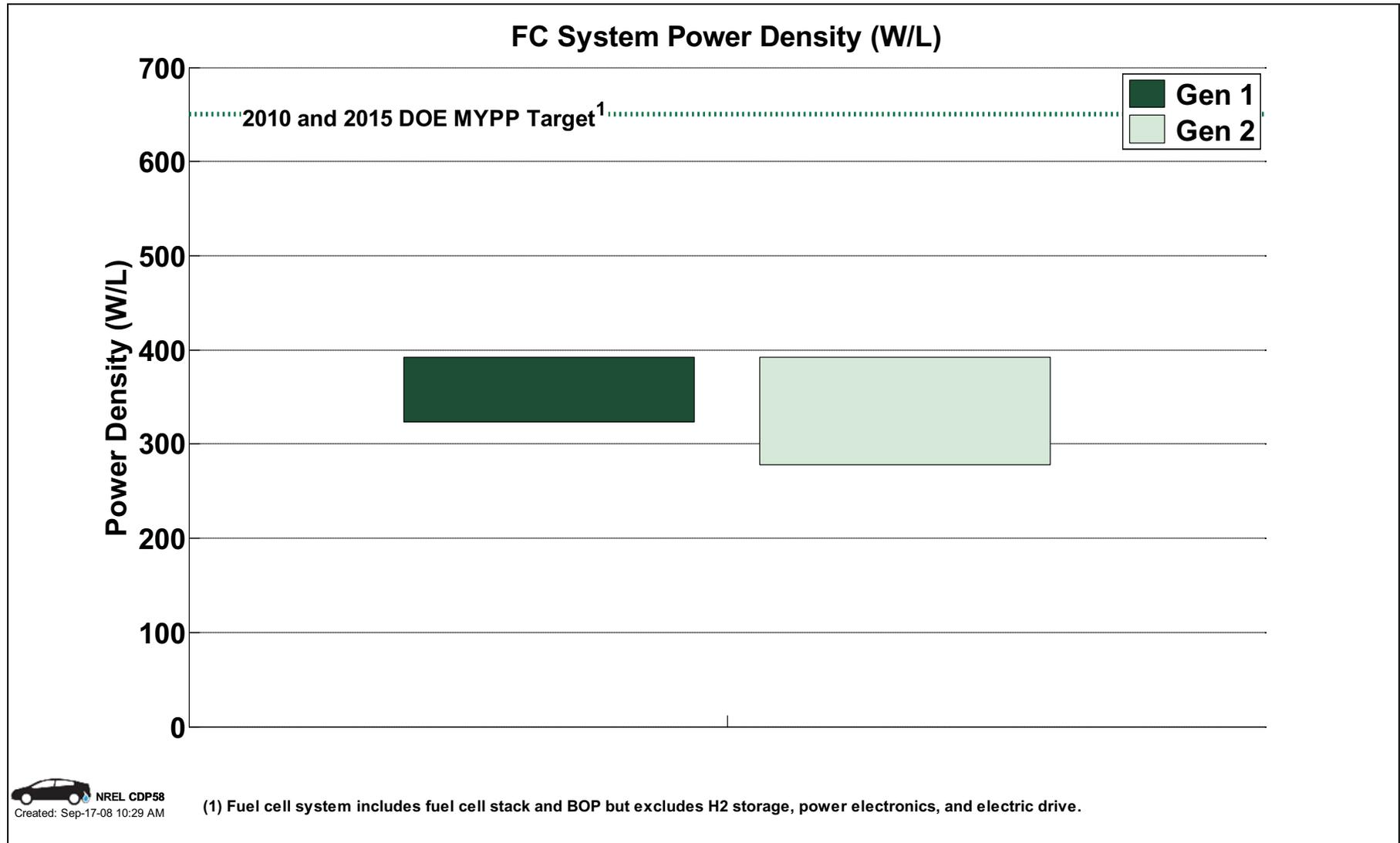
CDP#56: Daily Driving Distance



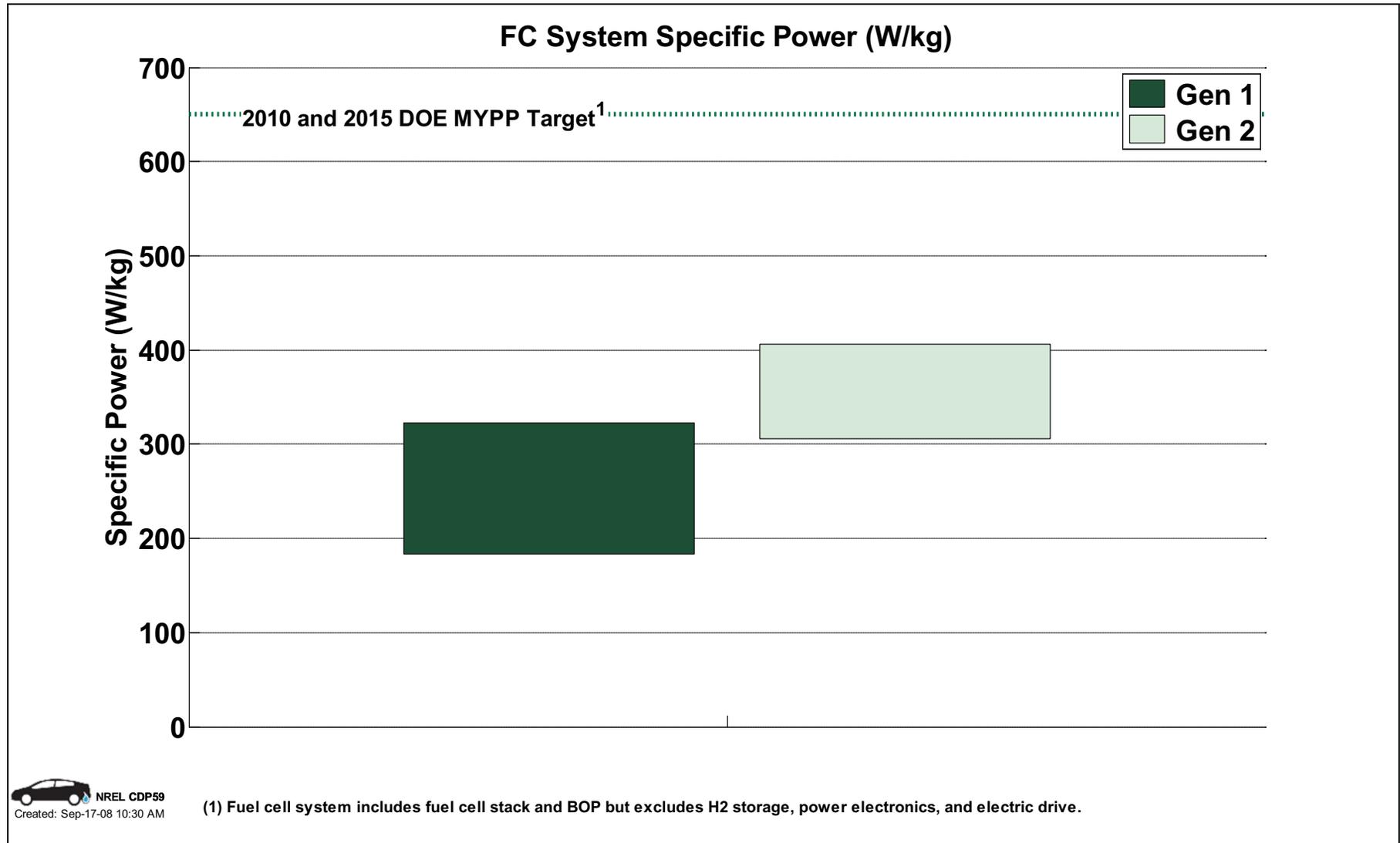
CDP#57: H2 Storage System Mass and Volume Breakdown



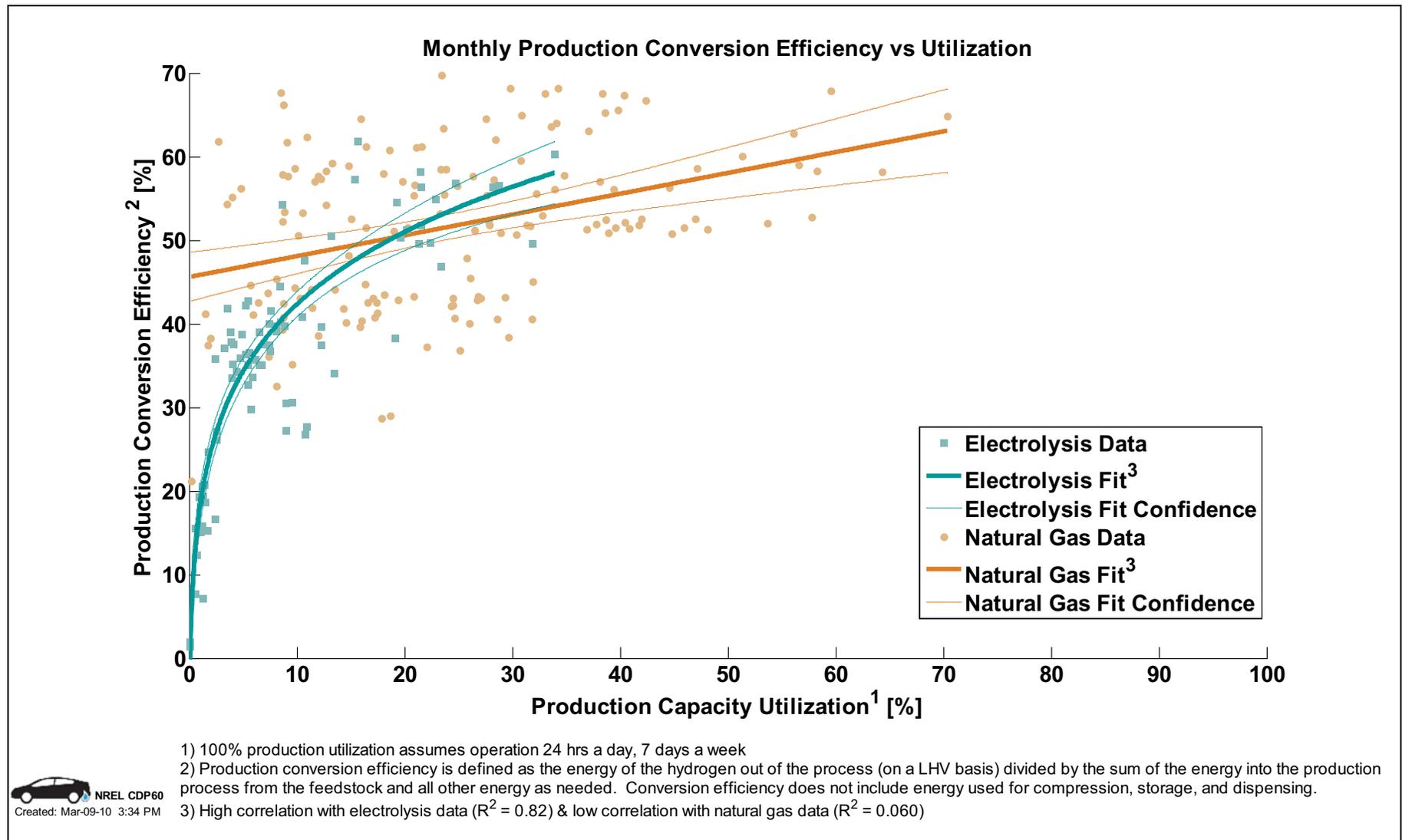
CDP#58: Fuel Cell System Power Density



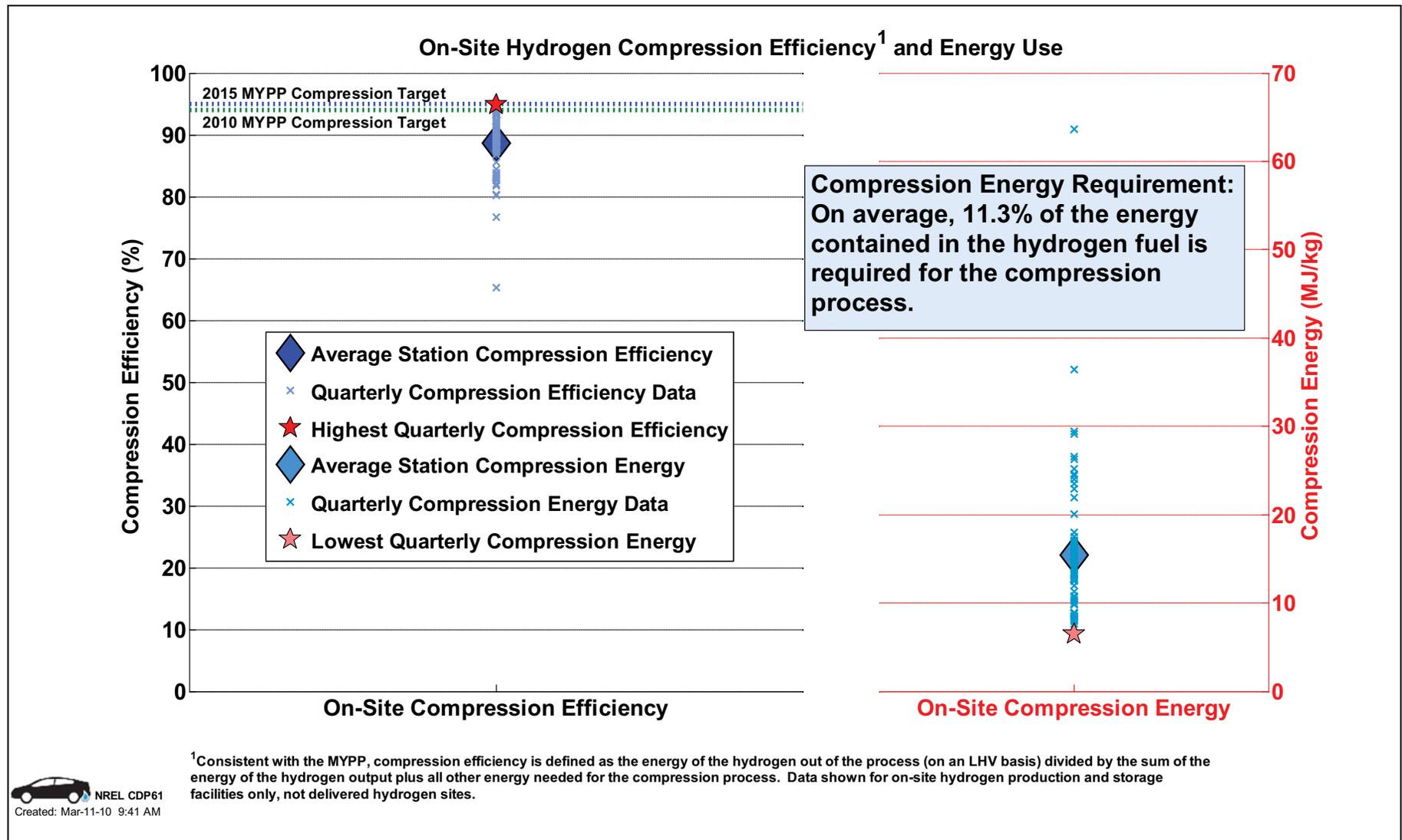
CDP#59: Fuel Cell System Specific Power



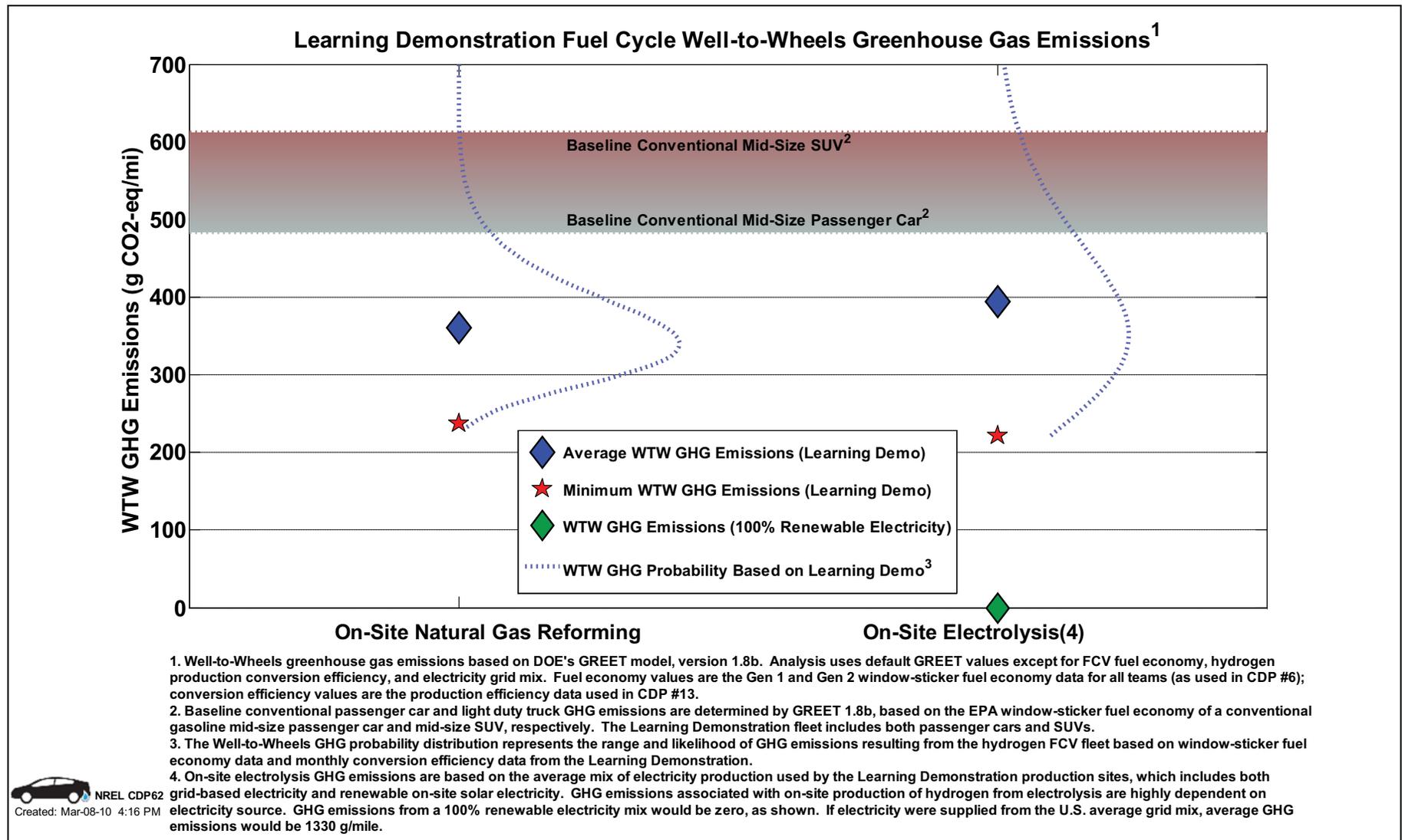
CDP#60: On-Site Hydrogen Production Efficiency vs. Capacity Utilization



CDP#61: Refueling Station Compressor Efficiency



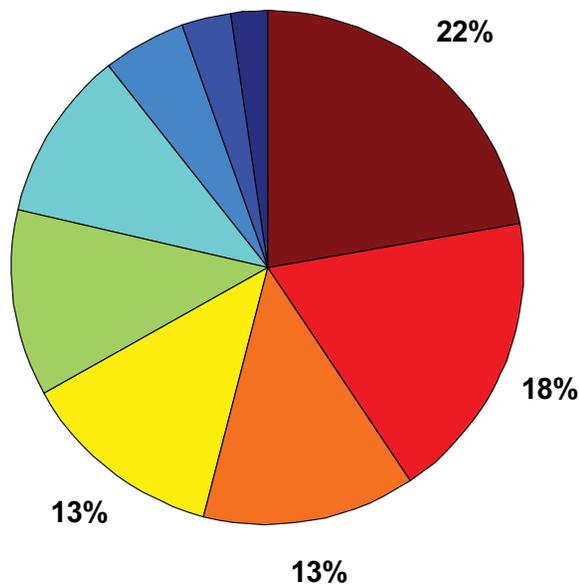
CDP#62: Learning Demonstration Vehicle Greenhouse Gas Emissions



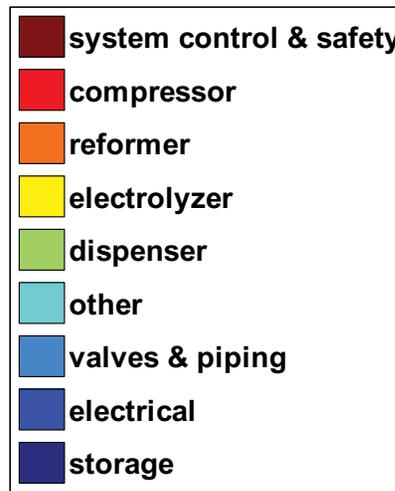
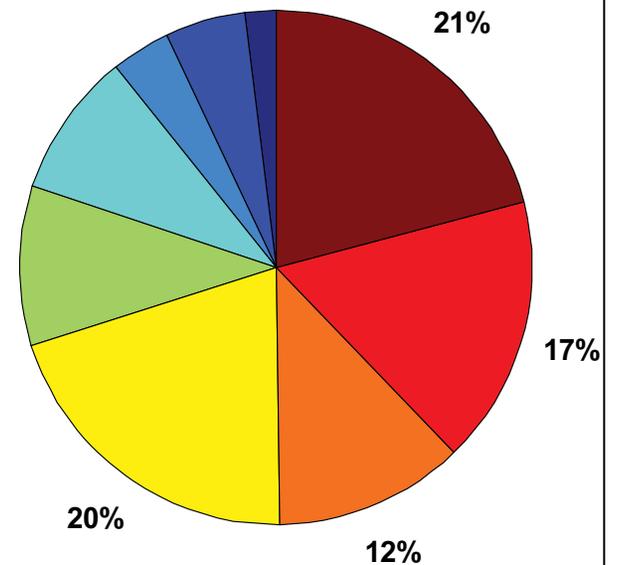
CDP#63: Hydrogen Fueling Station Maintenance by System

Hydrogen Fueling Station Maintenance

By Number of Events
Total Number of Events = 2491



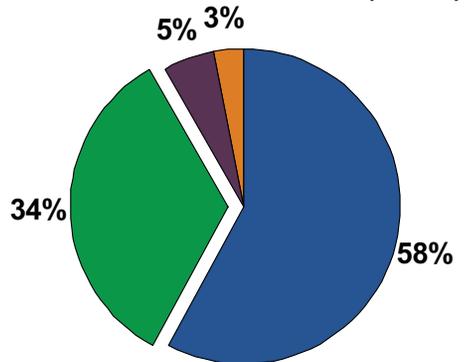
By Labor Hours
Total Hours = 11430



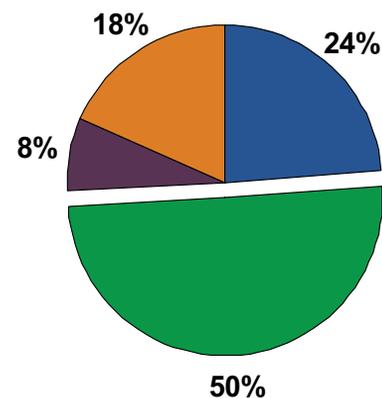
CDP#64: Fuel Cell Vehicle Maintenance by System

Fuel Cell Vehicle Maintenance Events and Labor Hours

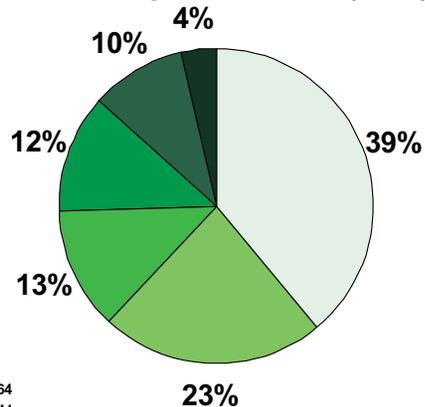
Fuel Cell Vehicle Events (11574)



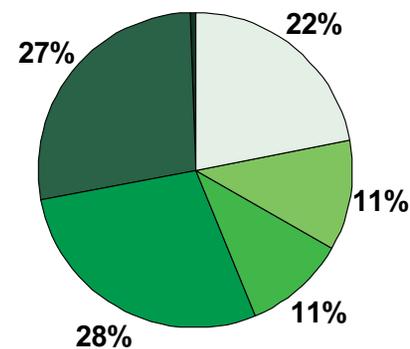
Fuel Cell Vehicle Labor (12522 hours)



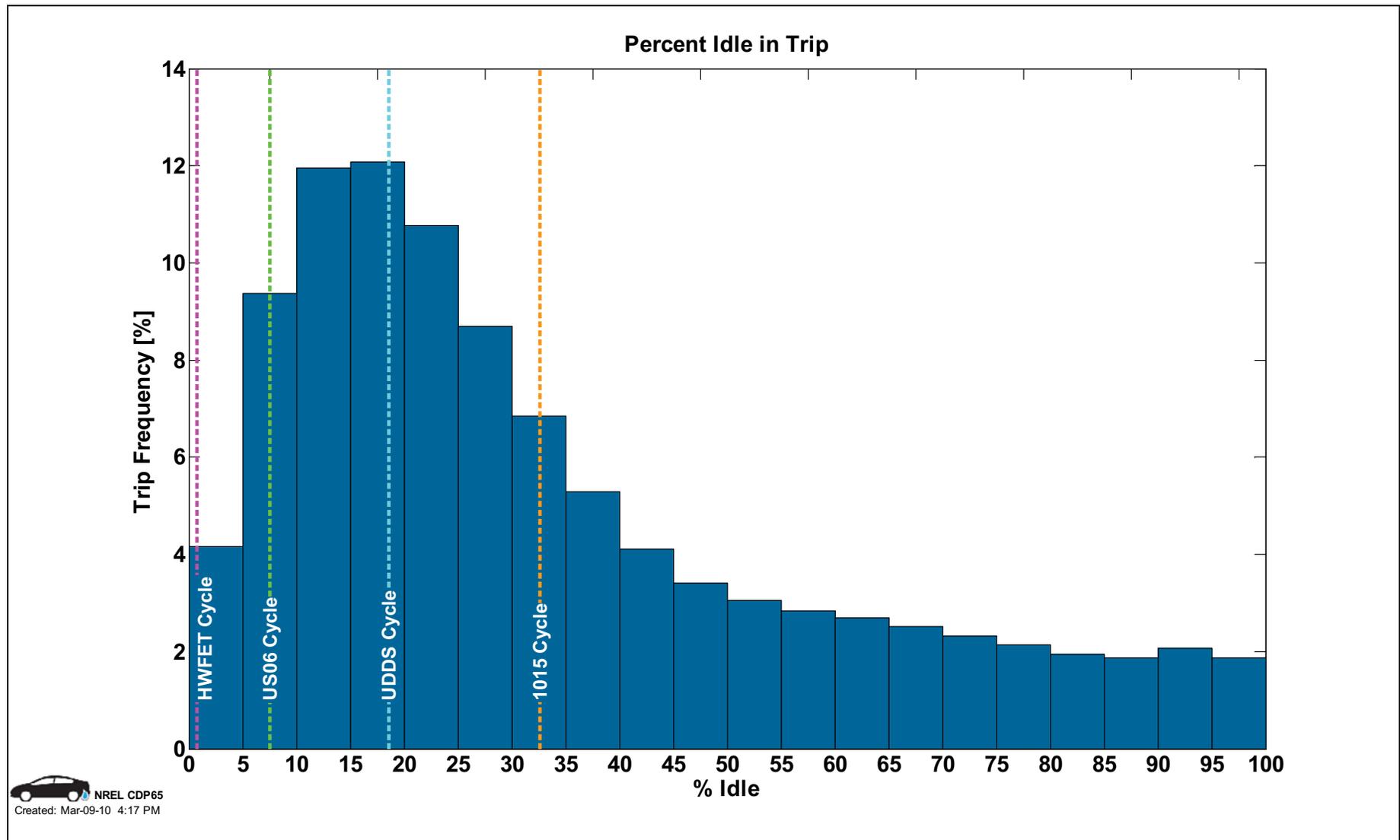
Fuel Cell System Events (3916)



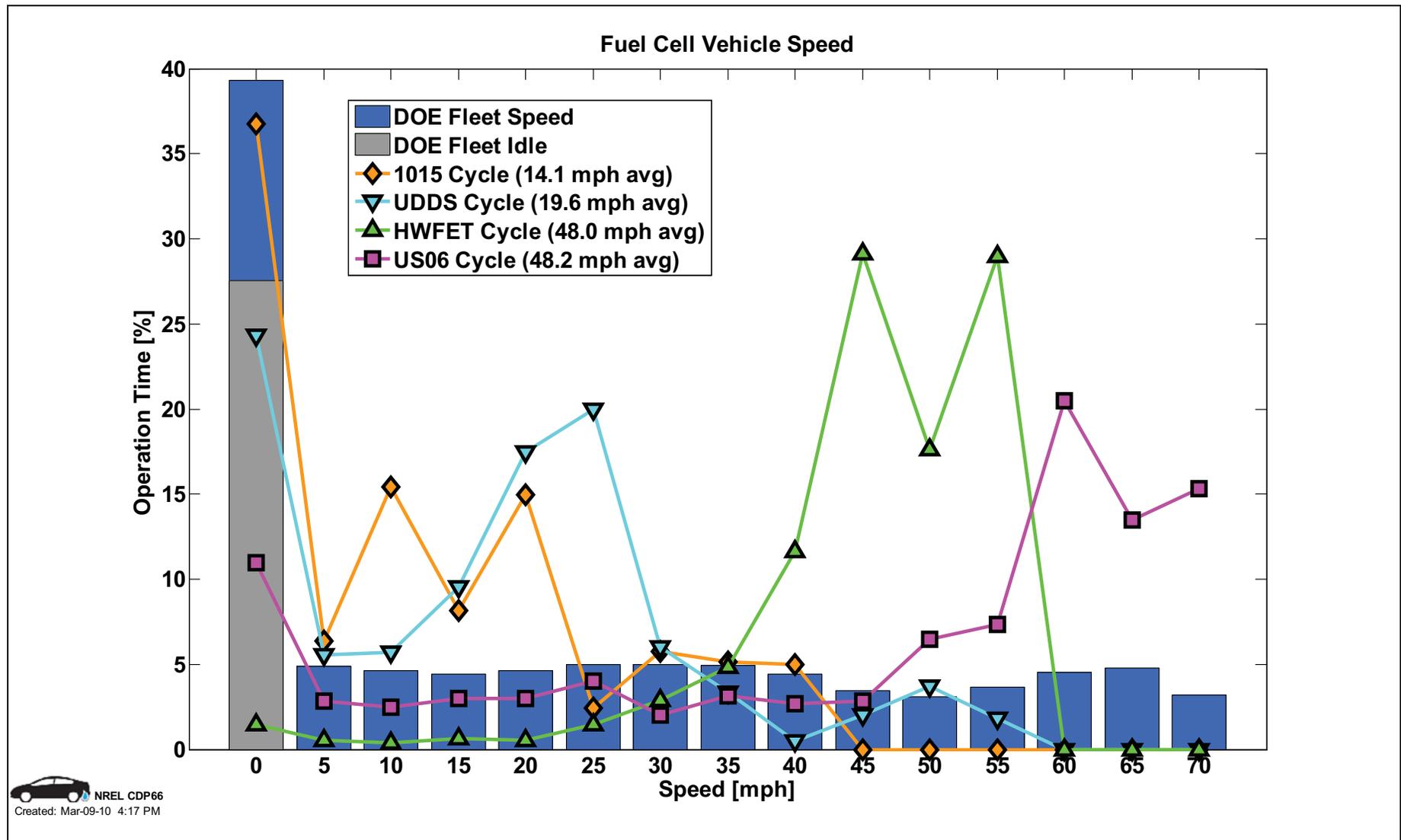
Fuel Cell System Labor (6304 hours)
< 1%



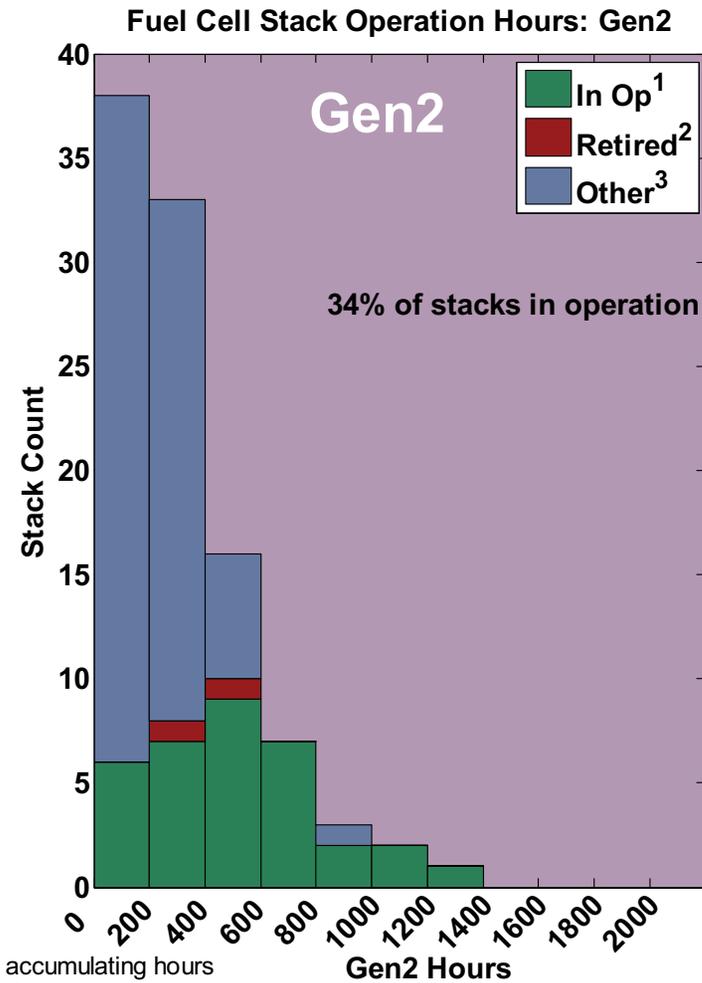
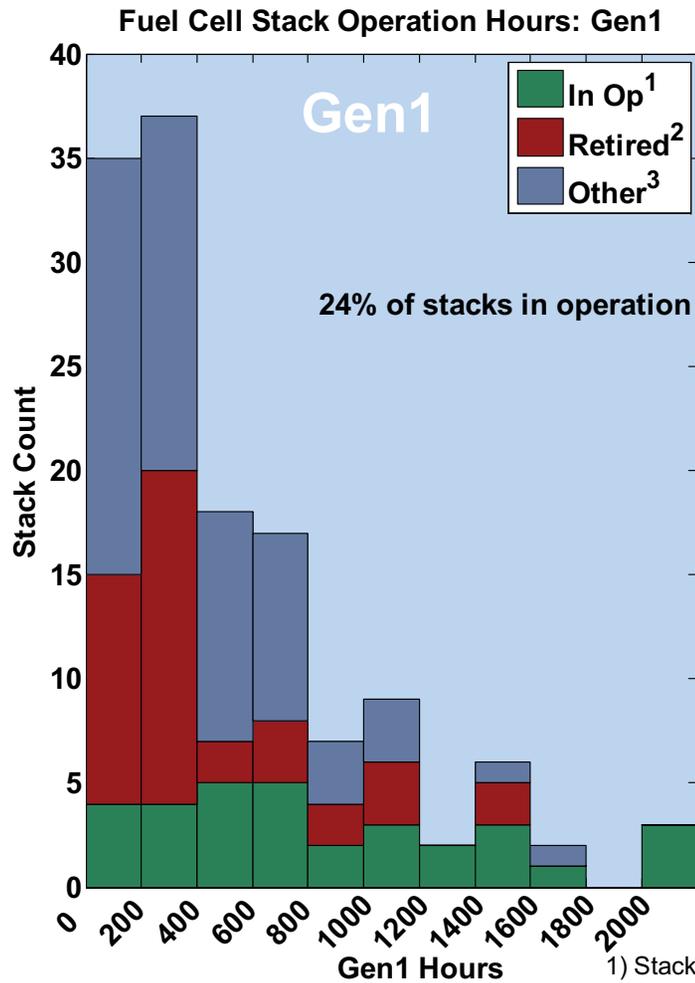
CDP#65: Percent Idle in Trip with Comparison to Standard Drive Cycles



CDP#66: FCV Speed with Comparison to Standard Drive Cycles

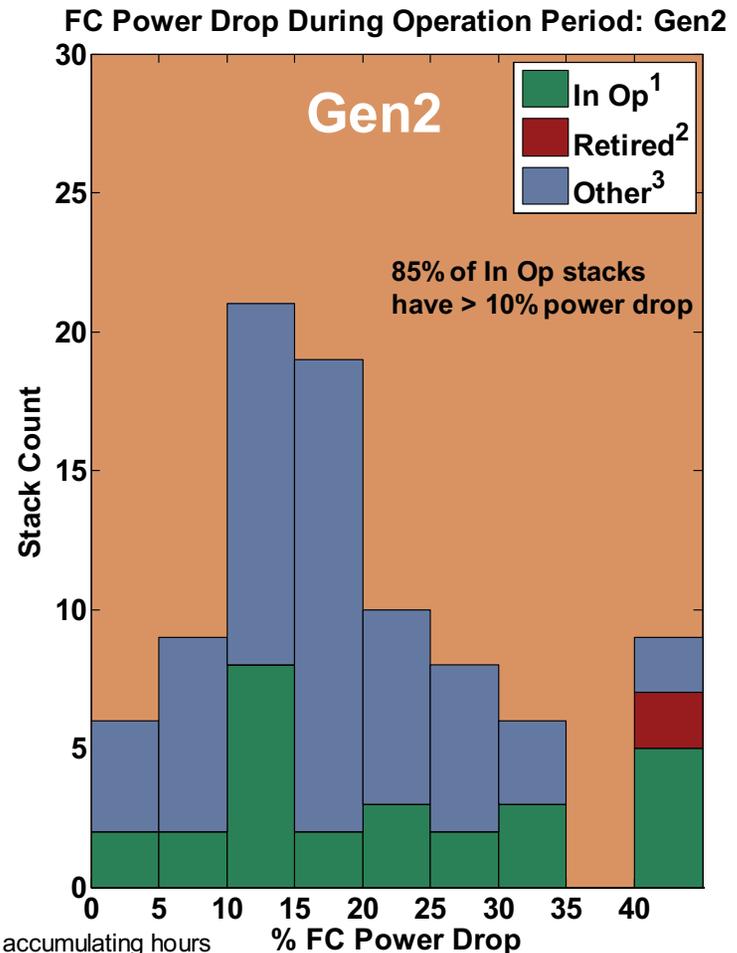
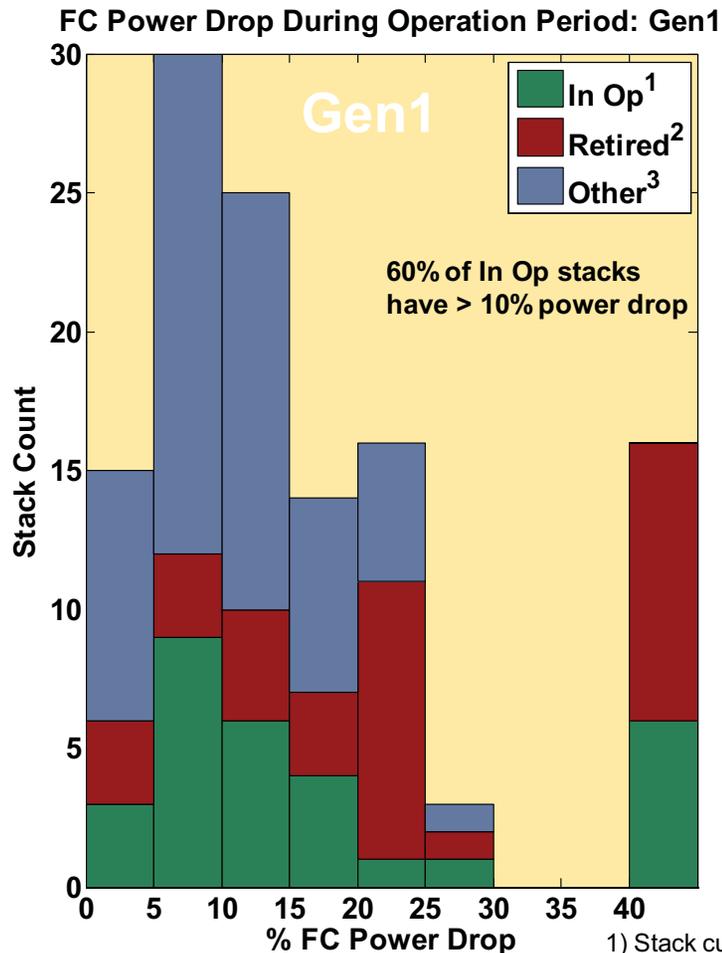


CDP#67: Fuel Cell Stack Operation Hours



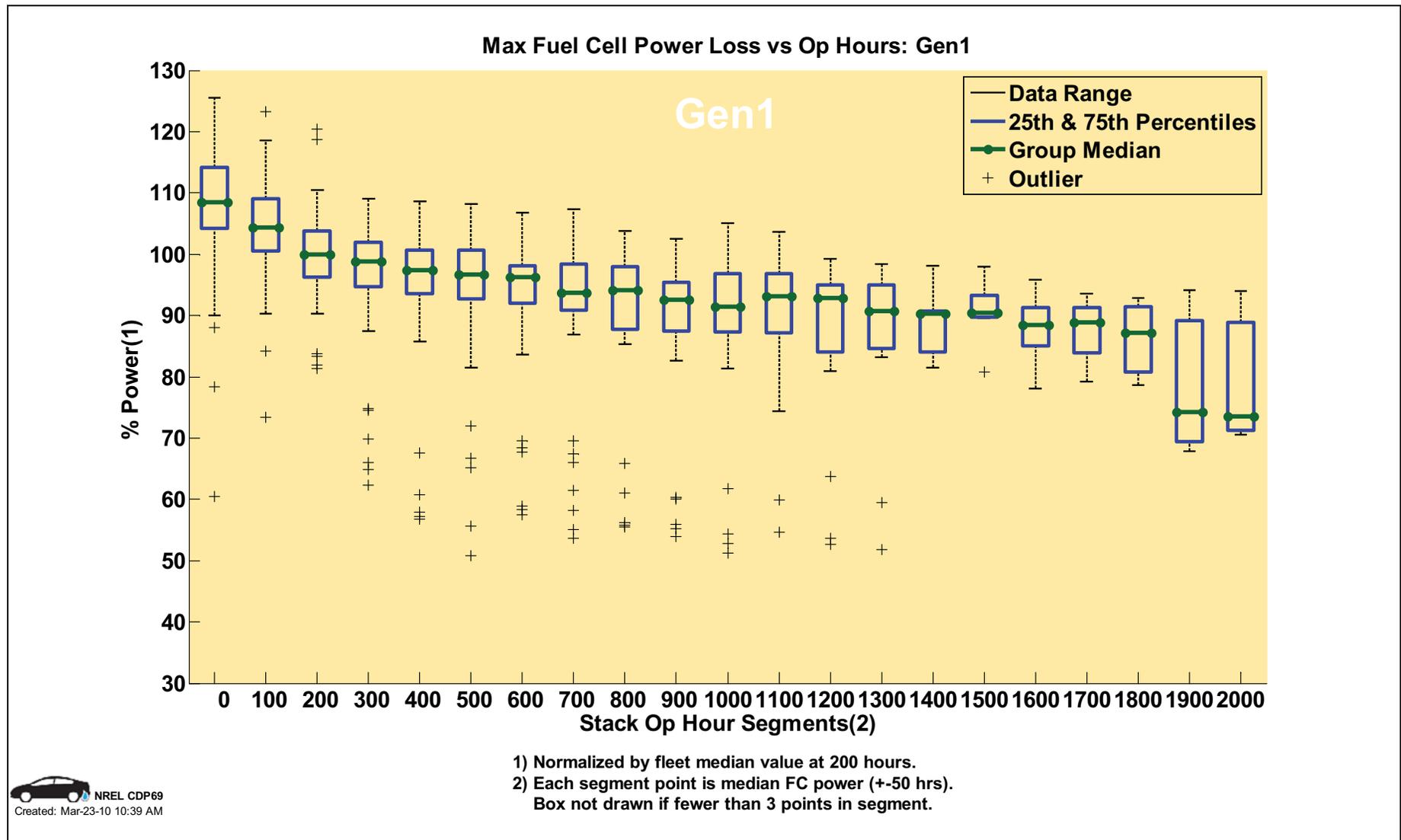
- 1) Stack currently accumulating hours
 - 2) Stack removed for low performance
 - 3) Stack not currently accumulating hours, but not removed because of low performance.
- Some project teams concluded in Fall/Winter 2009

CDP#68: Power Drop During Fuel Cell Stack Operation Period

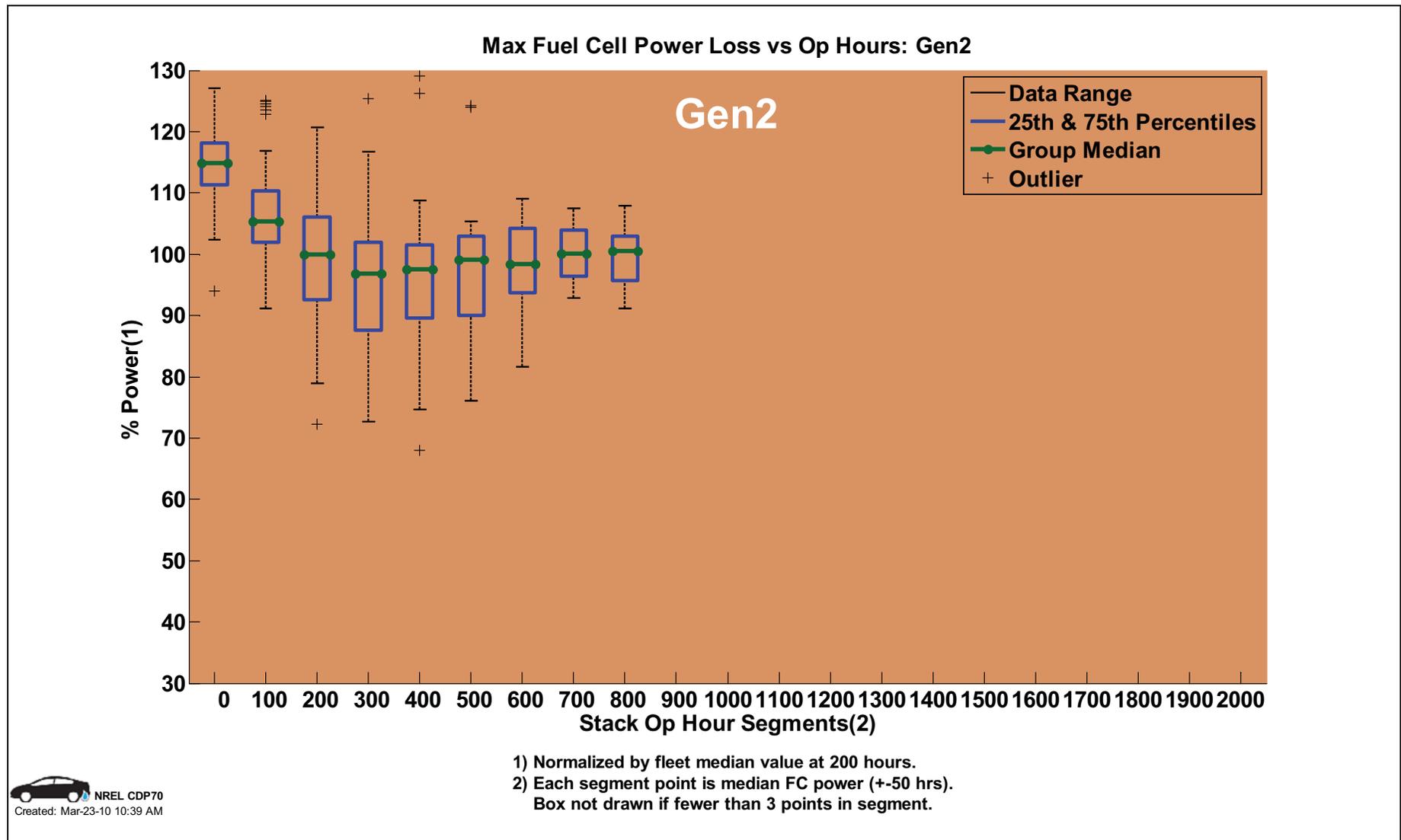


- 1) Stack currently accumulating hours
- 2) Stack removed for low performance
- 3) Stack not currently accumulating hours, but not removed because of low performance.
Some project teams concluded in Fall/Winter 2009

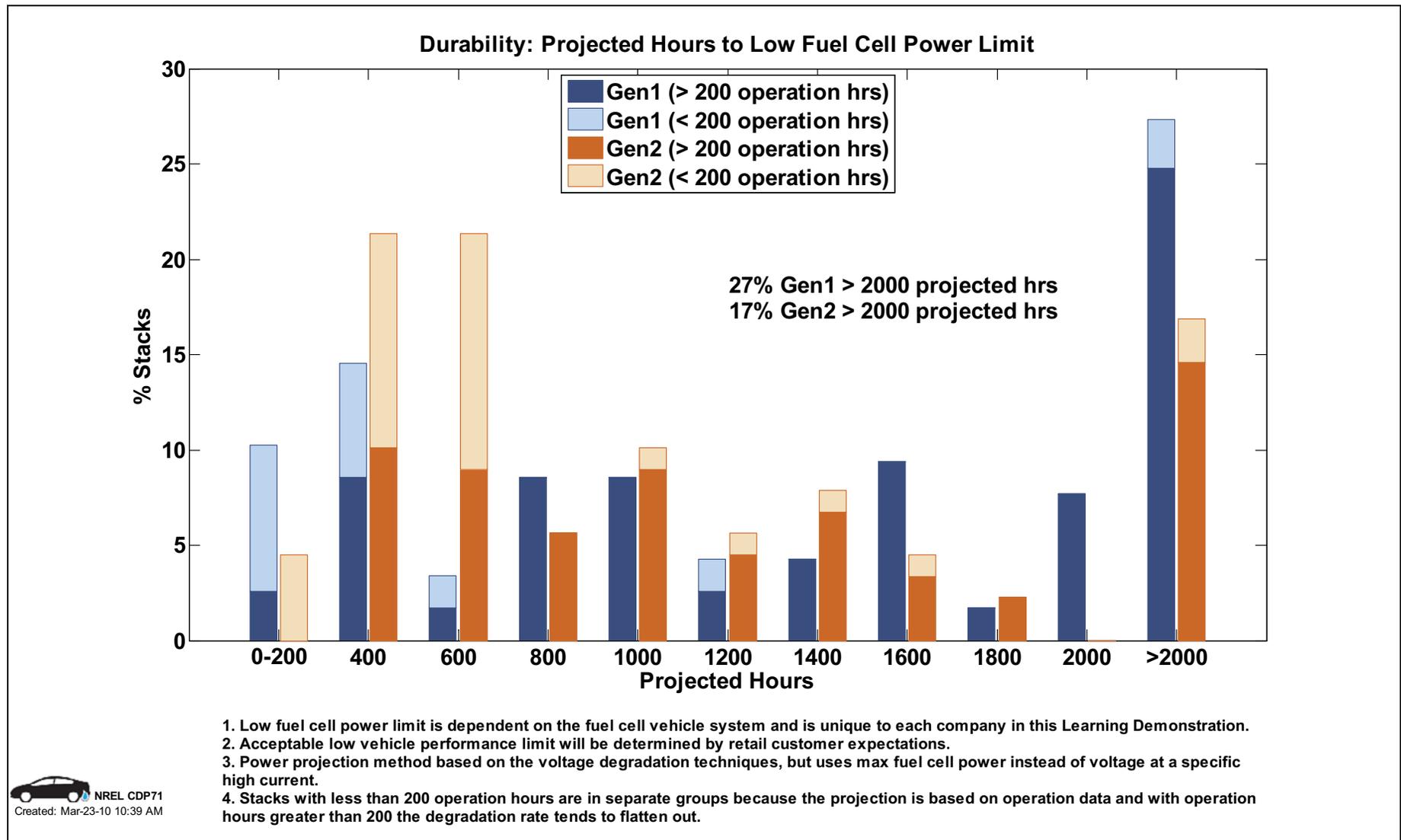
CDP#69: Max Fuel Cell Power Degradation – Gen 1



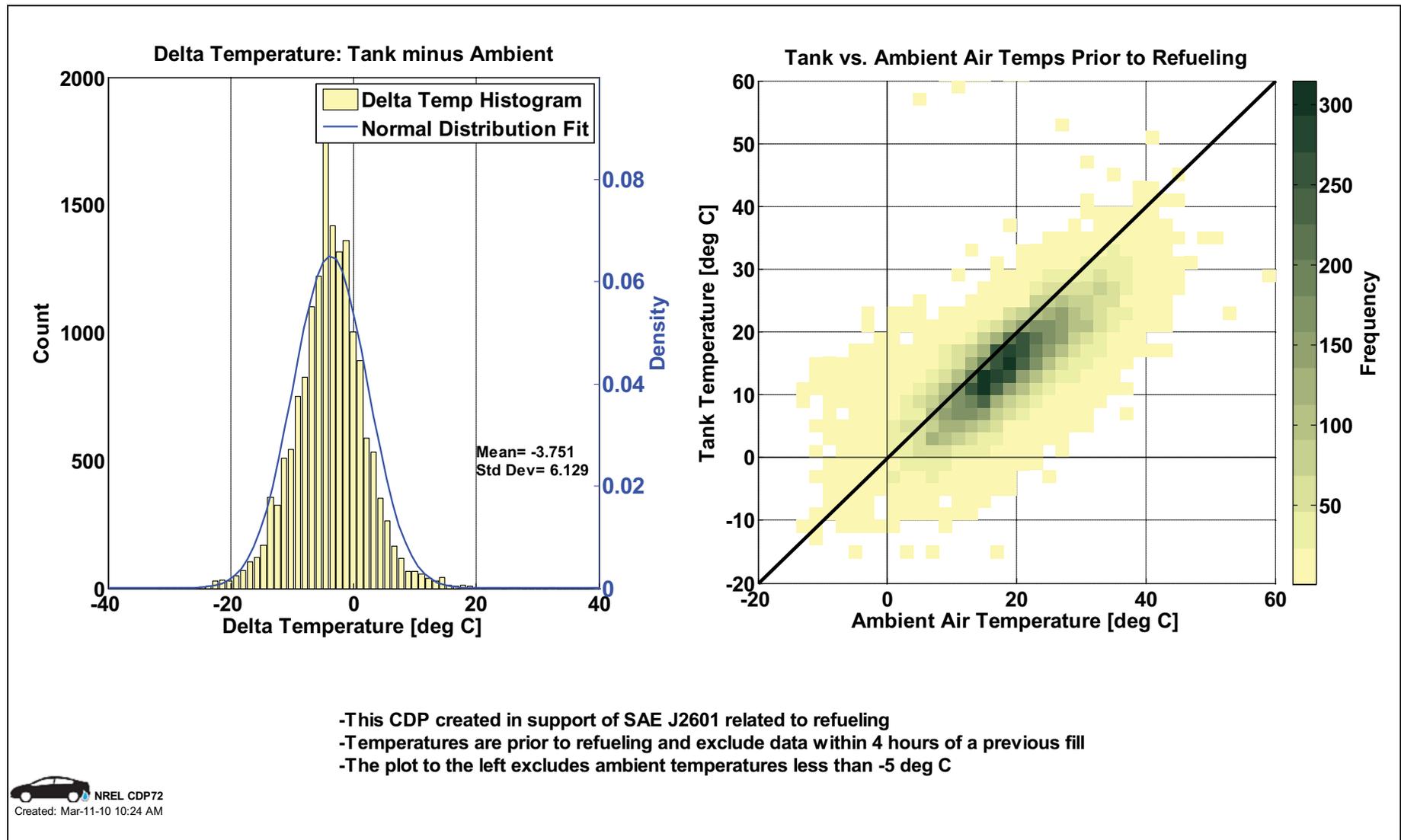
CDP#70: Max Fuel Cell Power Degradation – Gen 2



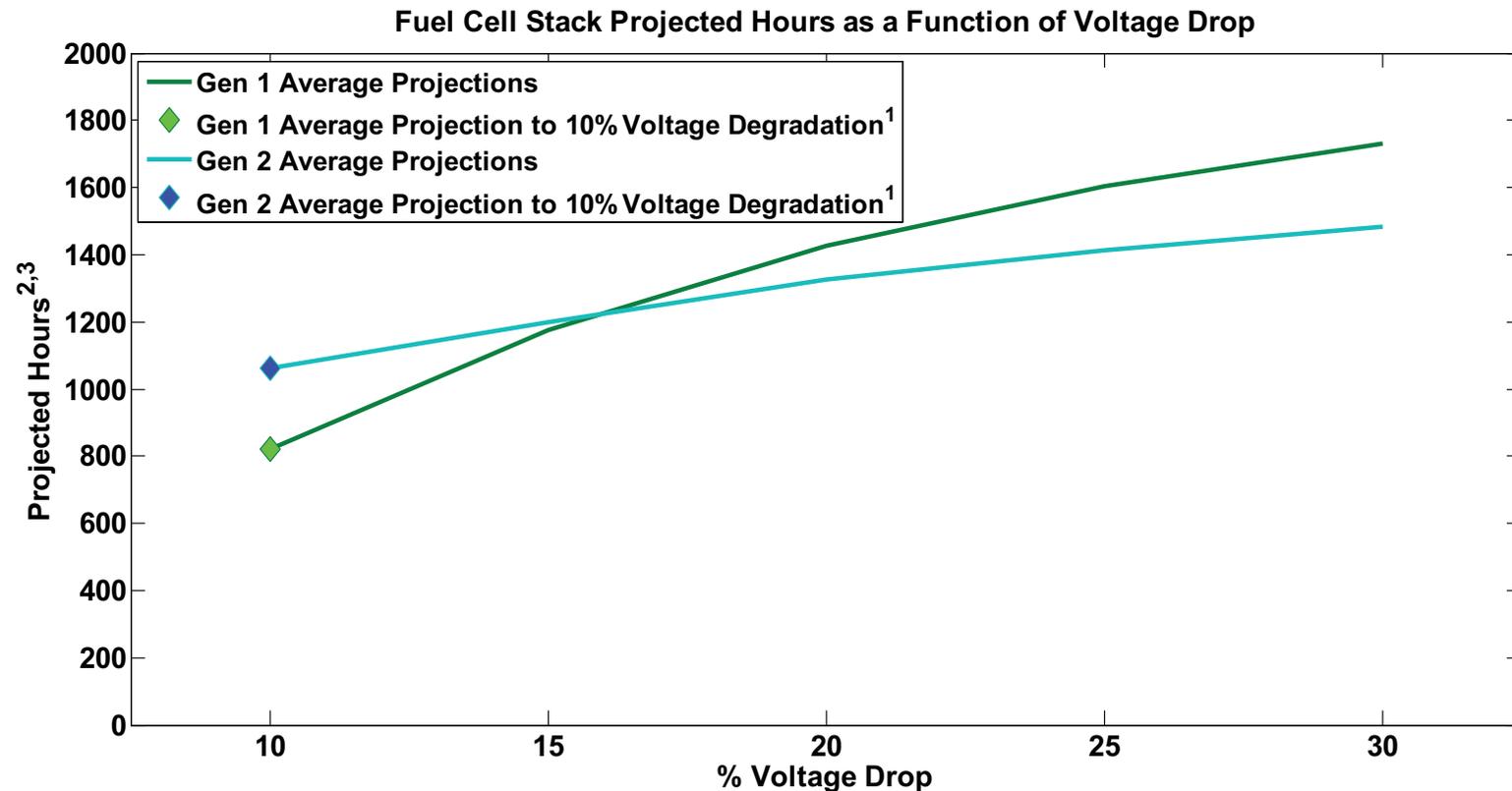
CDP#71: Projected Hours to OEM Low Power Operation Limit



CDP#72: Difference Between Tank and Ambient Temperature Prior to Refueling

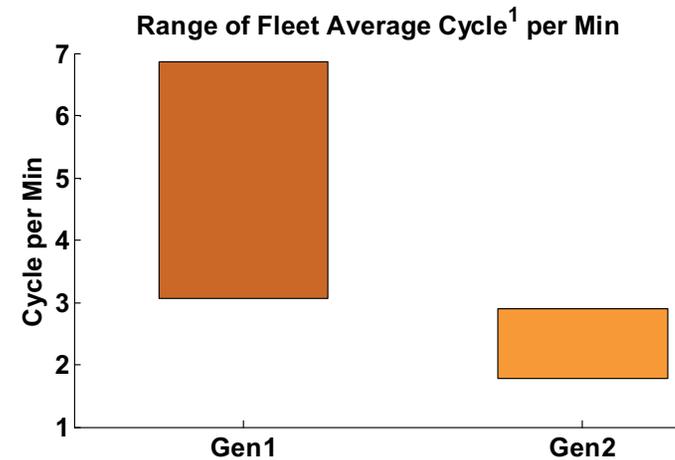
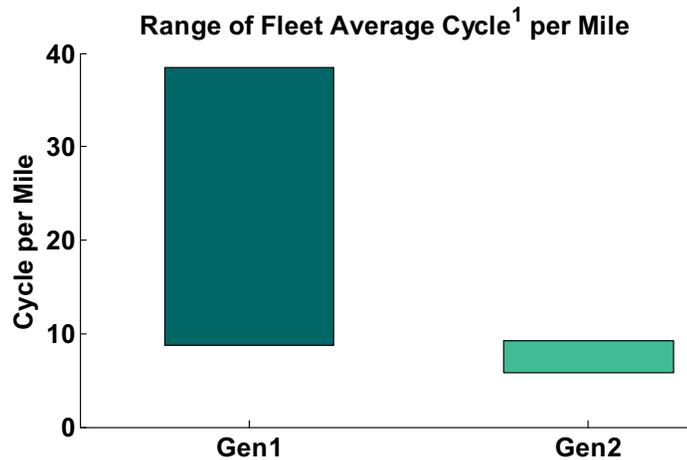
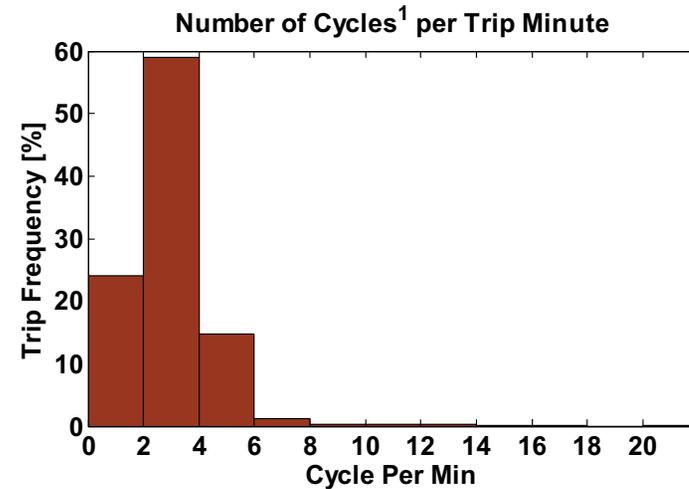
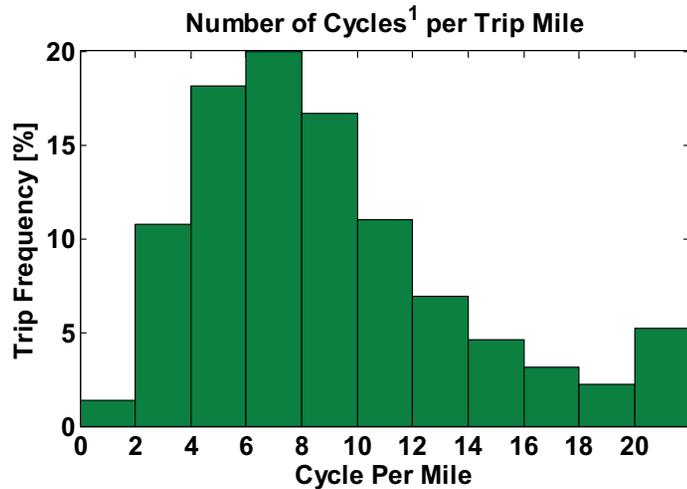


CDP#73: Fuel Cell Stack Projected Hours as a Function of Voltage Drop



- (1) 10% Voltage degradation is a DOE metric for assessing fuel cell performance.
- (2) Projections using on-road data -- degradation calculated at high stack current.
- (3) Curves generated using the Learning Demonstration average of each individual fleet average at various voltage degradation levels.
- (4) The projection curves display the sensitivity to percentage of voltage degradation, but the projections do not imply that all stacks will (or do) operate at these voltage degradation levels.
- (5) The voltage degradation levels are not an indication of an OEM's end-of-life criteria and do not address catastrophic stack failures such as membrane failure.
- (6) All OEM Gen 2 average fleet projections are higher than Gen1 projections, however due to less operation data for Gen 2, these projections are limited by demonstrated operation hours to minimize extrapolations.

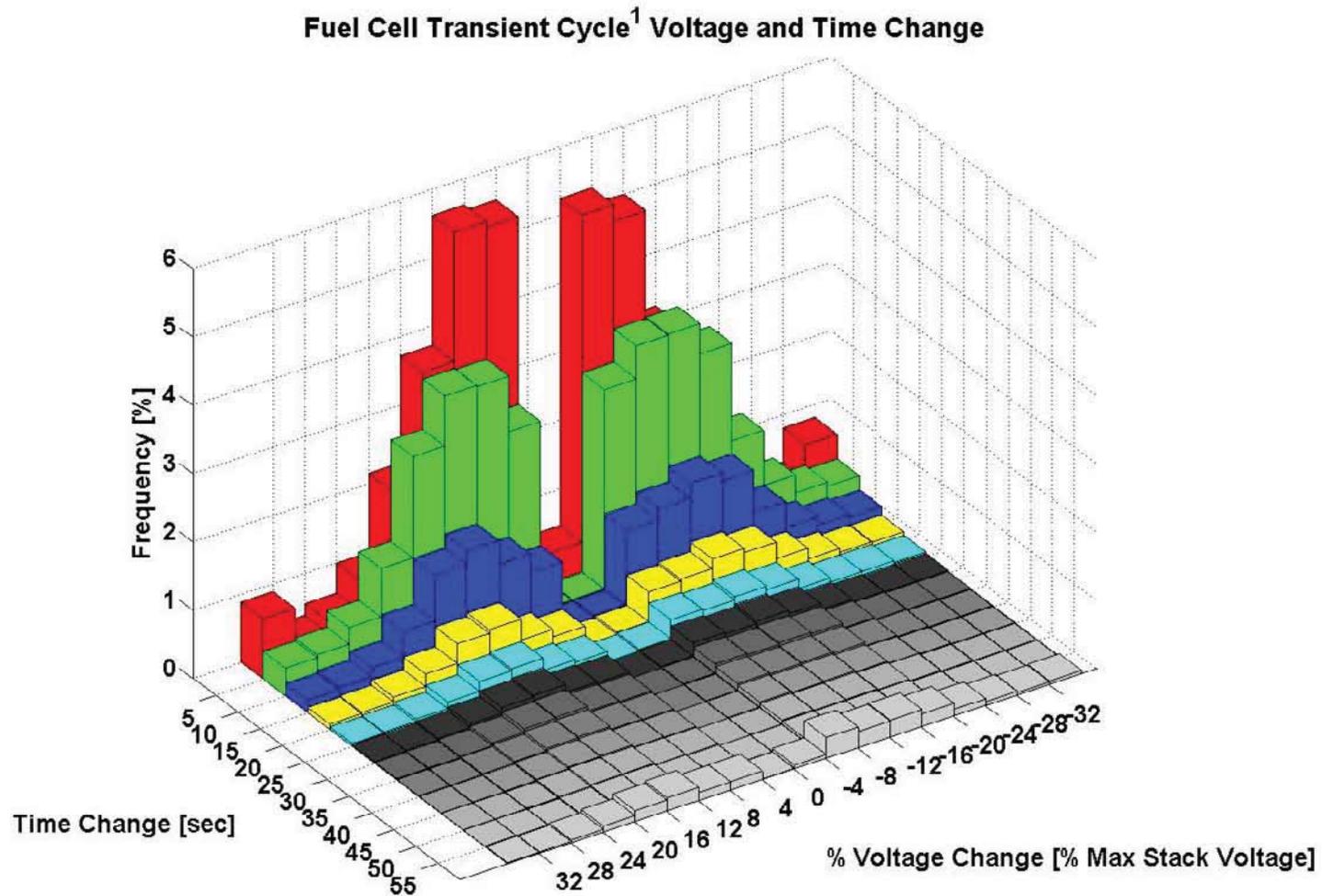
CDP#74: Fuel Cell Transient Cycle Count per Mile and per Minute



 NREL CDP74
Created: Mar-22-10 4:46 PM

1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

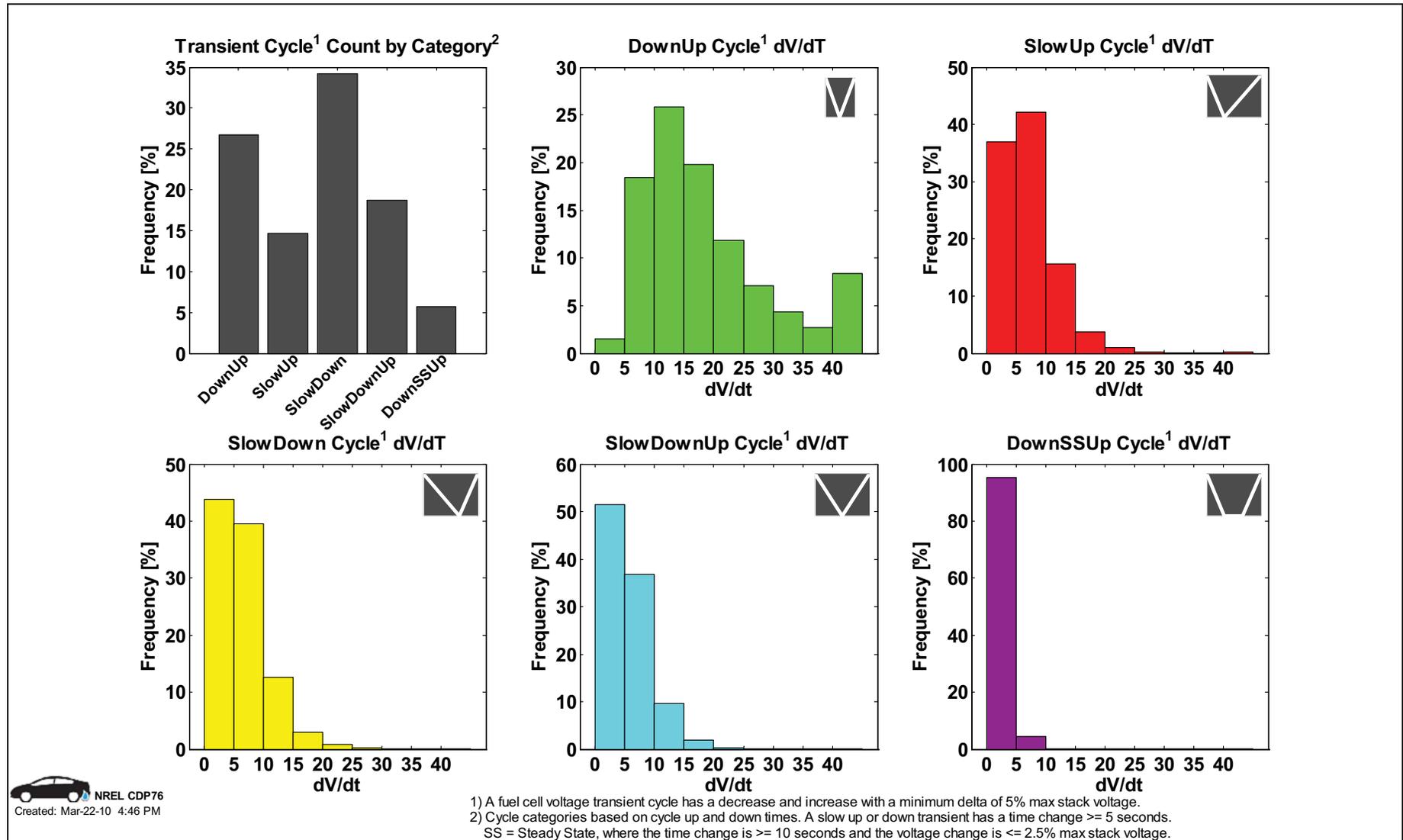
CDP#75: Fuel Cell Transient Voltage and Time Change



 NREL CDP75
Created: Mar-22-10 4:46 PM

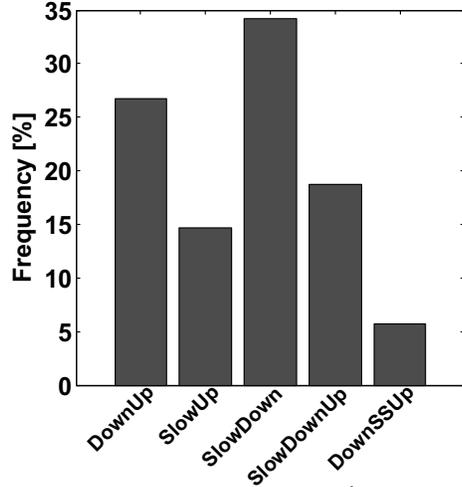
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

CDP#76: Fuel Cell Transient Rate by Cycle Category

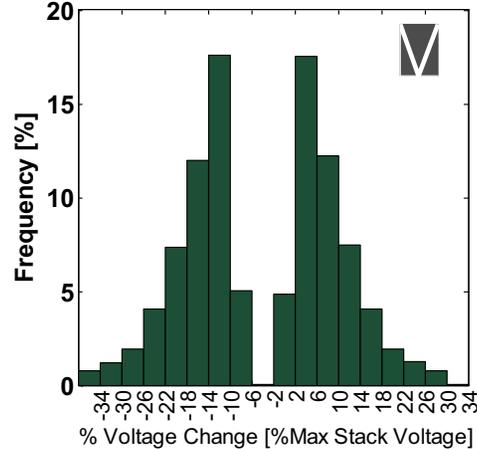


CDP#77: Fuel Cell Transient Voltage Changes by Cycle Category

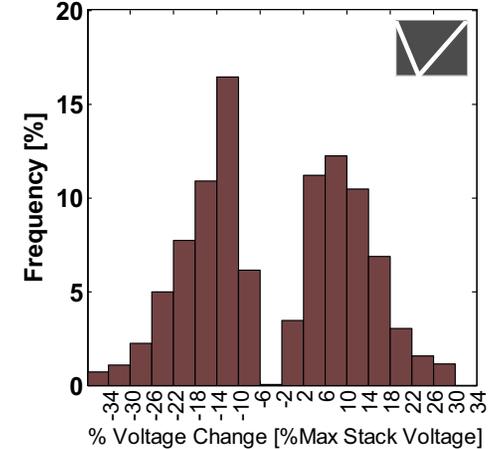
Transient Cycle¹ Count by Category²



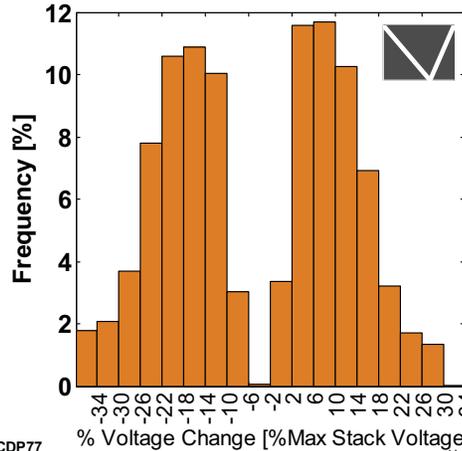
DownUp Cycle¹ dV



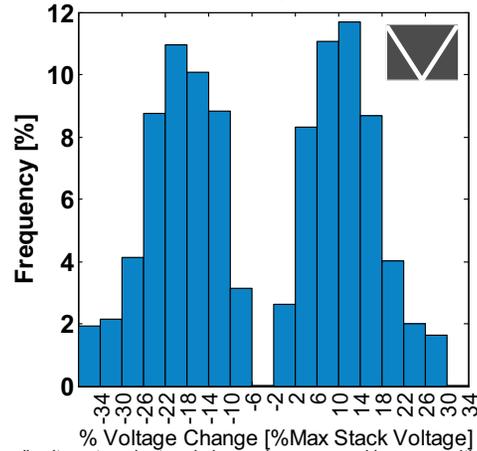
SlowUp Cycle¹ dV



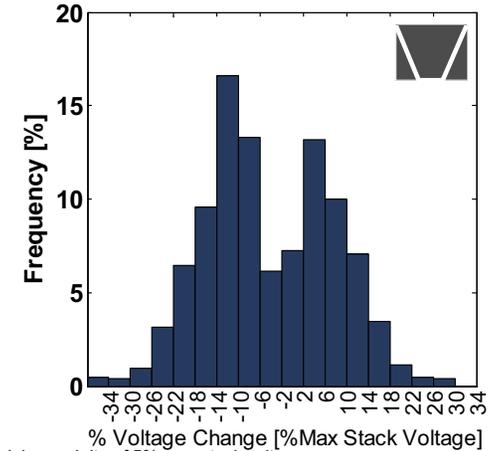
SlowDown Cycle¹ dV



SlowDownUp Cycle¹ dV



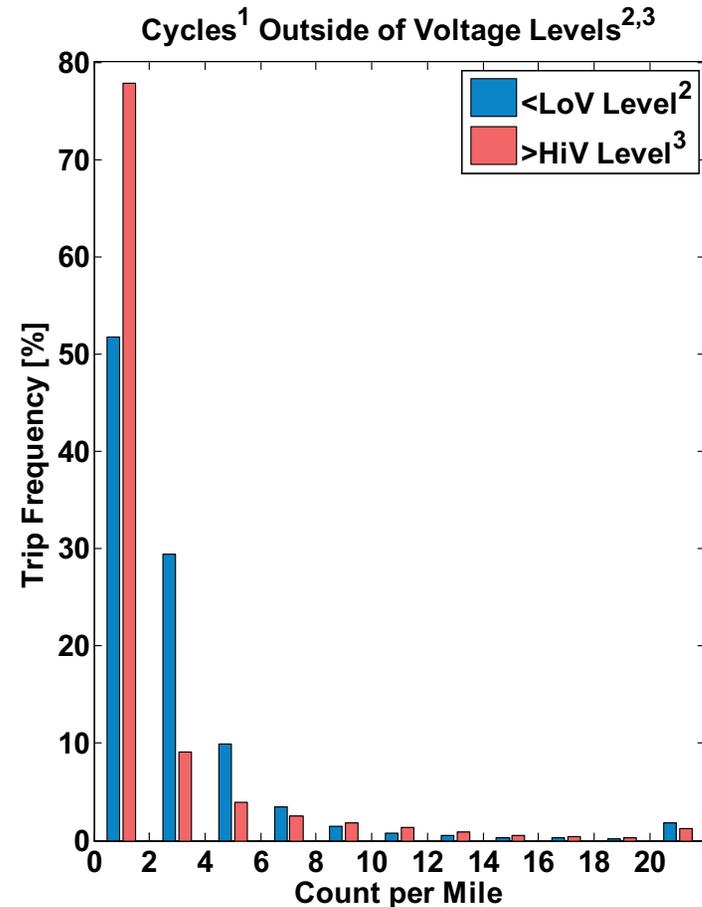
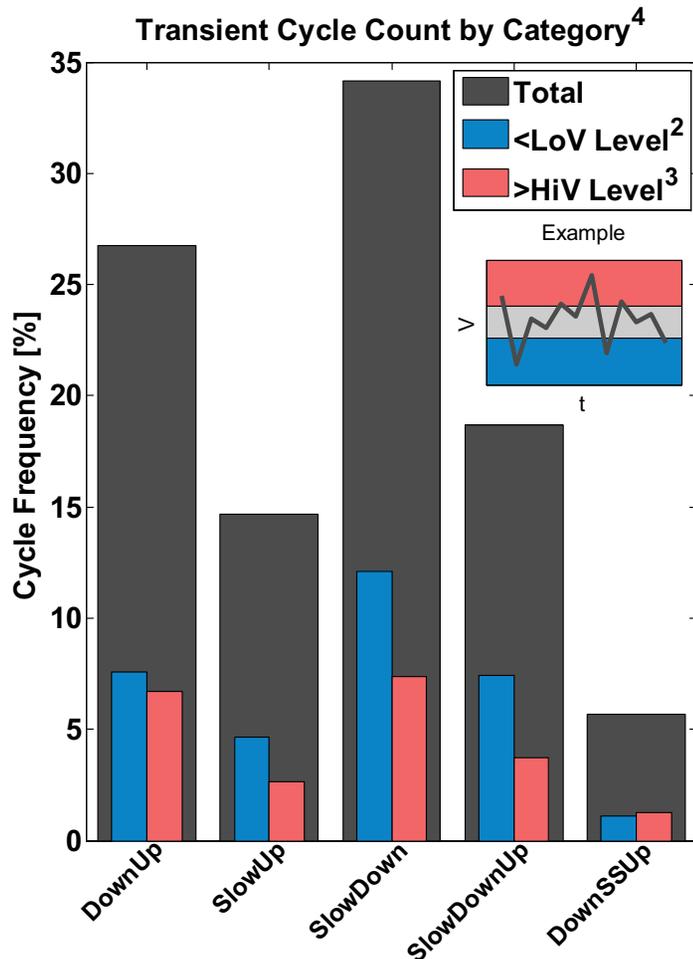
DownSSUp Cycle¹ dV



 NREL CDP77
Created: Mar-22-10 4:46 PM

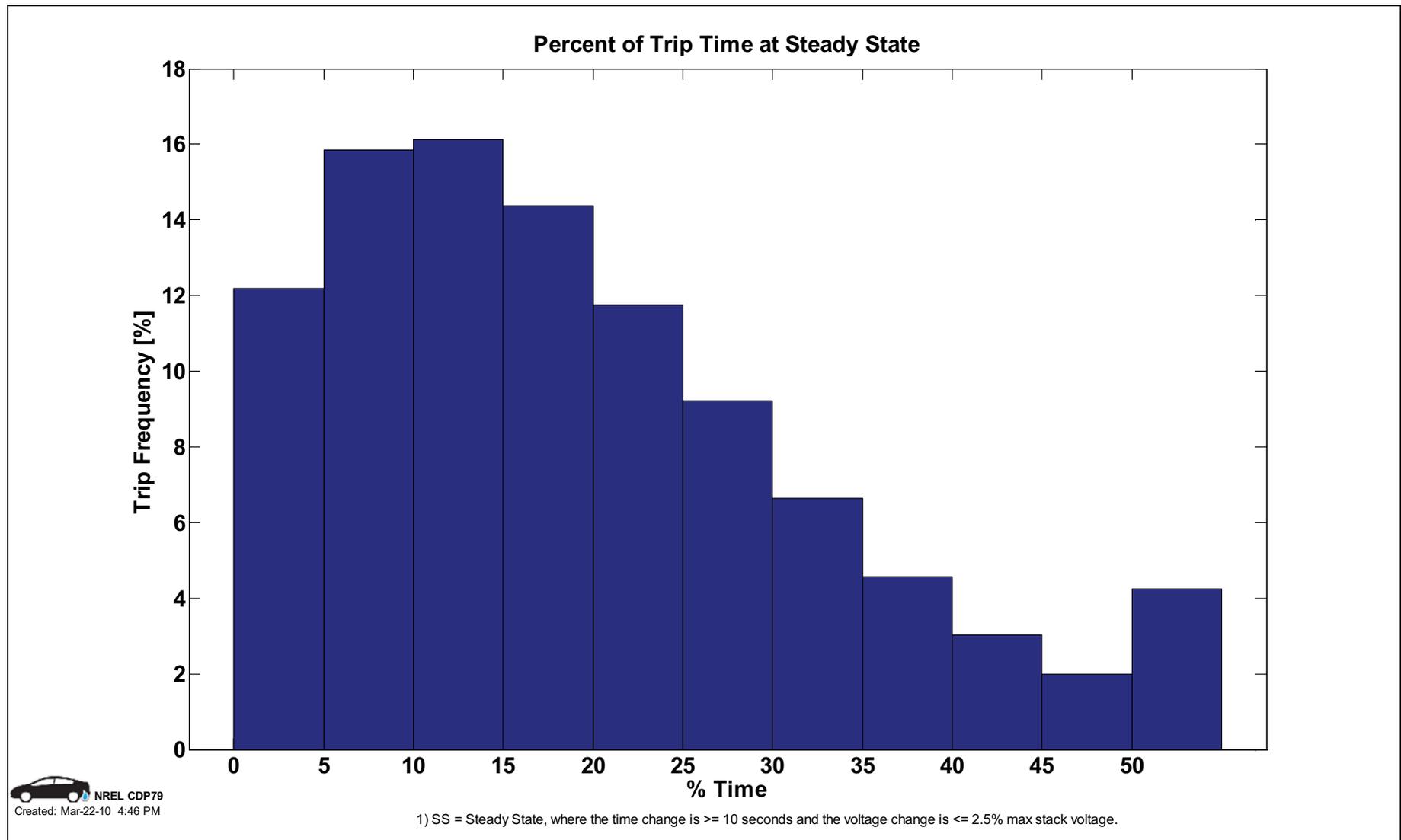
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change ≥ 5 seconds.
SS = Steady State, where the time change is ≥ 10 seconds and the voltage change is $\leq 2.5\%$ max stack voltage.

CDP#78: Fuel Cell Transient Cycles Outside of Specified Voltage Levels



1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
 2) The low voltage level is 70% Max Stack Voltage
 3) The high voltage level is 90% Max Stack Voltage
 4) Cycle categories based on cycle up and down times. A slow up or down transient has a time change ≥ 5 seconds.
 SS = Steady State, where the time change is ≥ 10 seconds and the voltage change is $\leq 2.5\%$ max stack voltage.

CDP#79: Percentage of Trip Time at Steady State



CDP#80: Miles Between Refuelings

