




Technical Report
NREL/TP-5600-49642
September 2010

Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Fall 2010
All Composite Data Products
With Updates Through September 17, 2010

Keith Wipke, Sam Sprik, Jennifer Kurtz, Todd Ramsden

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All Composite Data Products

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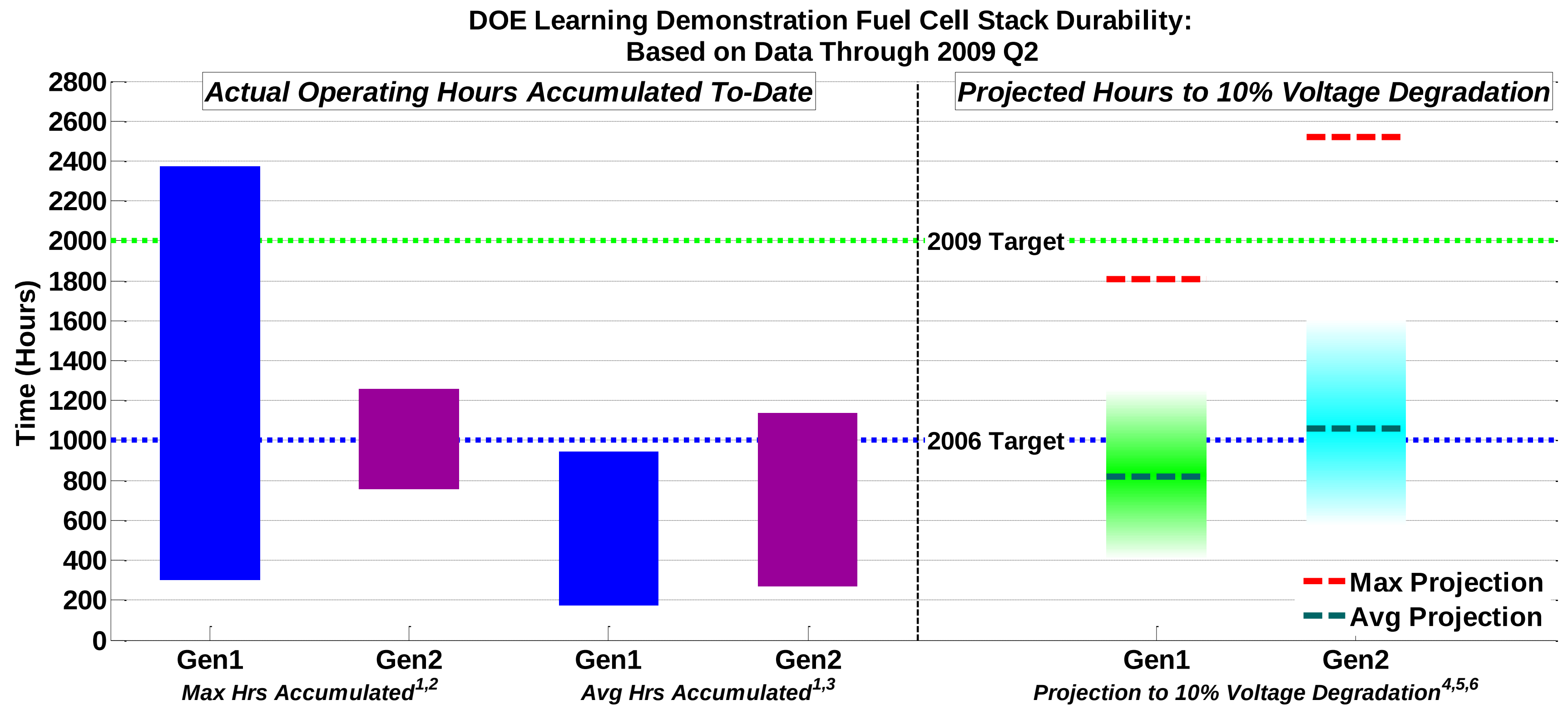
CDP#1: Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation



(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 projection bars 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 2009 Q2 data, includes an upper projection limit based on demonstrated op hours.

NREL CDP01
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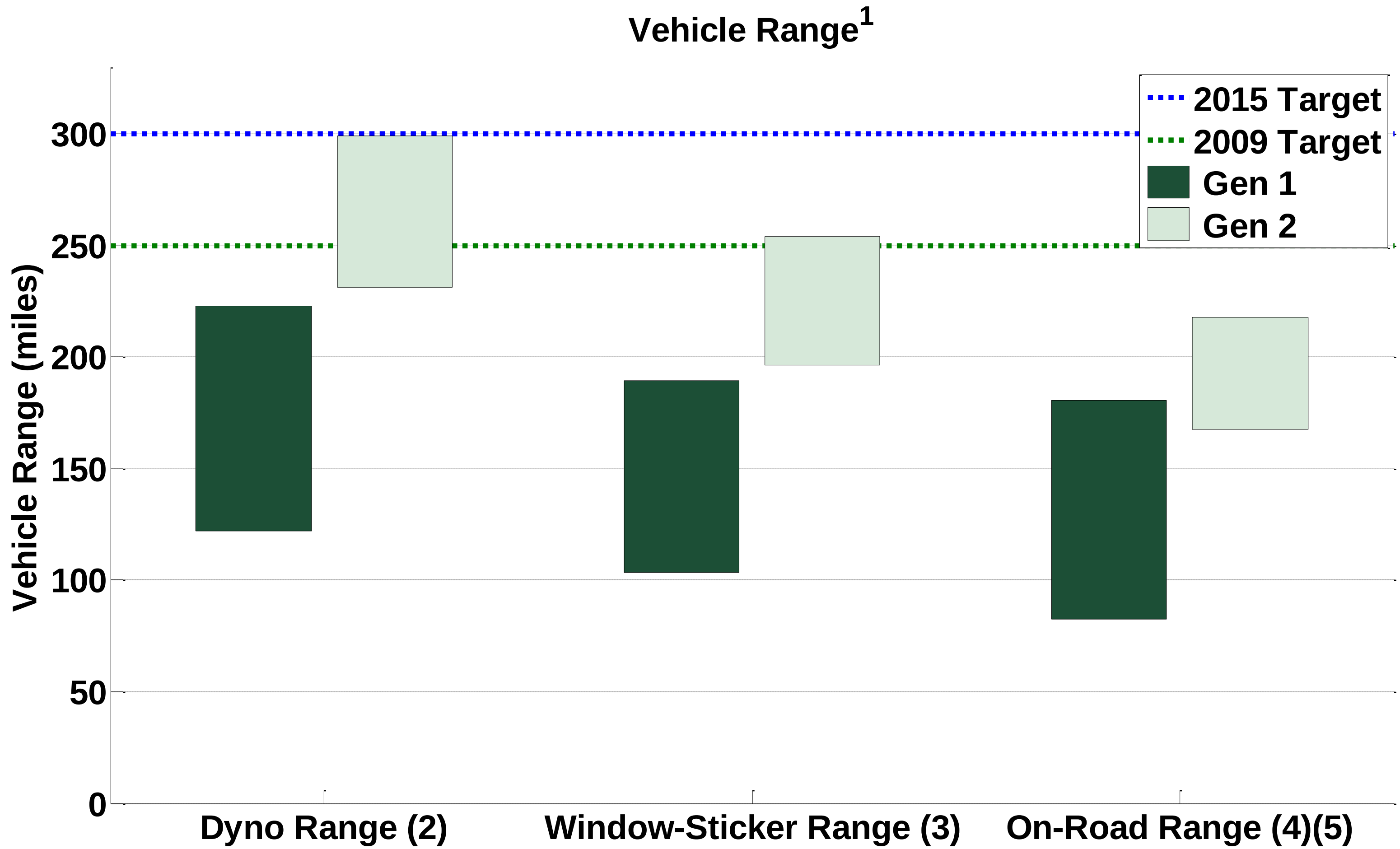
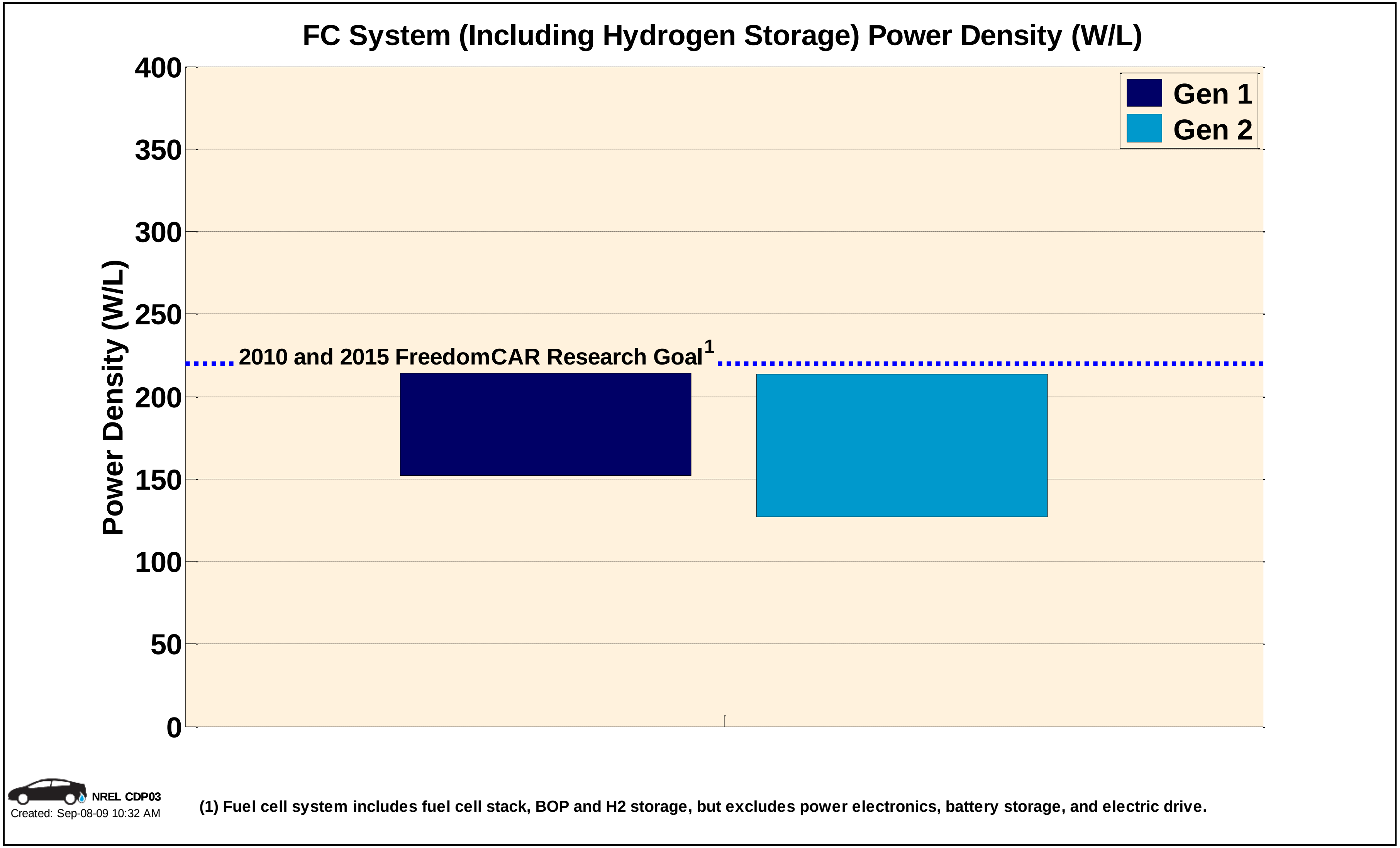
CDP#2: Vehicle Range



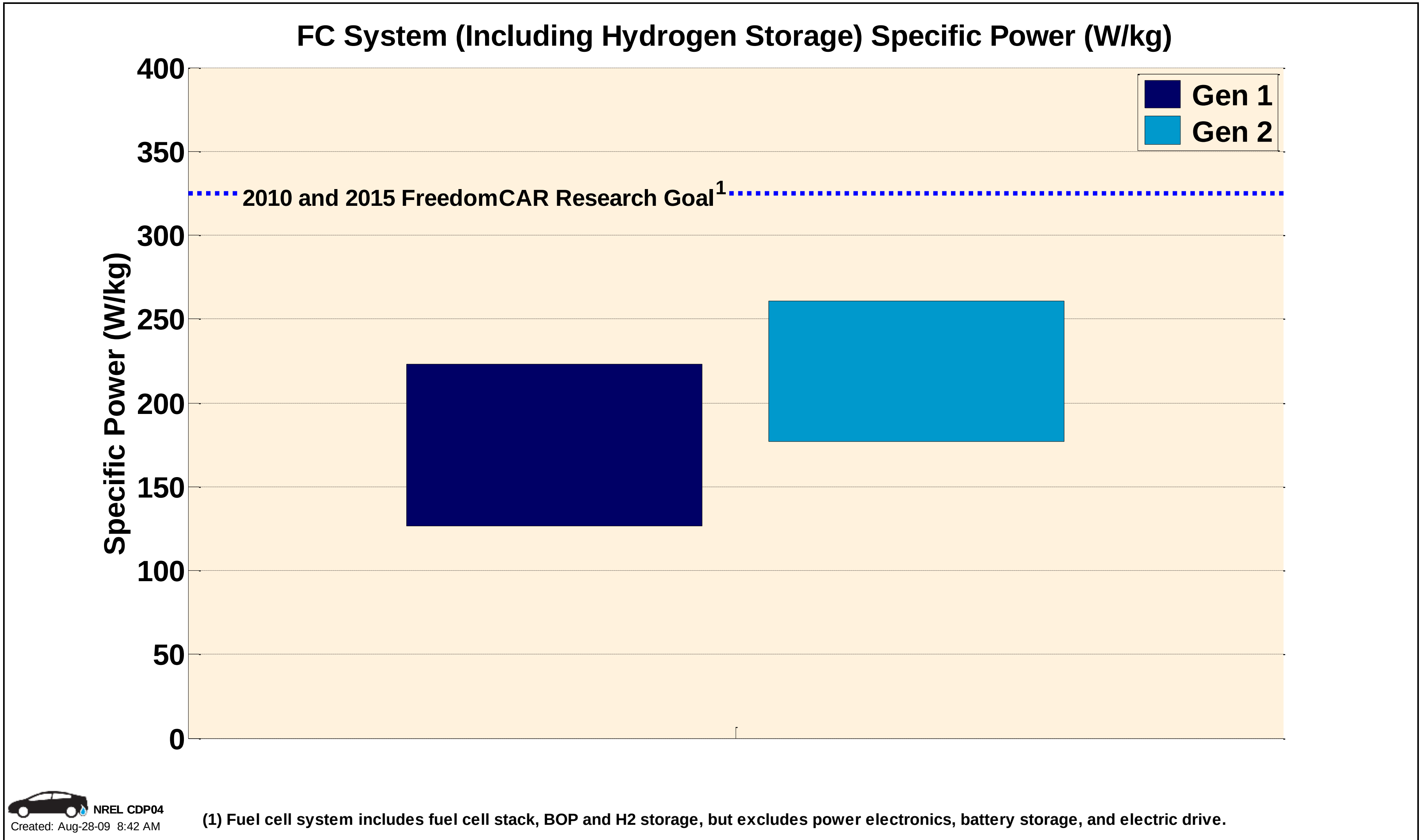
(1) Range is based on fuel economy and usable hydrogen on-board the vehicle. One data point for each make/model.
(2) Fuel economy from unadjusted combined City/Hwy per DRAFT SAE J2572.
(3) Fuel economy from EPA Adjusted combined City/Hwy (0.78 x Hwy, 0.9 x City).
(4) Excludes trips < 1 mile. One data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

NREL CDP02
Created: Mar-10-10 1:18 PM

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

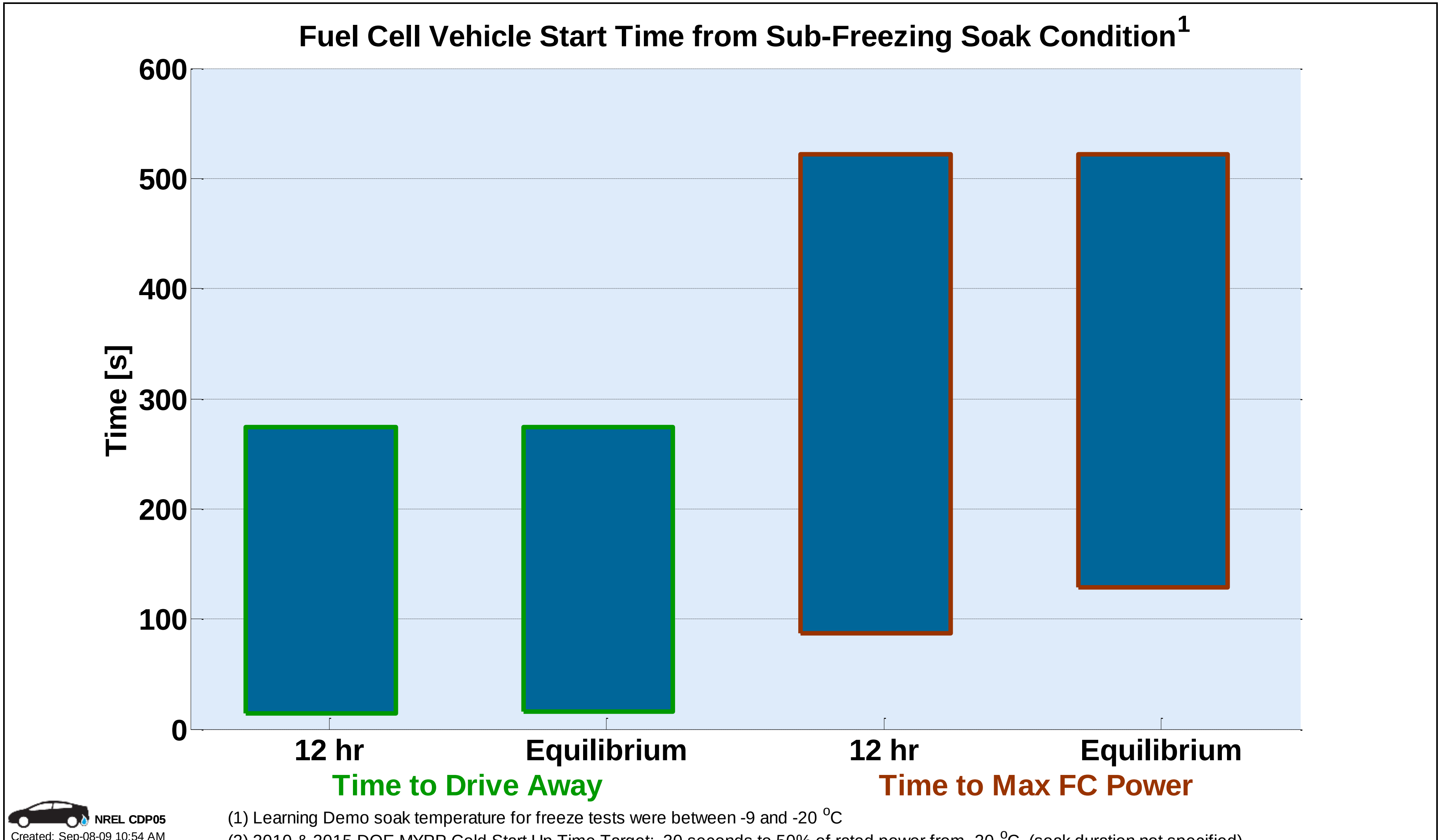


CDP#4: Fuel Cell System Specific Power, Including Hydrogen Storage



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

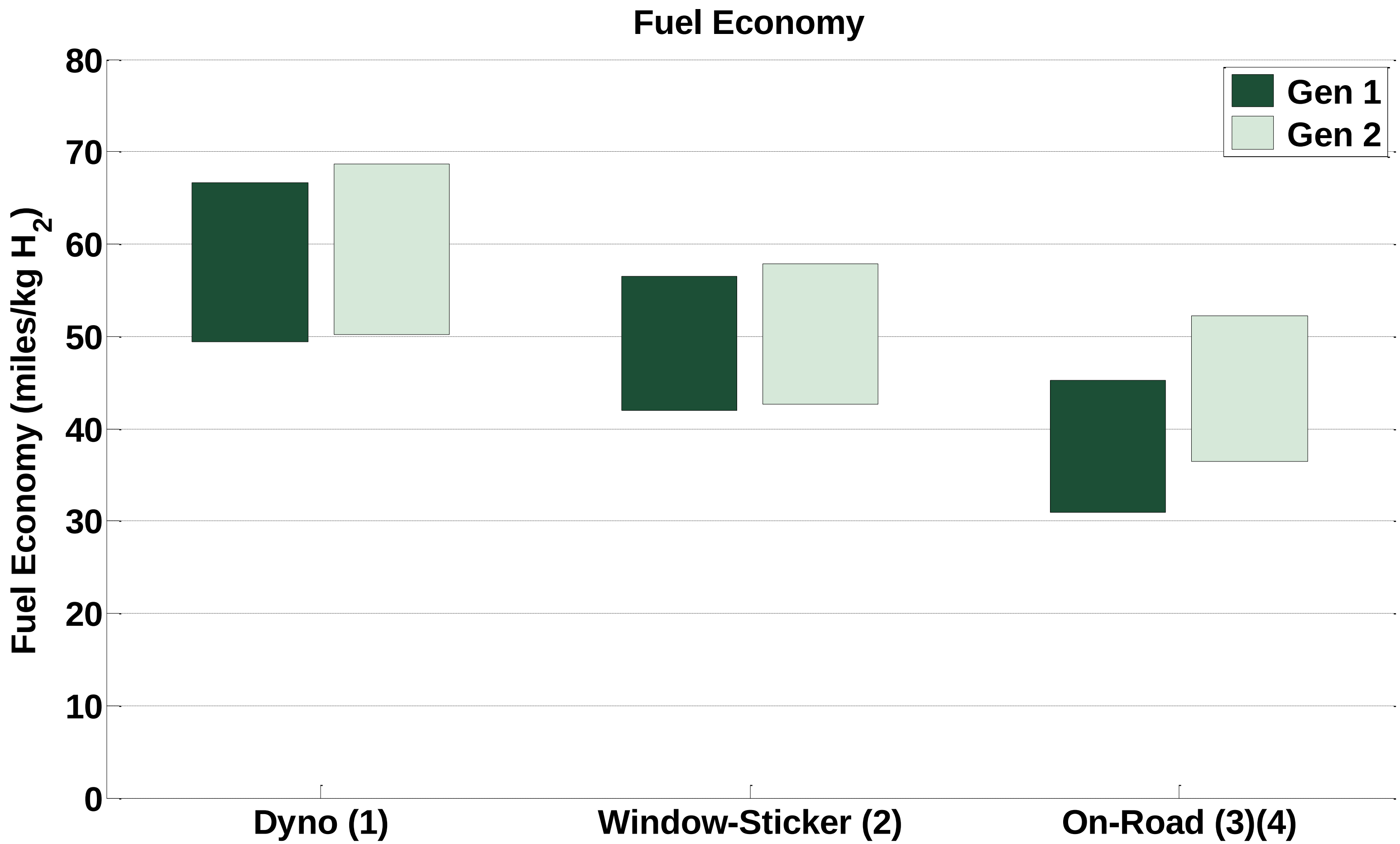
CDP#5: Fuel Cell Start Times from Sub-Freezing Soak Conditions



(1) Learning Demo soak temperature for freeze tests were between -9 and -20 °C

(2) 2010 & 2015 DOE MYPP Cold Start Up Time Target: 30 seconds to 50% of rated power from -20 °C (soak duration not specified).

CDP#6: Fuel Economy



(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.

NREL CDP06
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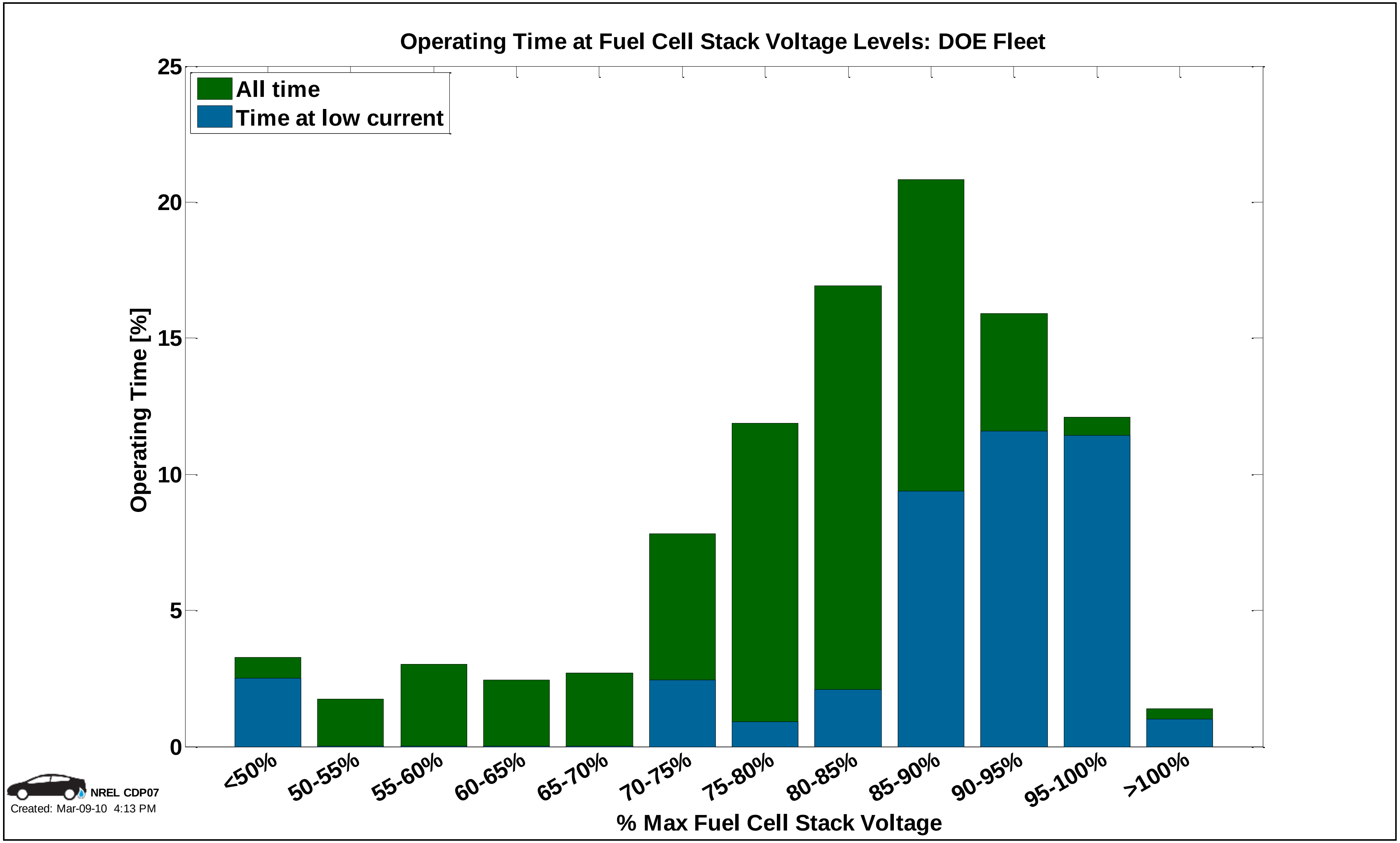
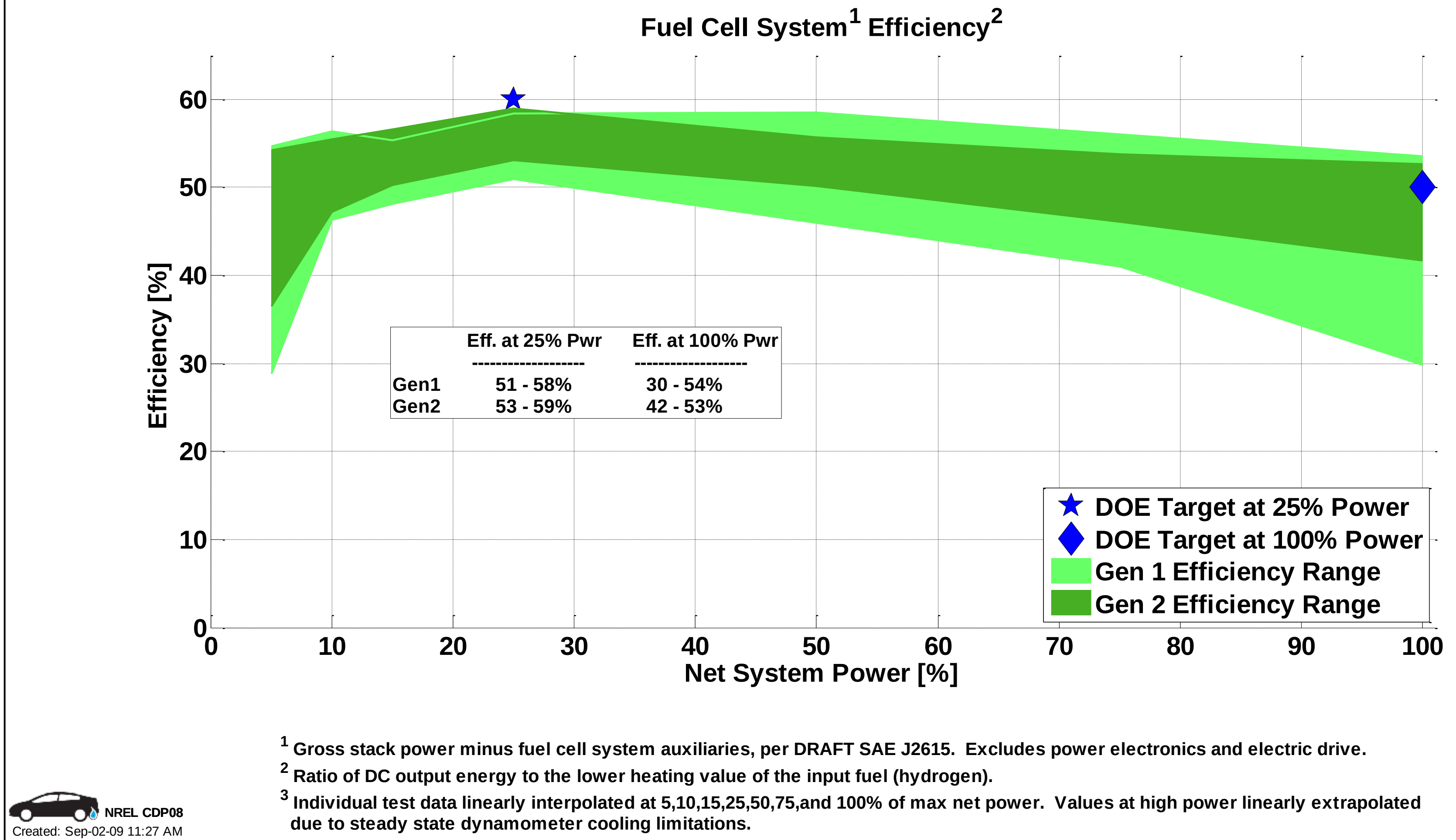
CDP#7: Fuel Cell Voltage



CDP#8: FC System Efficiency

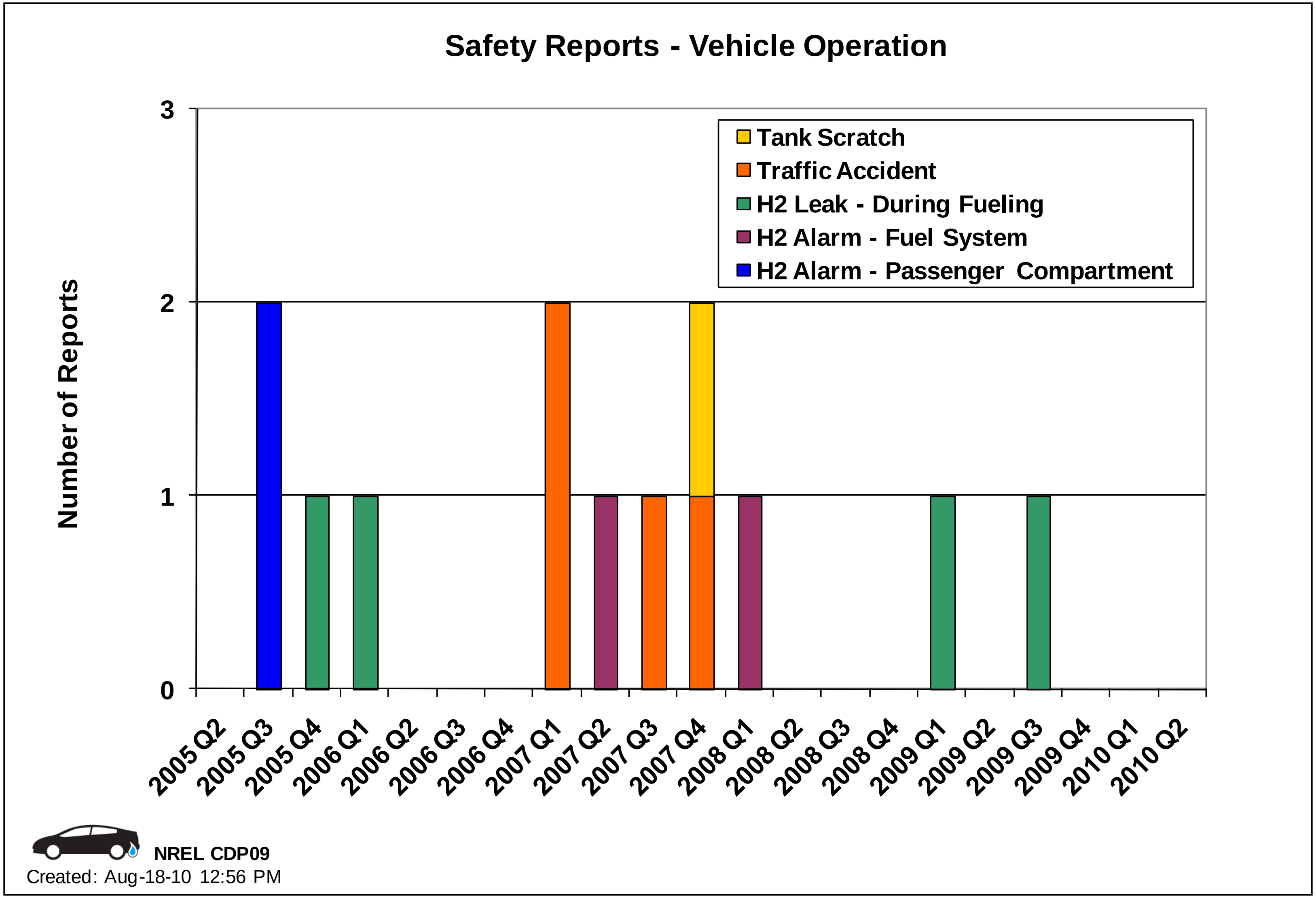


[1] Gross stack power minus fuel cell system auxiliaries, per DRAFT SAE J2615. Excludes power electronics and electric drive.

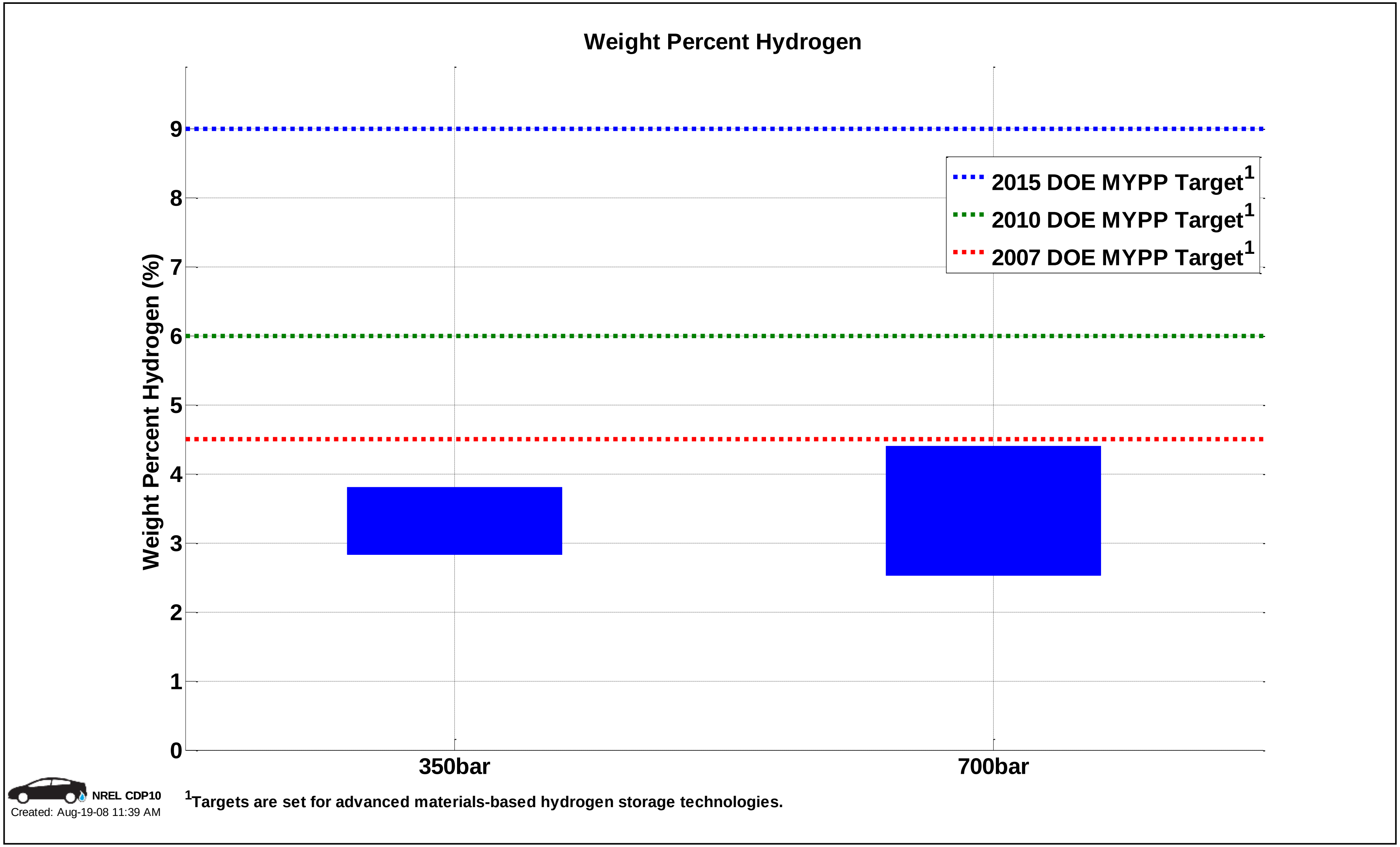
[2] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen).

[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.

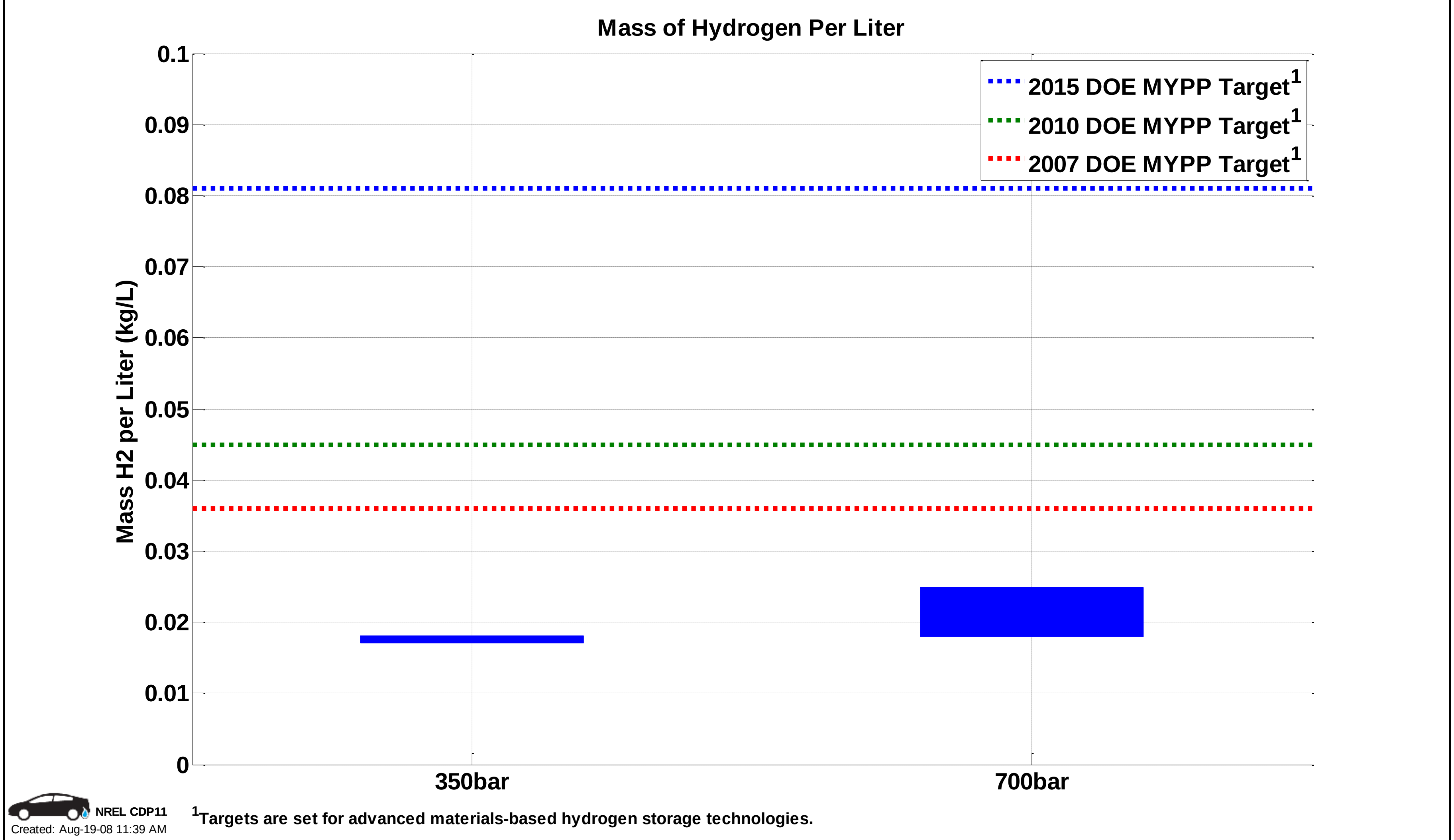
CDP#9: Safety Reports – Vehicles



CDP#10: Storage Weight % Hydrogen

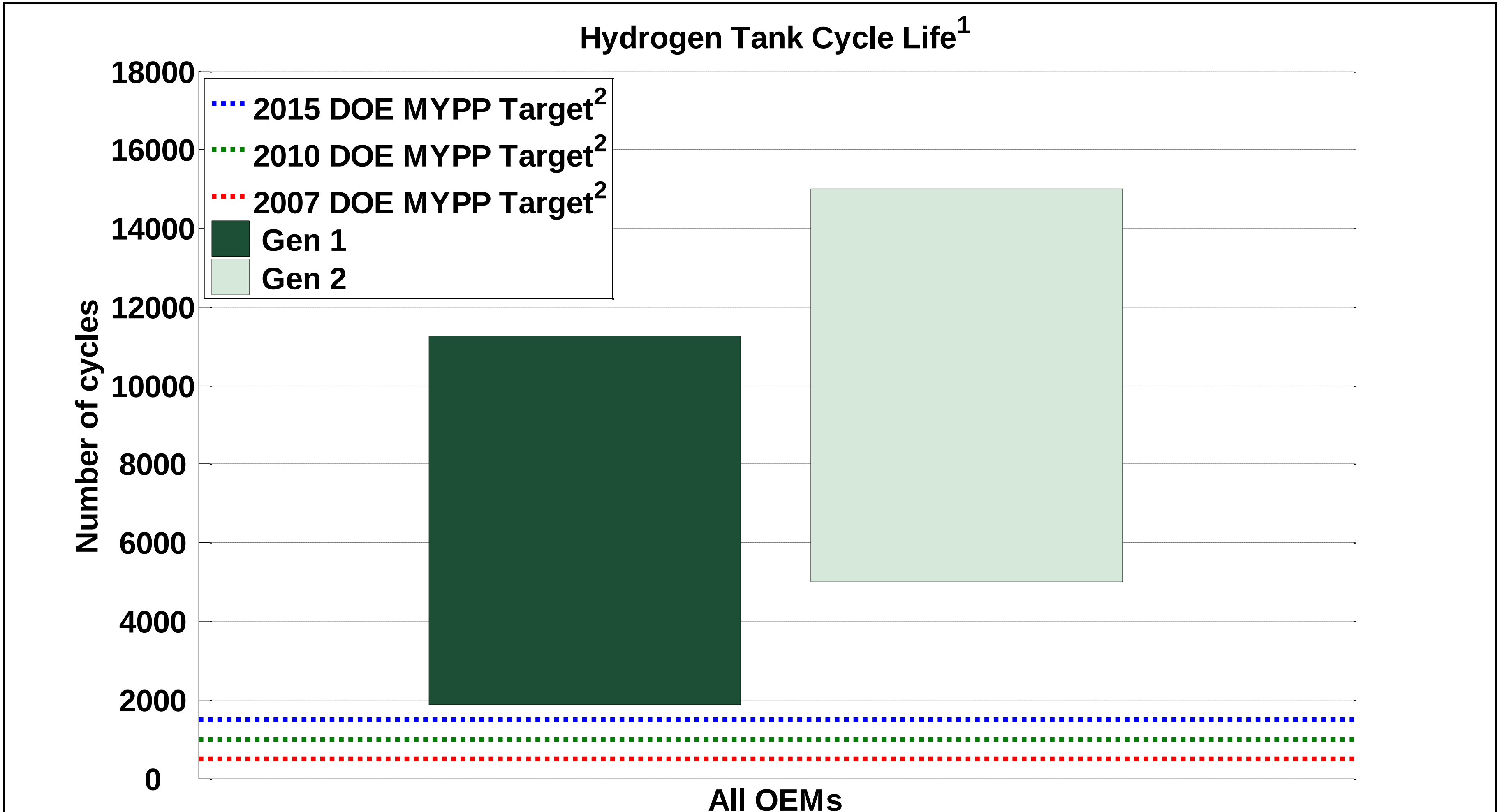


CDP#11: Volumetric Capacity of H2 Storage



[1]Targets are set for advanced materials-based hydrogen storage technologies.

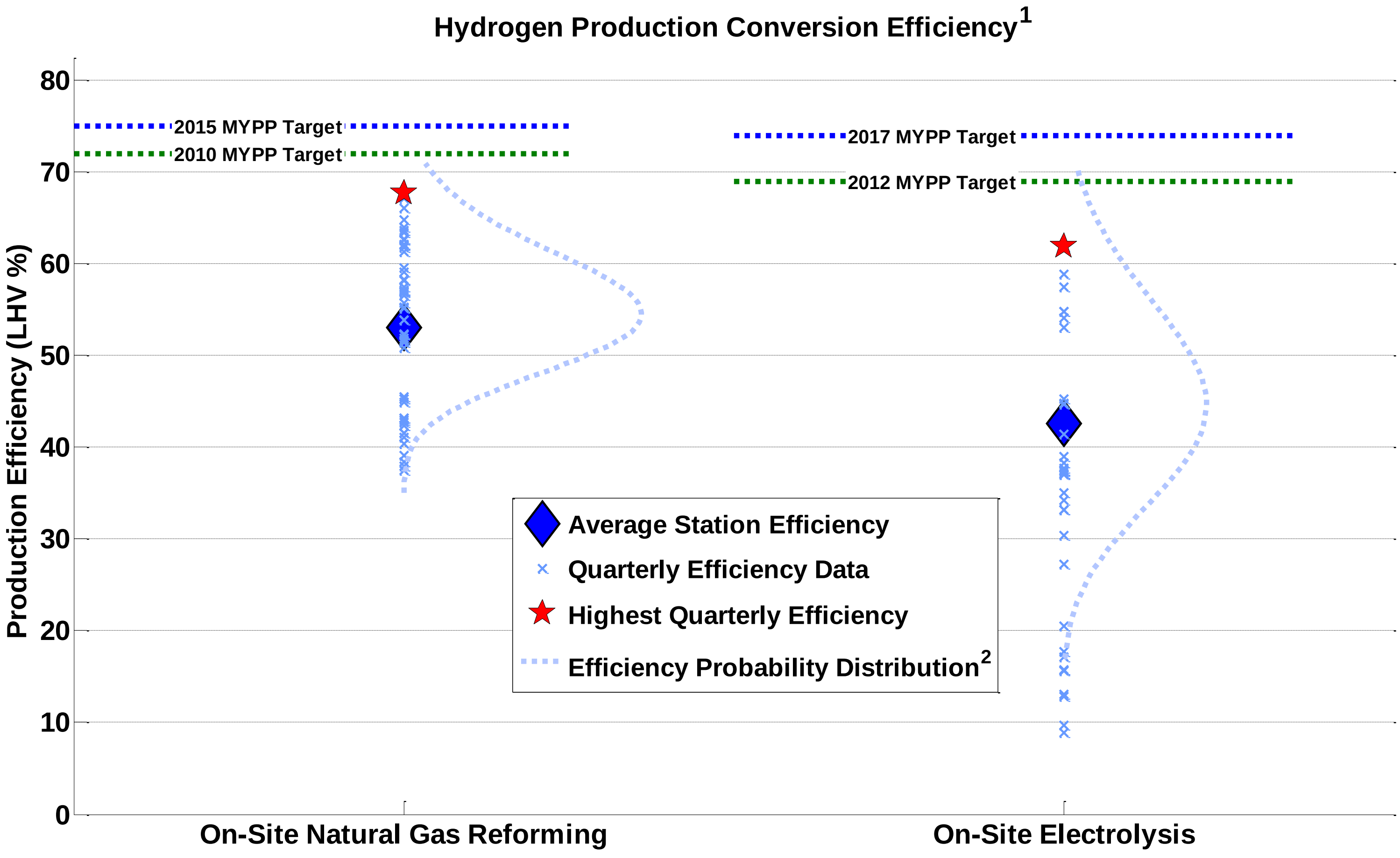
CDP#12: Vehicle Hydrogen Tank Cycle Life



[1]Data reported reference NGV2, HGV2, or EIHP standards.

[2]Some near-term targets have been achieved with compressed and liquid tanks. Emphasis is on advanced materials-based technologies.

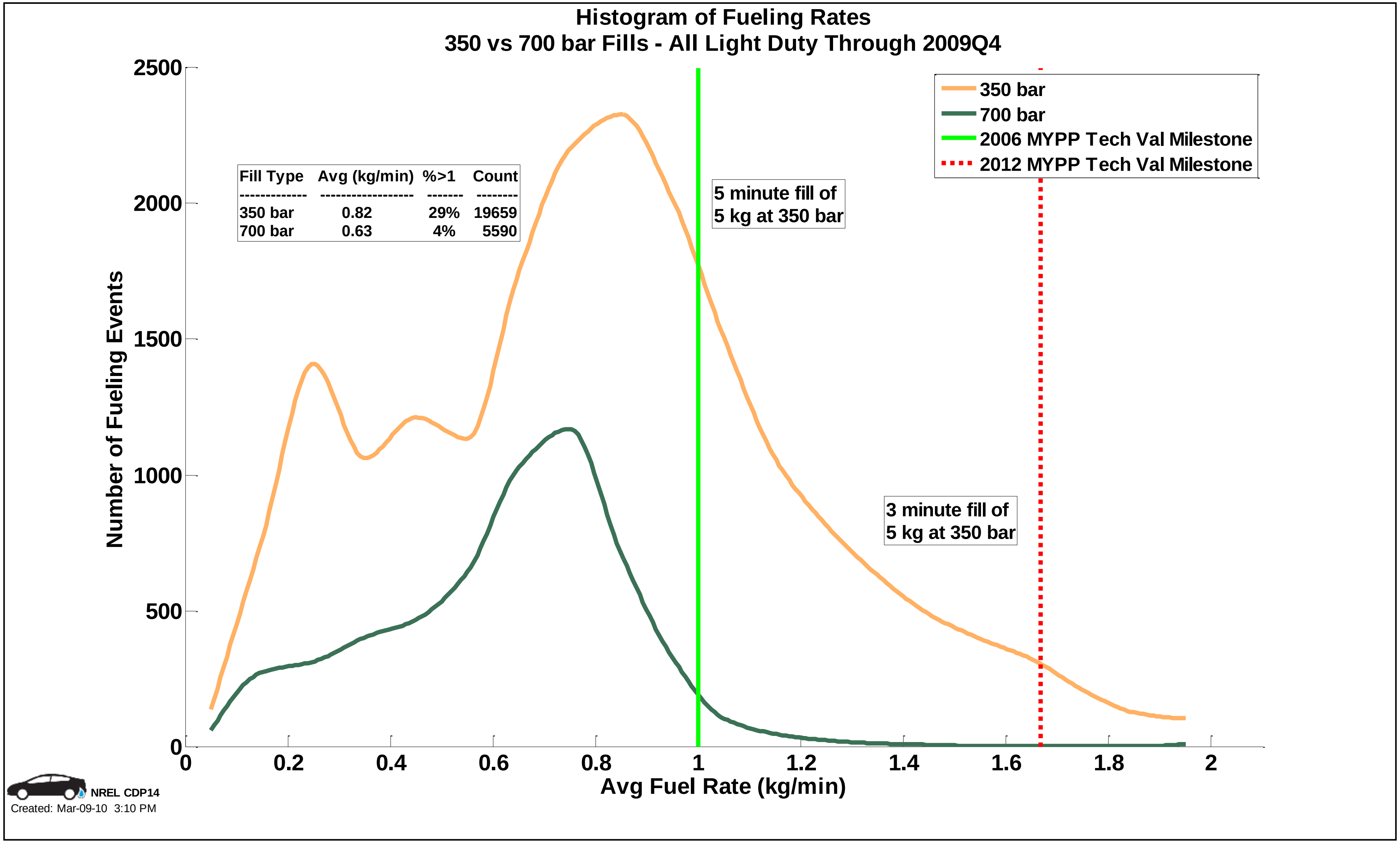
CDP#13: On-Site Hydrogen Production Efficiency



[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.

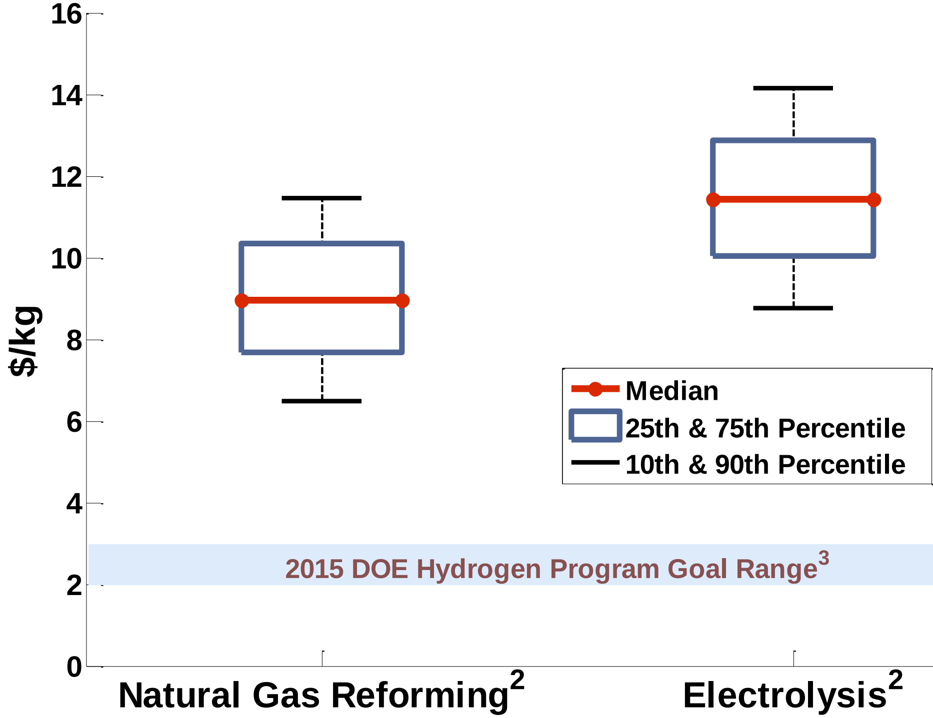
[2]The efficiency probability distribution represents the range and likelihood of hydrogen production conversion efficiency based on monthly conversion efficiency data from the Learning Demonstration.

CDP#14: Fueling Rates – 350 and 700 bar



CDP#15: H2 Production Cost vs. Process

Projected Early Market 1500 kg/day Hydrogen Cost[1]



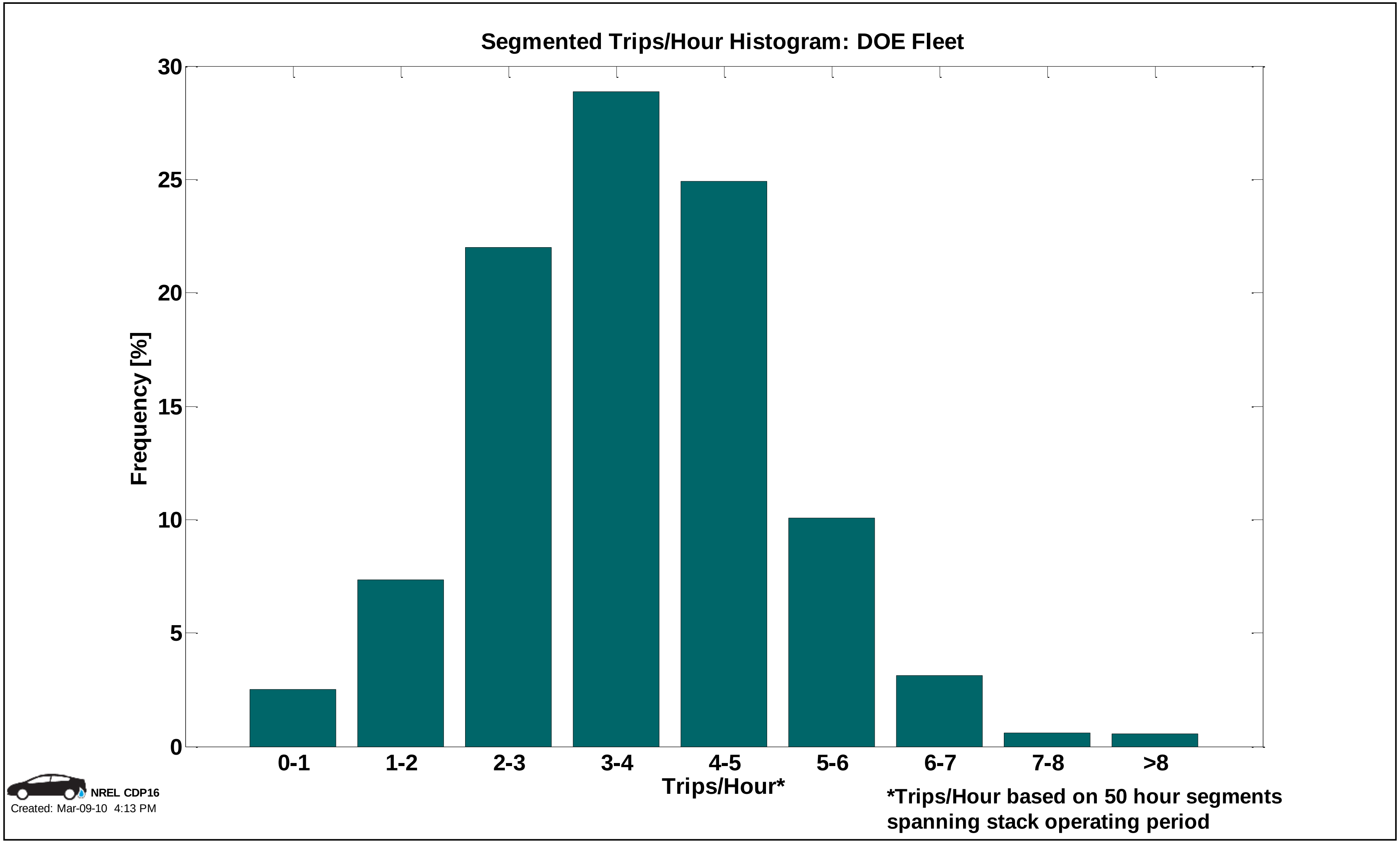
Key H2 Cost Elements and Ranges

Input Parameter	Minimum (P10)	Maximum (P90)
Facility Direct Capital Cost	$10M	$25M
Facility Capacity Utilization	85%	95%
Annual Maintenance & Repairs	$150K	$600K
Annual Other O&M	$100K	$200K
Annual Facility Land Rent	$50K	$200K
Natural Gas Prod. Efficiency (LHV)	65%	75%
Electrolysis Prod. Efficiency (LHV)	35%	62%

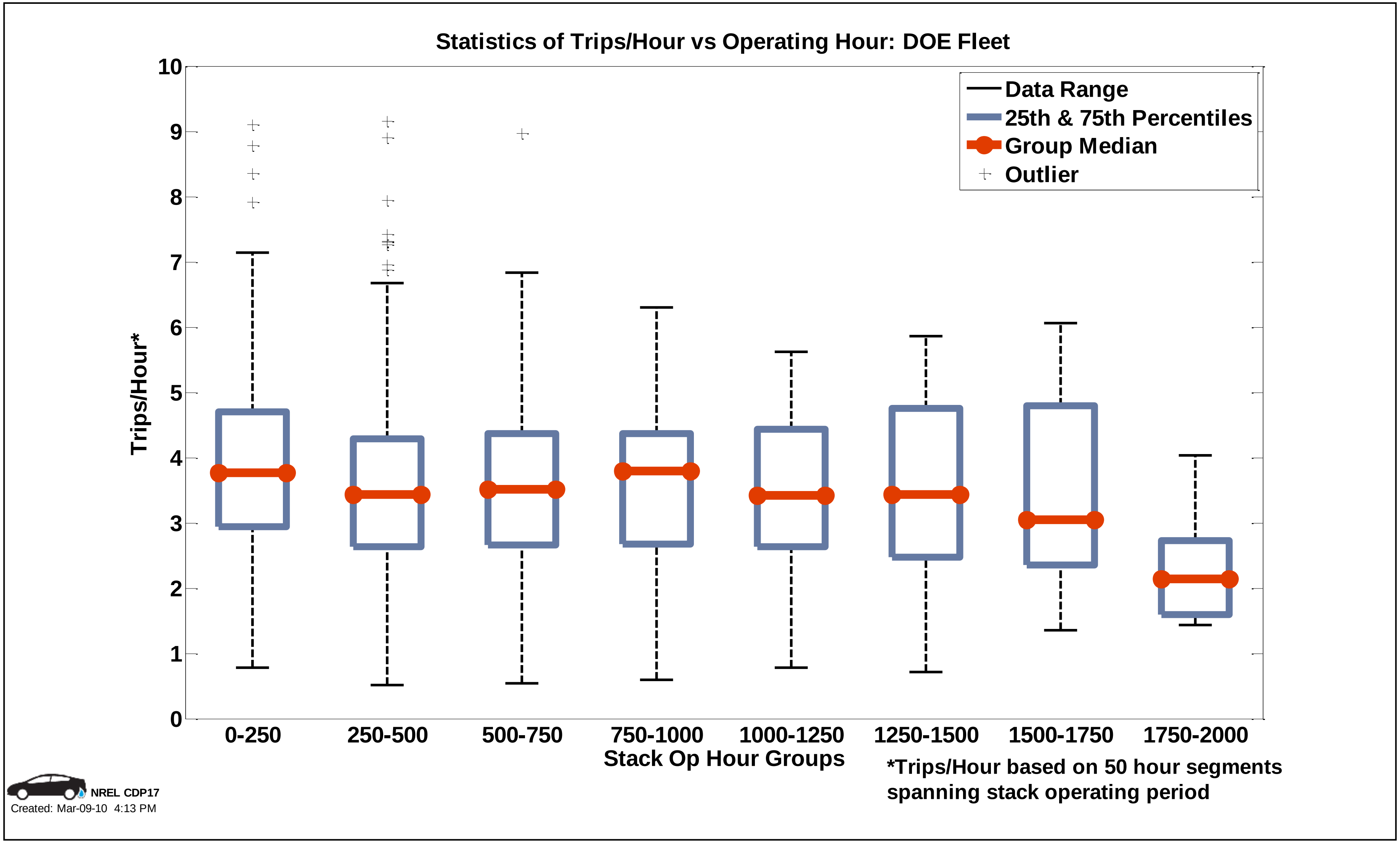
(1) Reported hydrogen costs are based on estimates of key cost elements from Learning Demonstration energy company partners and represent the cost of producing hydrogen on-site at the fueling station, using either natural gas reformation or water electrolysis, dispensed to the vehicle. Costs reflect an assessment of hydrogen production technologies, not an assessment of hydrogen market demand.
(2) Hydrogen production costs for 1500 kg/day stations developed using DOE's H2A Production model, version 2.1. Cost modeling represents the lifetime cost of producing hydrogen at fueling stations installed during an early market rollout of hydrogen infrastructure and are not reflective of the costs that might be seen in a fully mature market for hydrogen installations. Modeling uses default H2A Production model inputs supplemented with feedback from Learning Demonstration energy company partners, based on their experience operating on-site hydrogen production stations. H2A-based Monte Carlo simulations (2,000 trials) were completed for both natural gas reforming and electrolysis stations using default H2A values and 10th percentile to 90th percentile estimated ranges for key cost parameters as shown in the table. Capacity utilization range is based on the capabilities of the production technologies and could be significantly lower if there is inadequate demand for hydrogen.
(3) DOE has a hydrogen cost goal of $2-$3/kg for future (2015) 1500 kg/day hydrogen production stations installed at a rate of 500 stations per year.

NREL CDP15
Created: Jan-19-10 11:08 AM

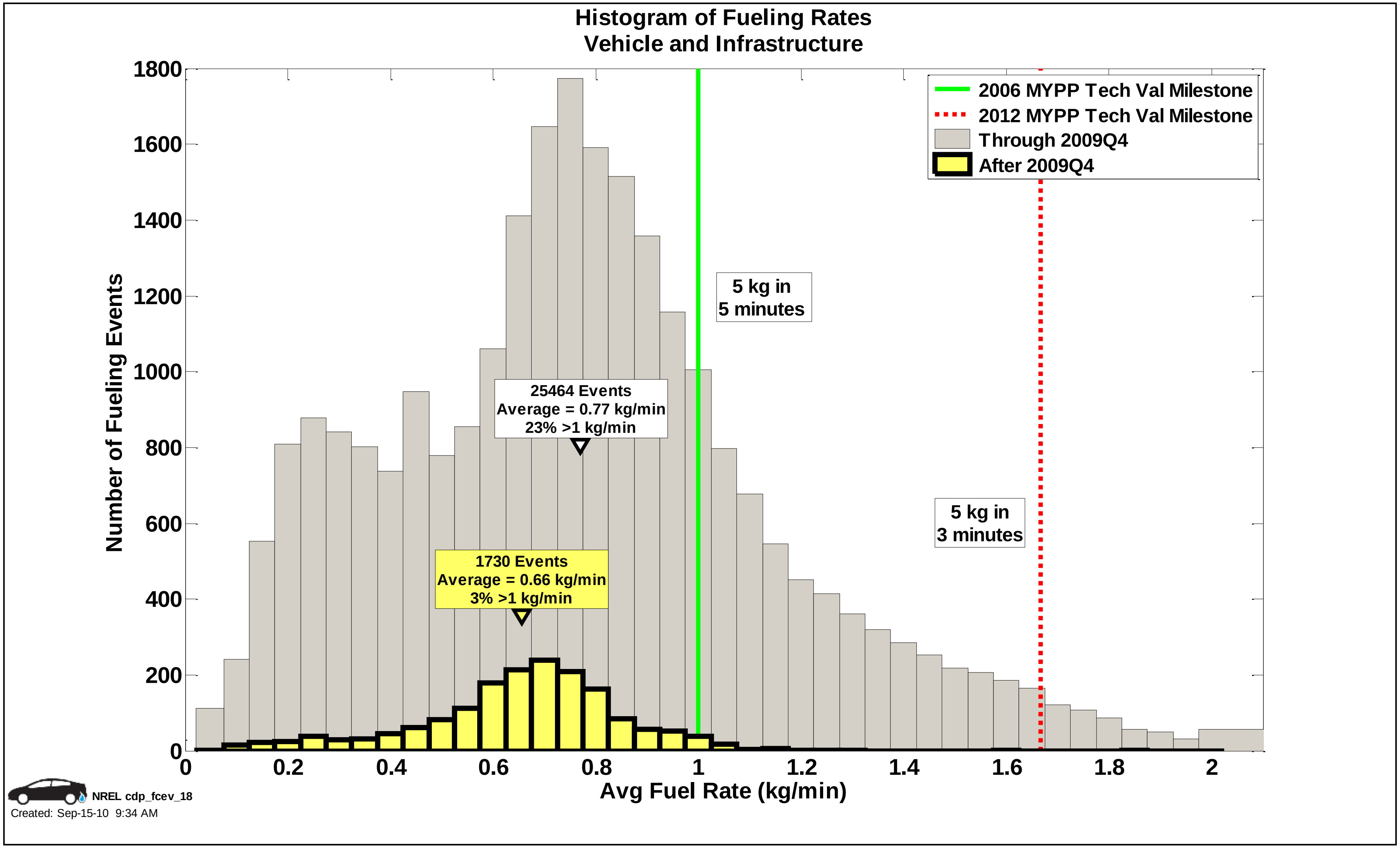
CDP#16: Fuel Cell Stack Trips Per Hour Histogram



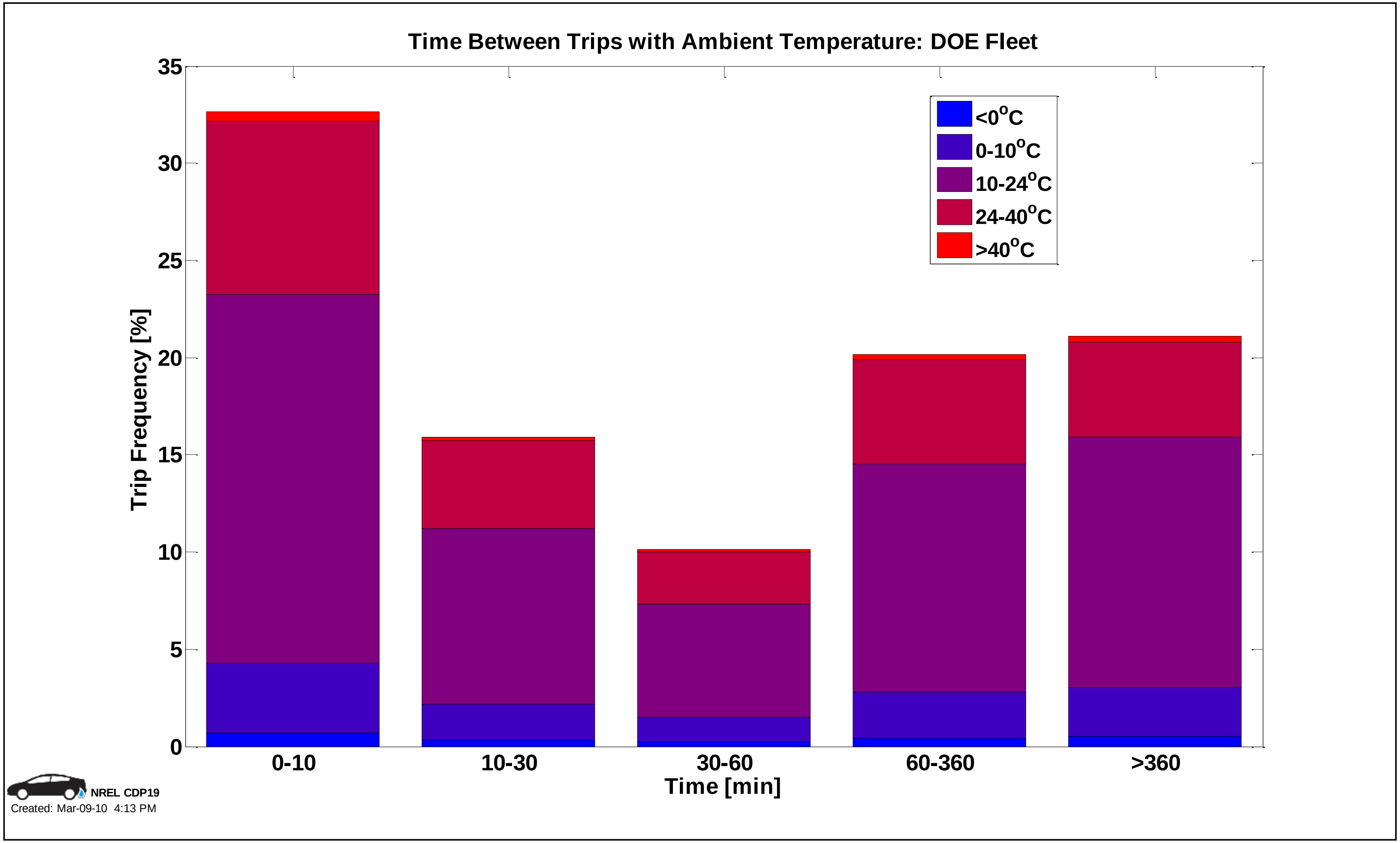
CDP#17: Statistics of Trips/Hour vs. Operating Hour



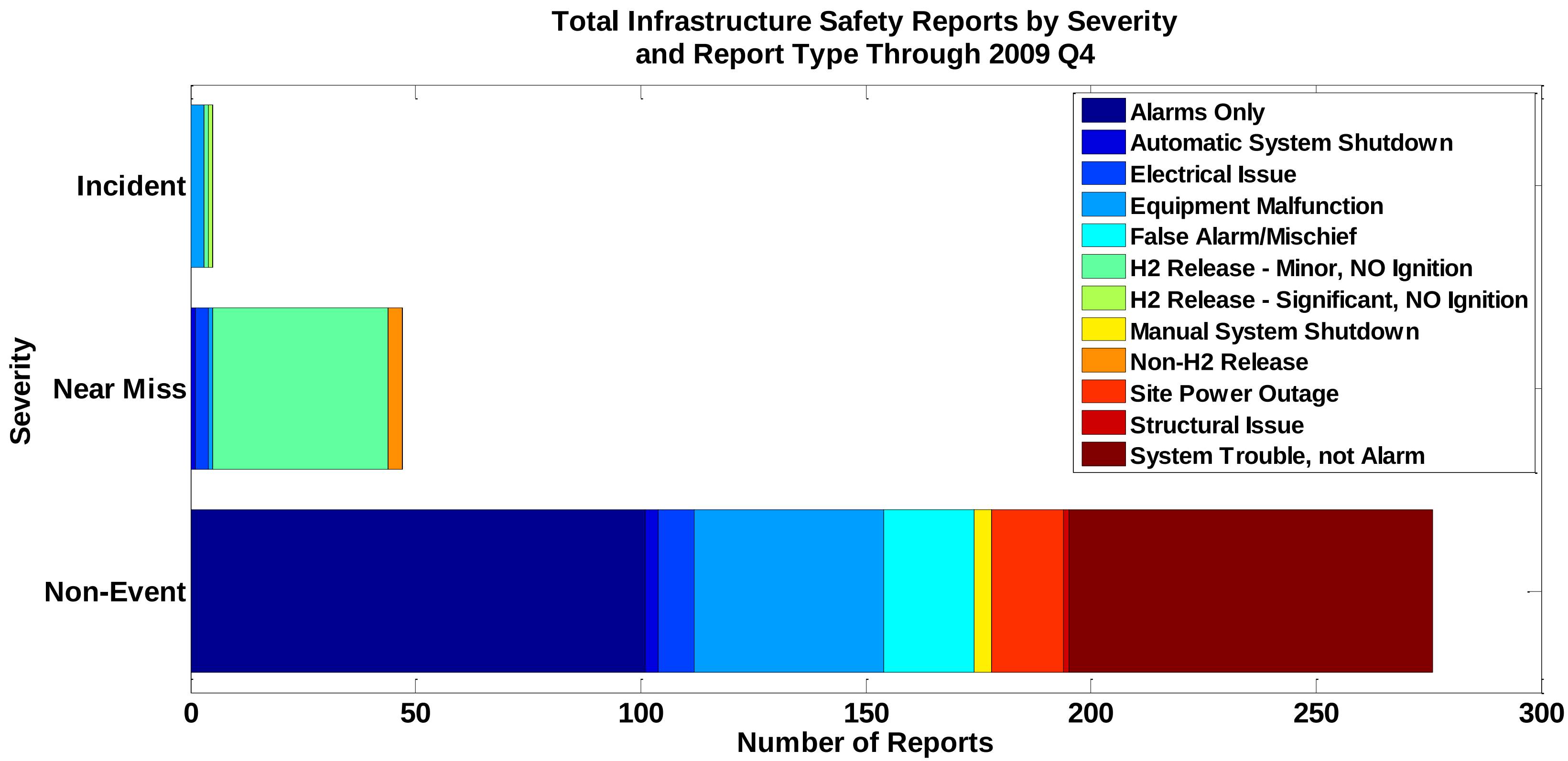
CDP#18: Refueling Rates



CDP#19: Time Between Trips & Ambient Temperature



CDP#20: Safety Reports – Infrastructure



An INCIDENT is an event that results in:

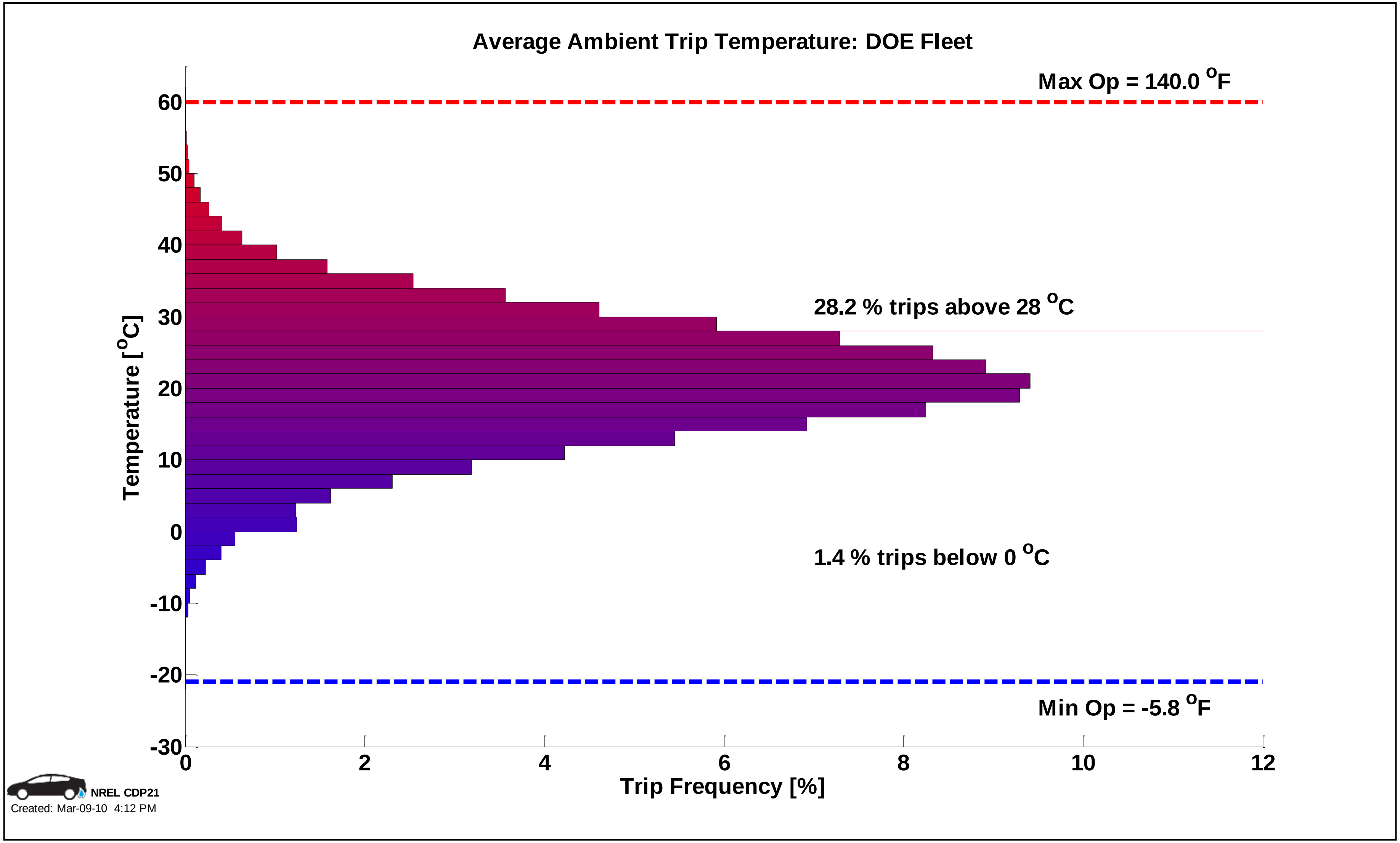
- a lost time accident and/or injury to personnel
- damage/unplanned downtime for project equipment, facilities or property
- impact to the public or environment
- any hydrogen release that unintentionally ignites or is sufficient to sustain a flame if ignited
- release of any volatile, hydrogen containing compound (other than the hydrocarbons used as common fuels)

A NEAR-MISS is:

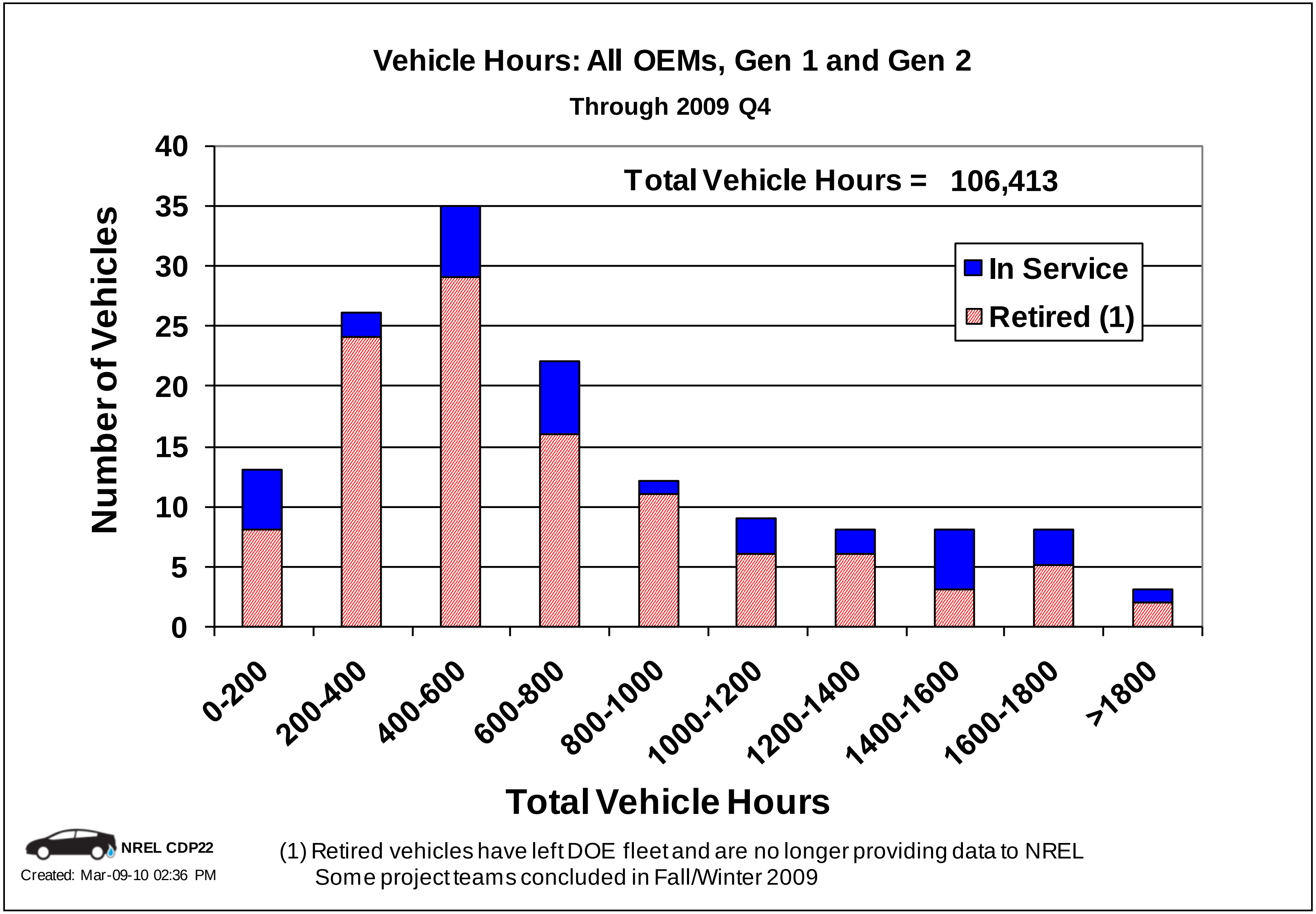
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

NREL CDP20
Created: Mar-11-10 2:45 PM

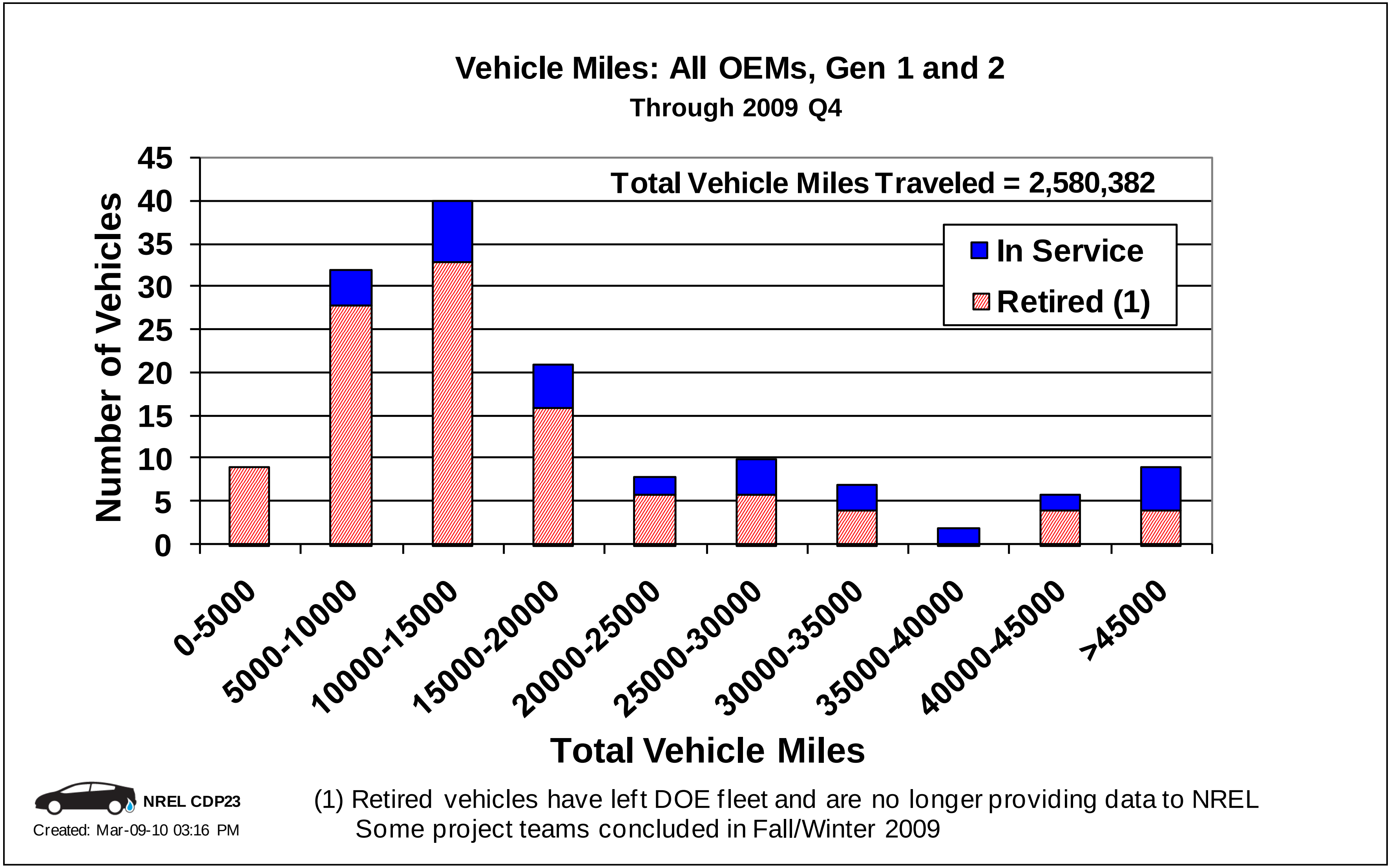
CDP#21: Range of Ambient Temperature During Vehicle Operation



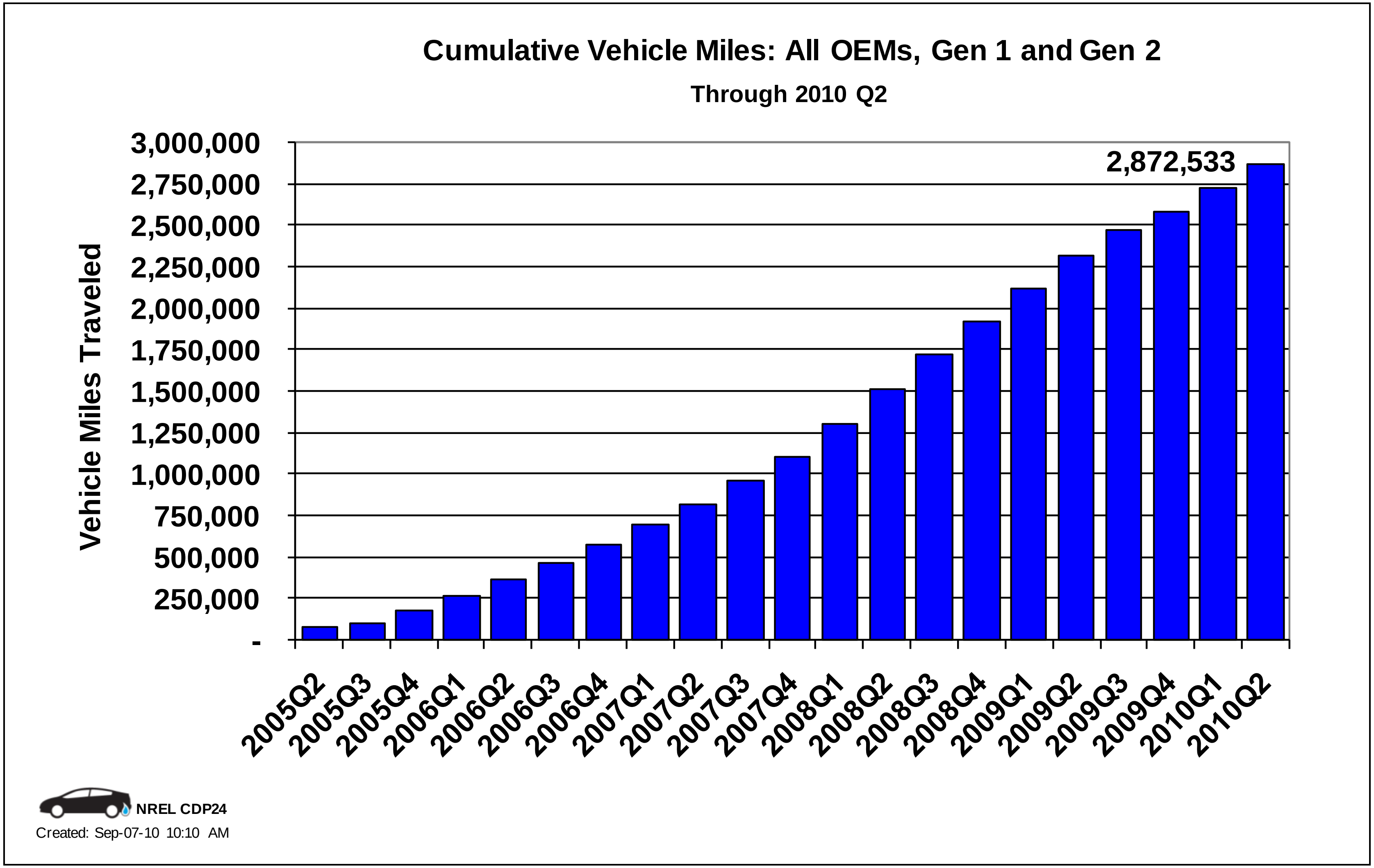
CDP#22: Vehicle Operating Hours



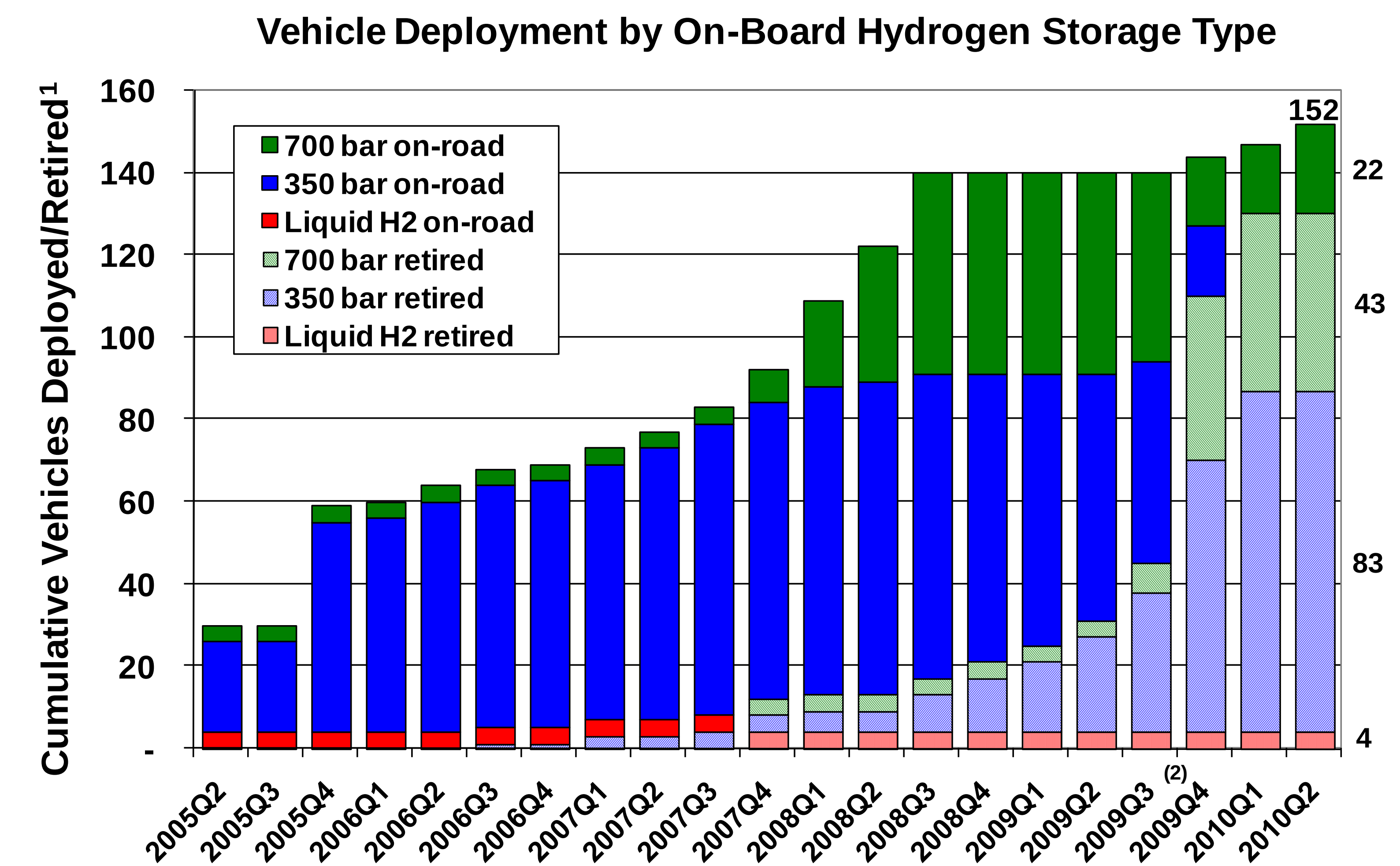
CDP#23: Vehicles vs. Miles Traveled



CDP#24: Cumulative Vehicle Miles Traveled

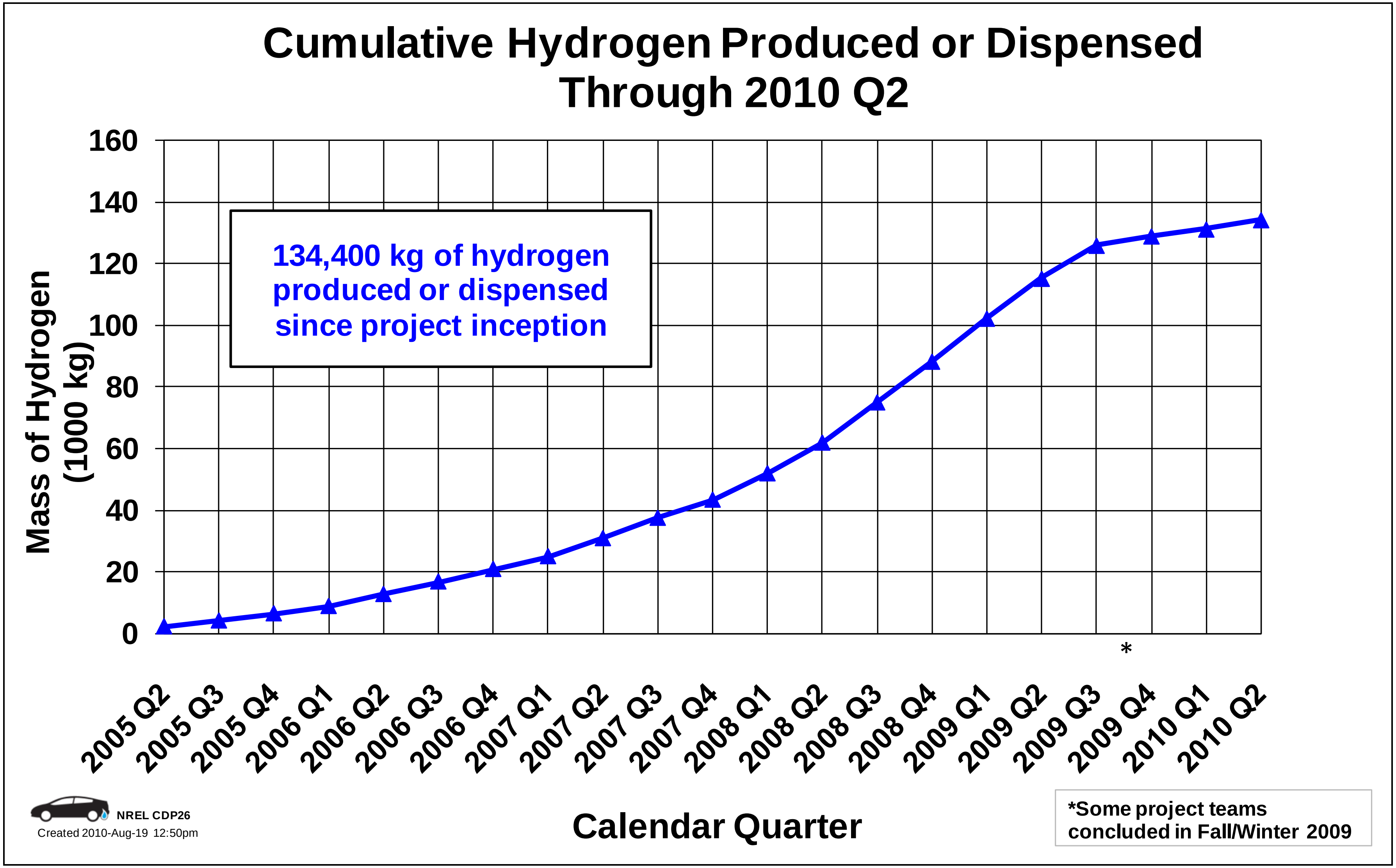


CDP#25: Vehicle H2 Storage Technologies

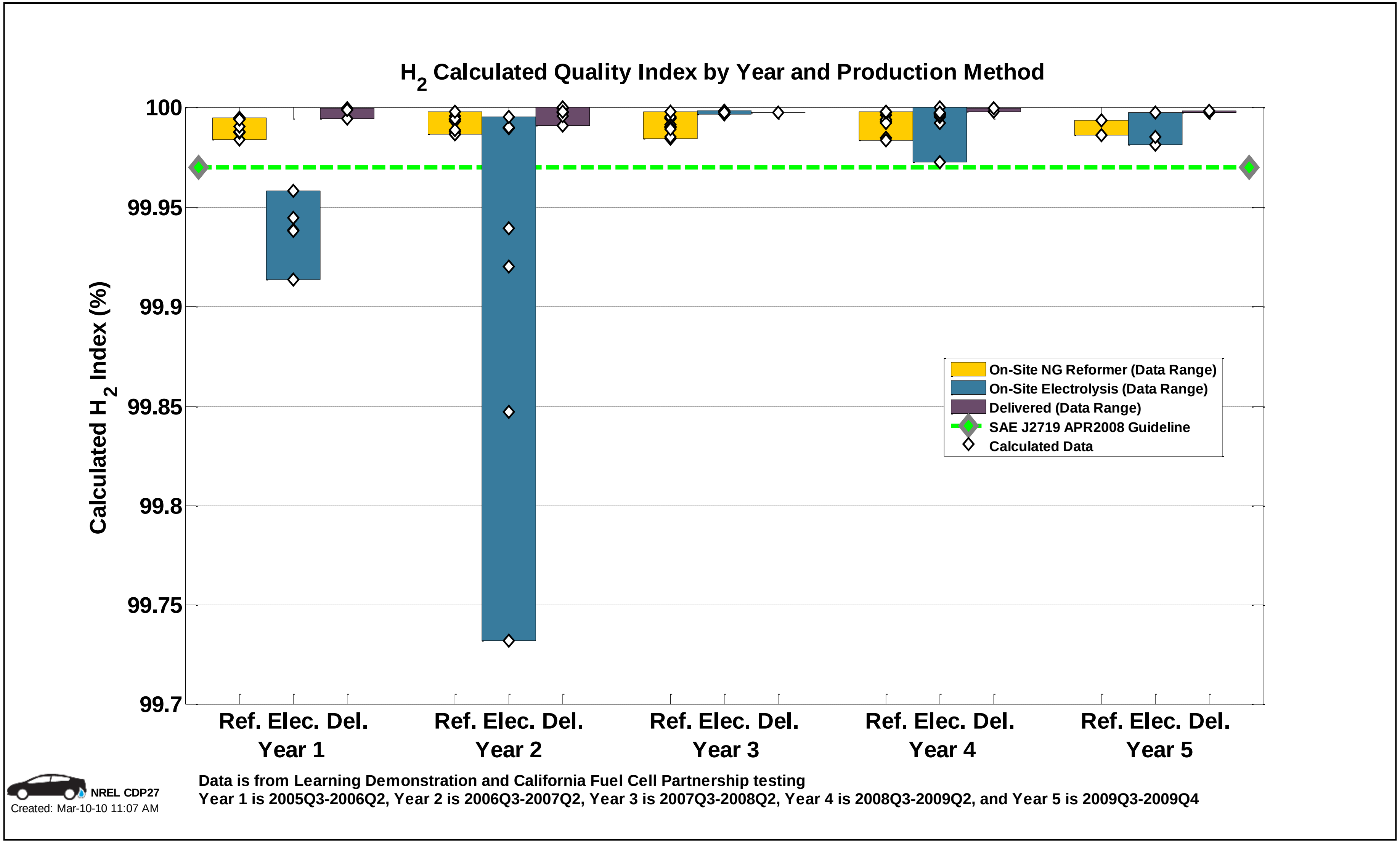


(1) Retired vehicles have left DOE fleet and are no longer providing data to NREL
(2) Two project teams concluded in Fall/Winter 2009

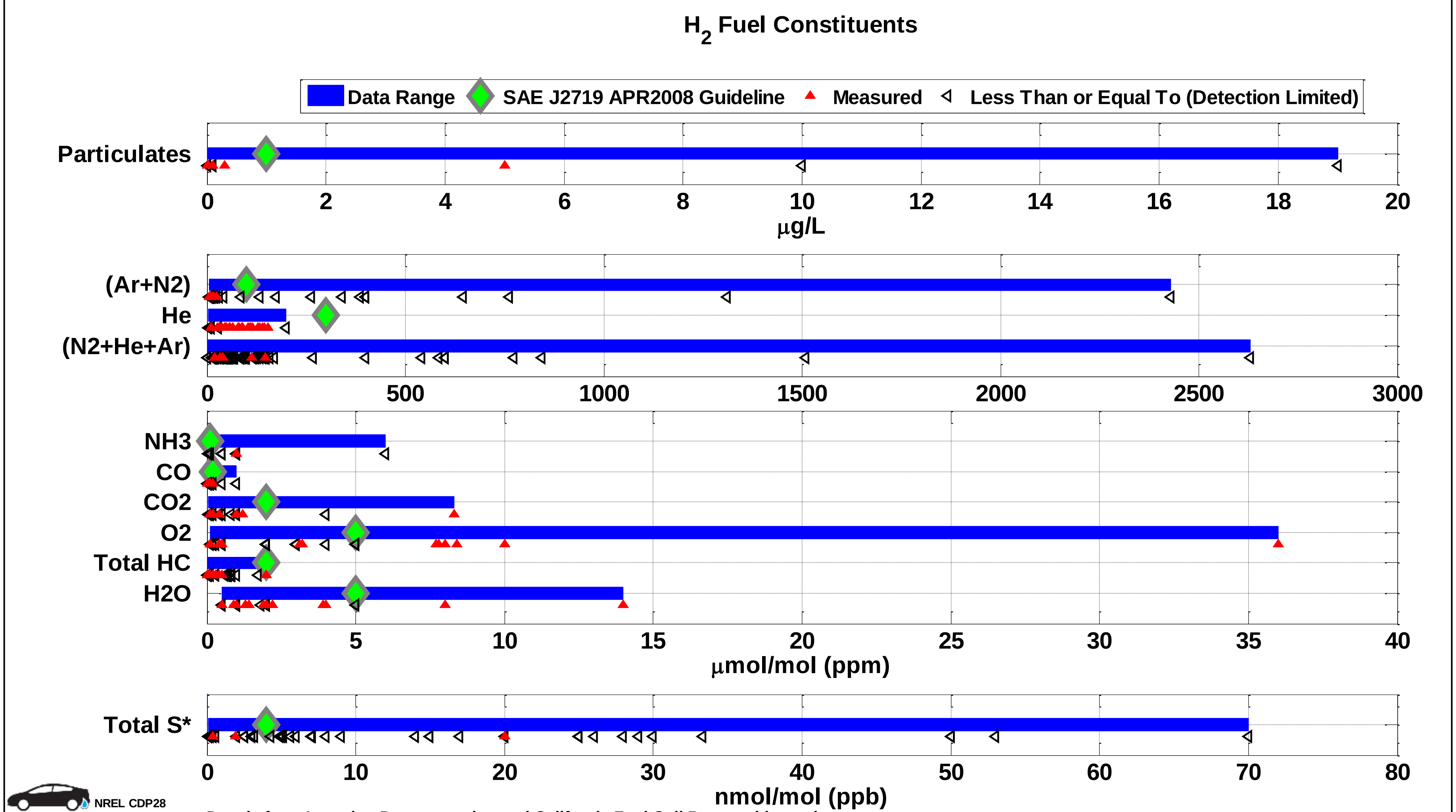
CDP#26: Cumulative H2 Produced or Dispensed



CDP#27: Hydrogen Quality Index

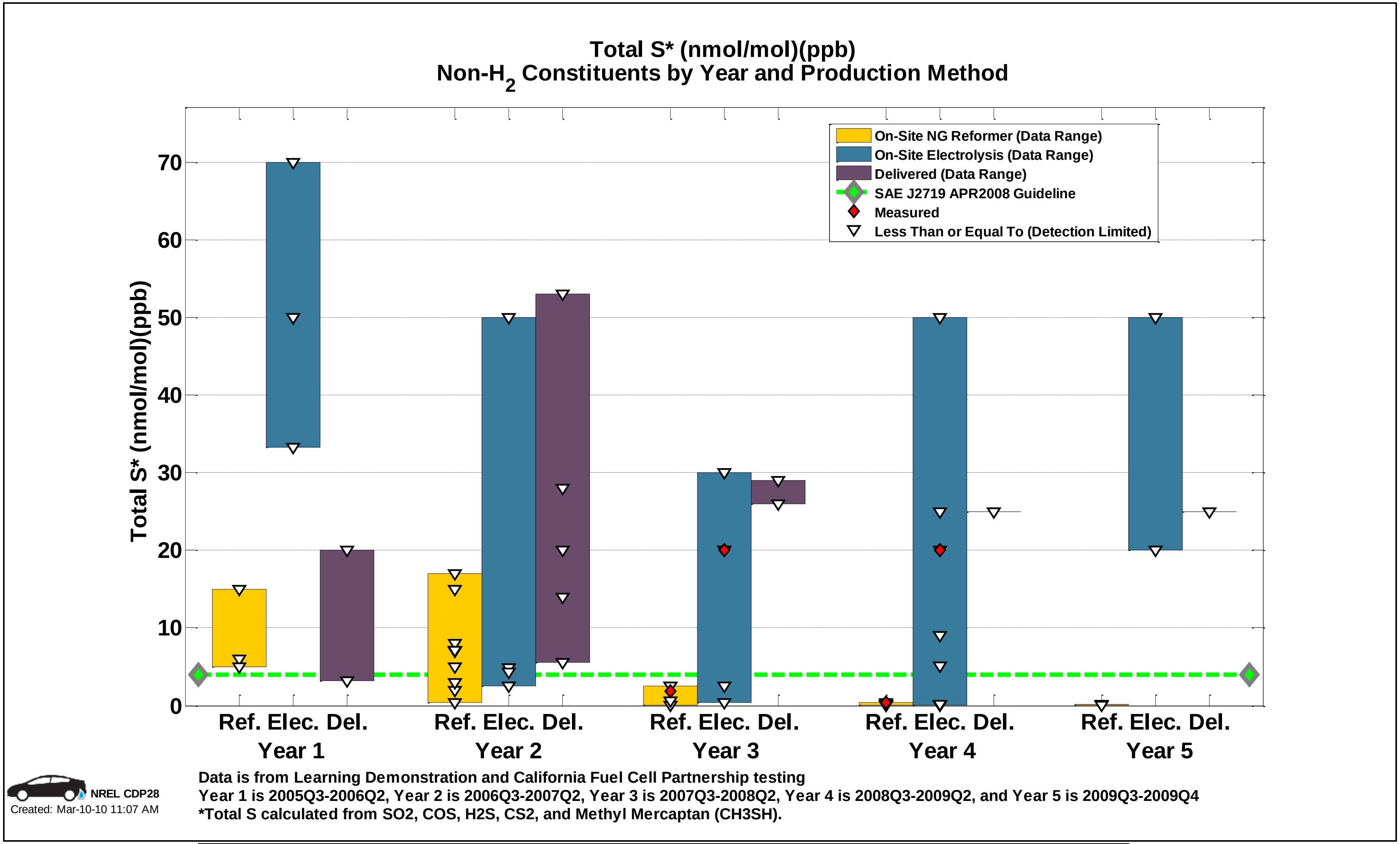


CDP#28: Hydrogen Fuel Constituents



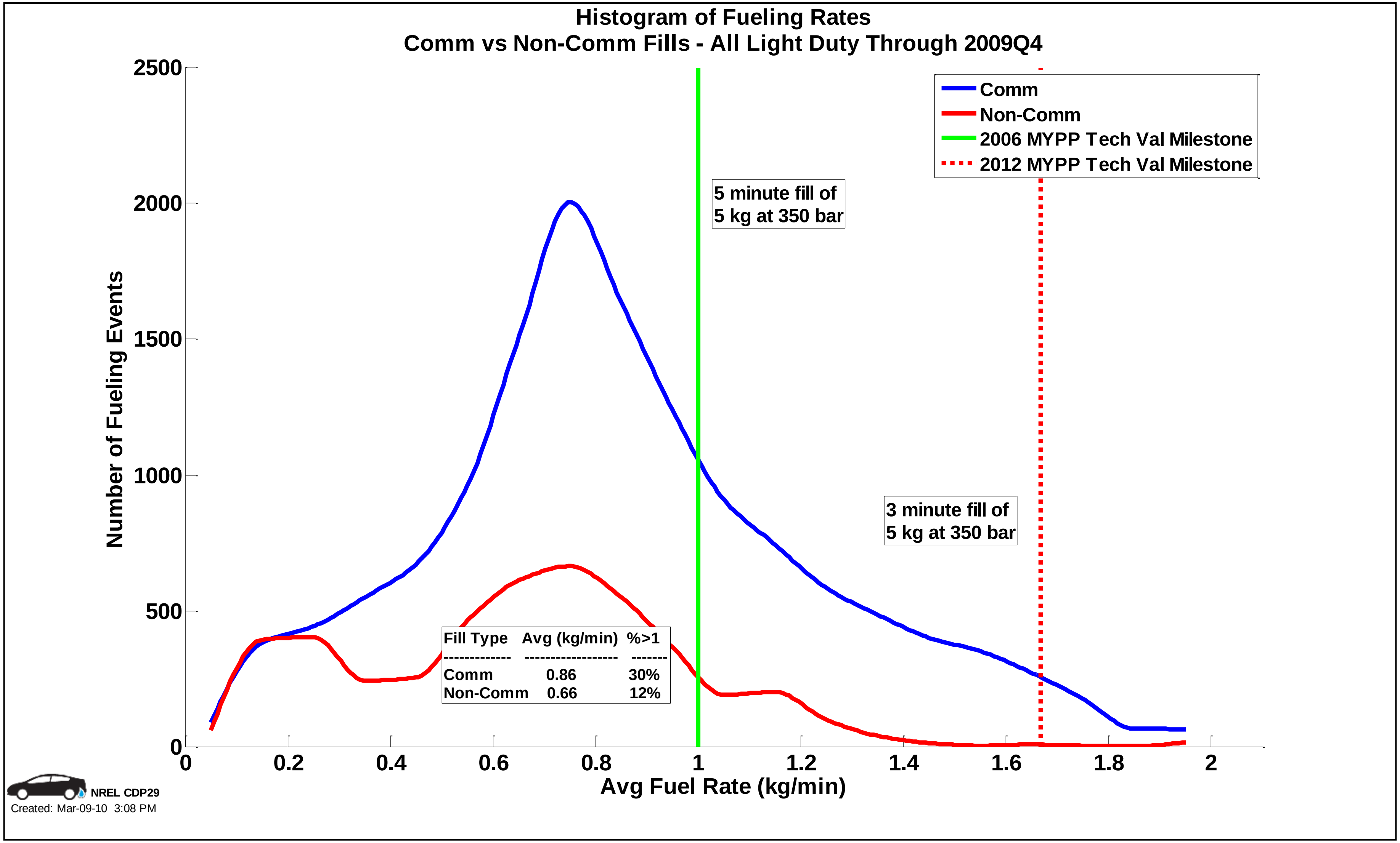
Data is from Learning Demonstration and California Fuel Cell Partnership testing
*Total S calculated from SO2, COS, H2S, CS2, and Methyl Mercaptan (CH3SH).

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

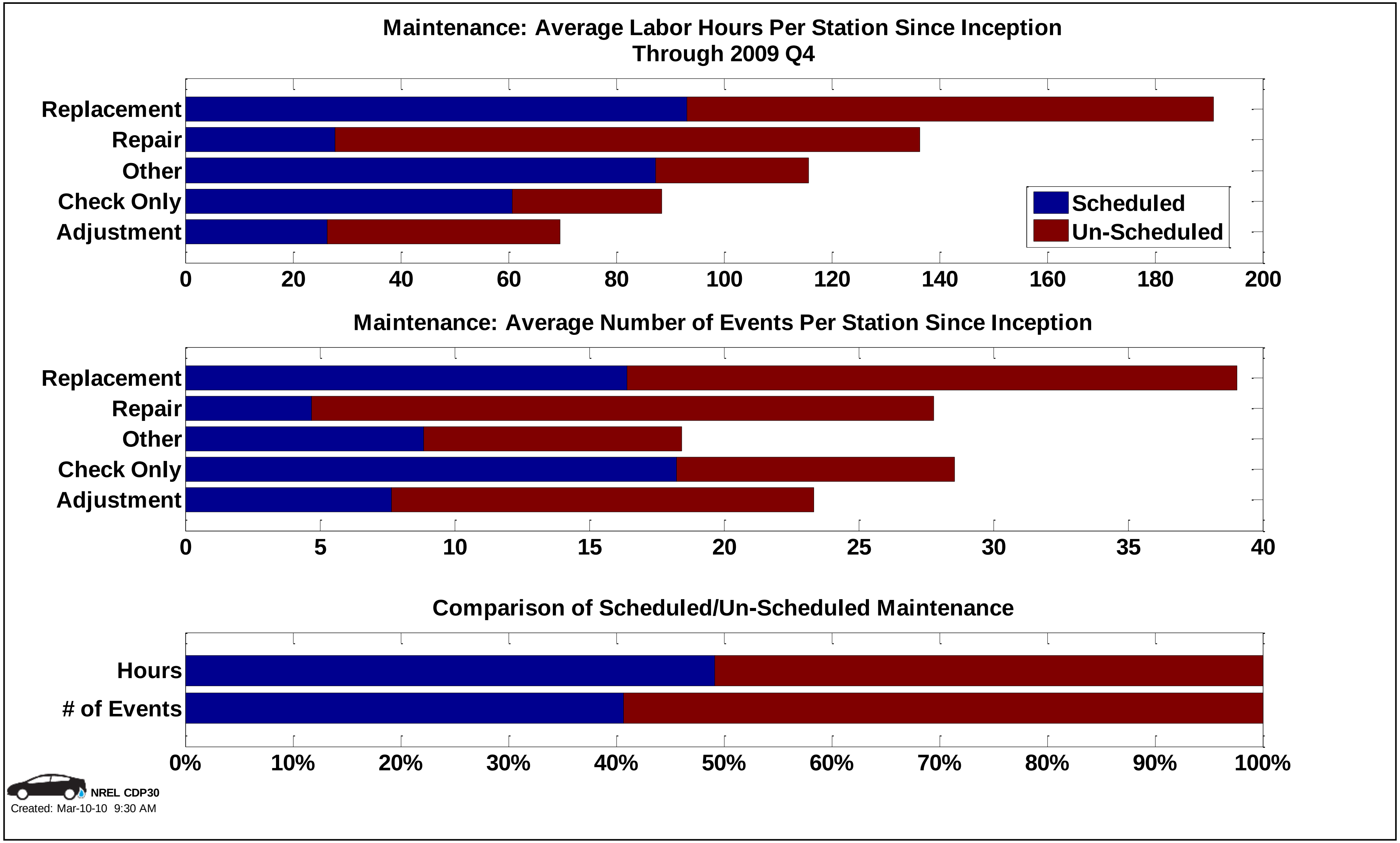


(This slide contains 18 graphs (1 for each constituent): view in slide-show mode)

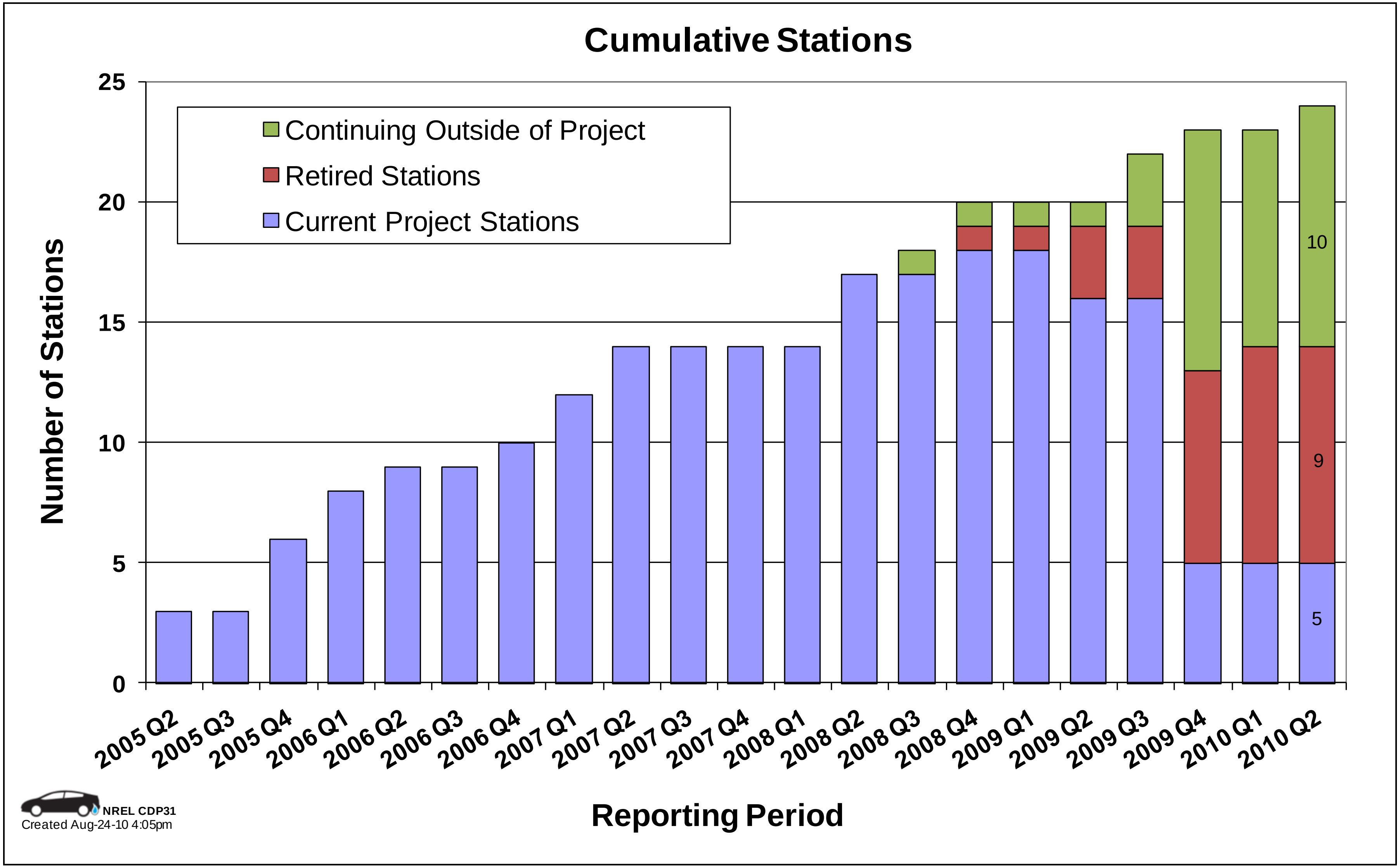
CDP#29: Fueling Rates Communication and Non-Communication Fills



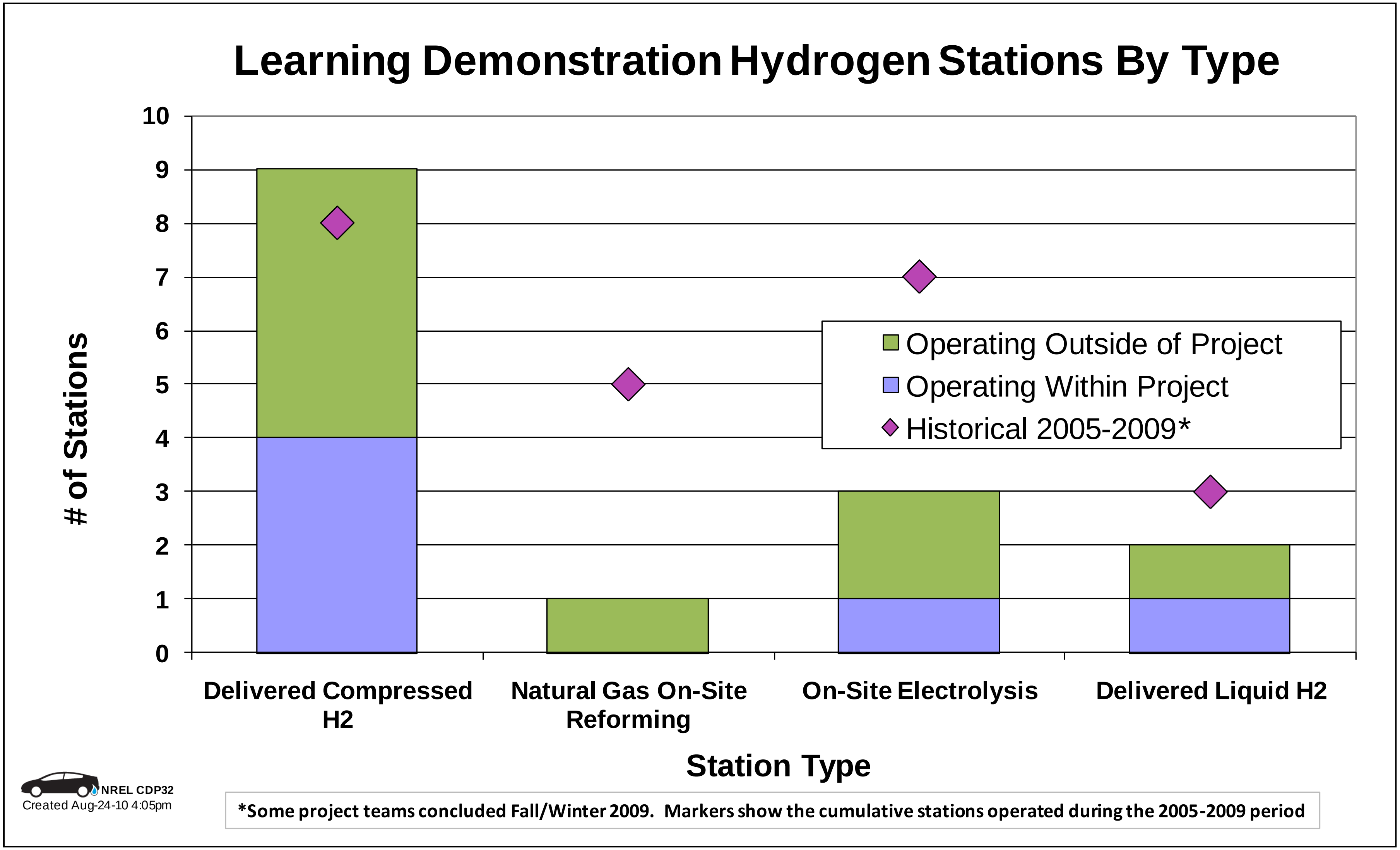
CDP#30: Infrastructure Maintenance



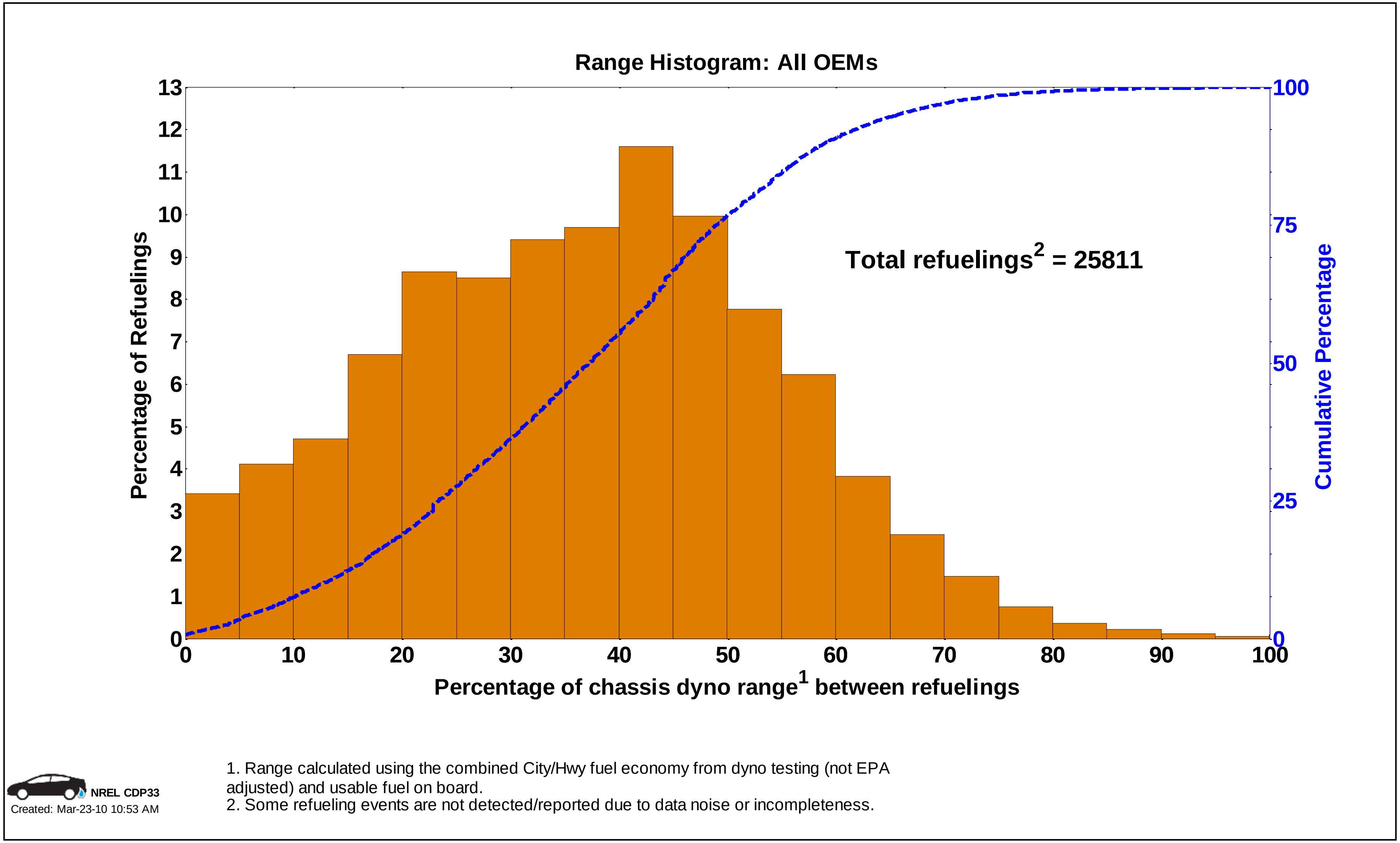
CDP#31: Number of Online Stations



CDP#32: Infrastructure Hydrogen Production Methods

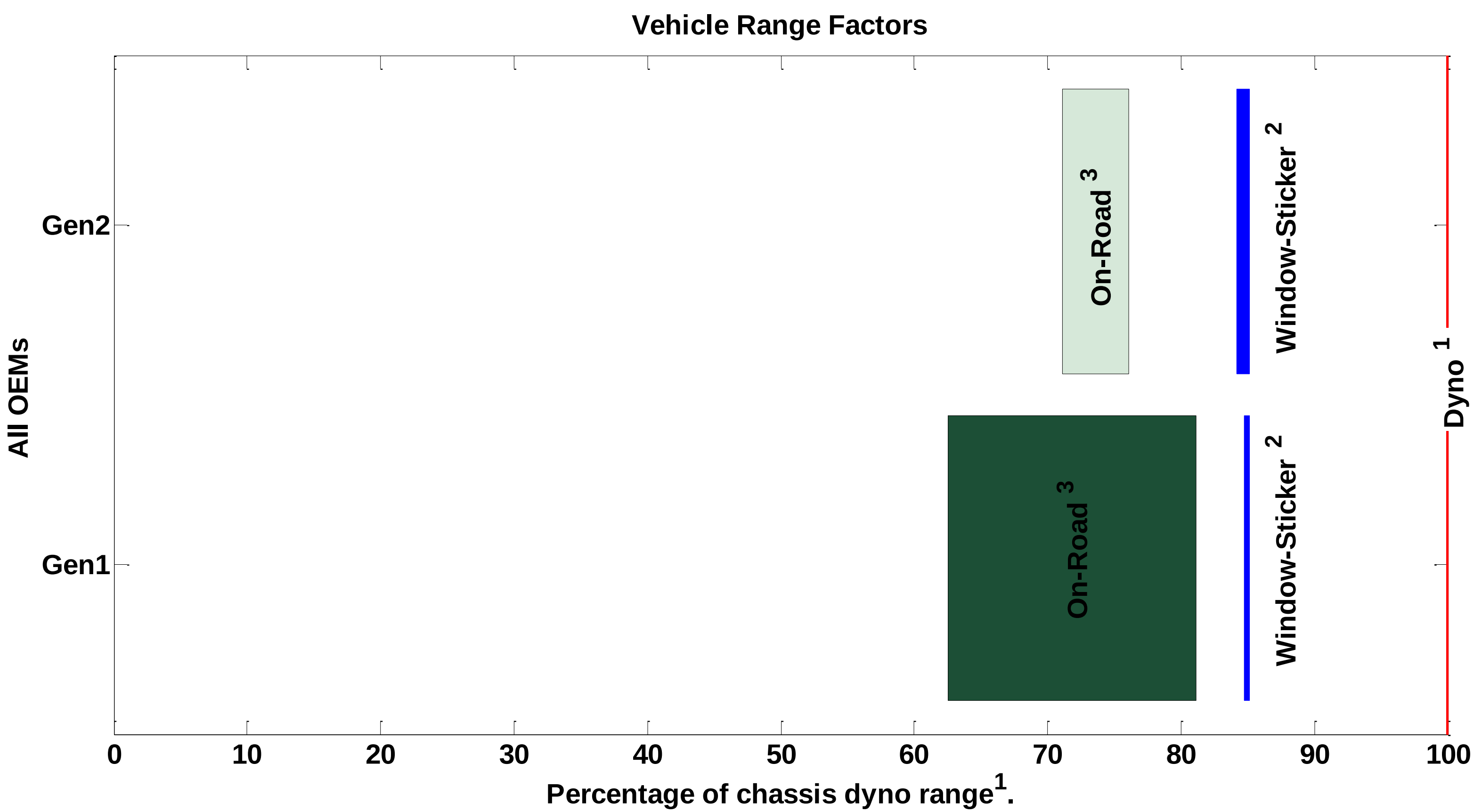


CDP#33: Percentage of Theoretical Range Traveled Between Refuelings



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.

CDP#34: Effective Vehicle Range



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

NREL CDP34
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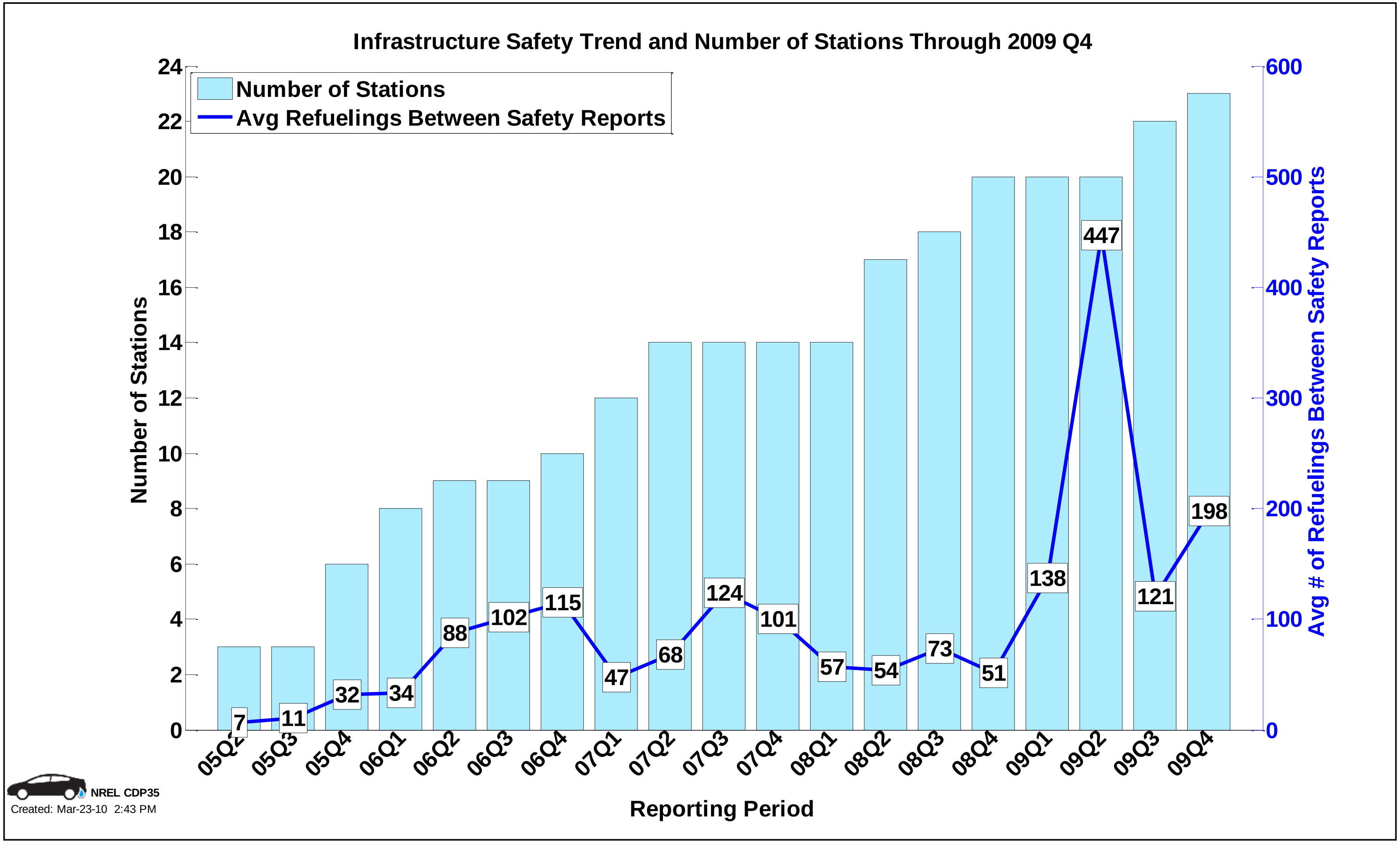
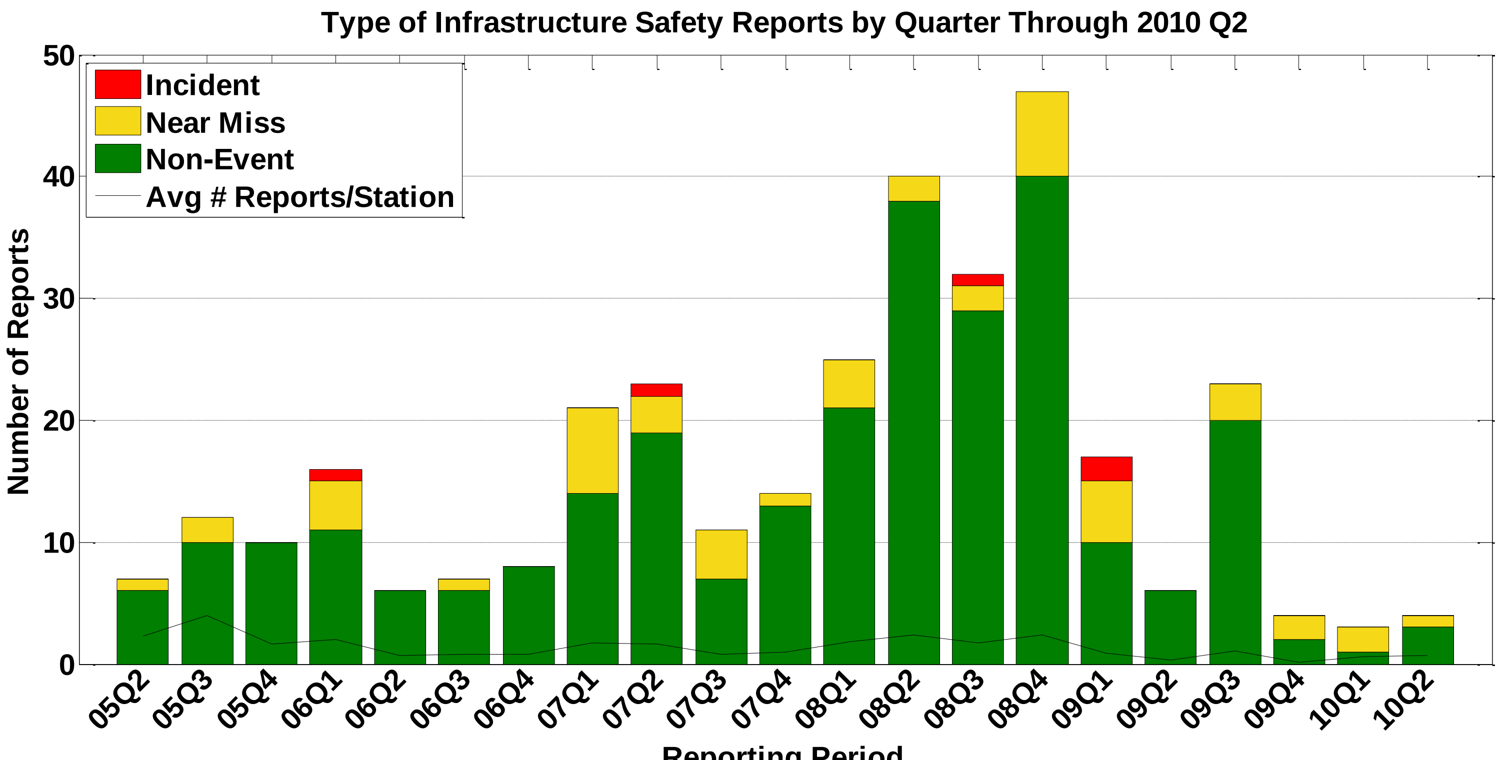
CDP#35: Average Refuelings Between Infrastructure Safety Reports



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)

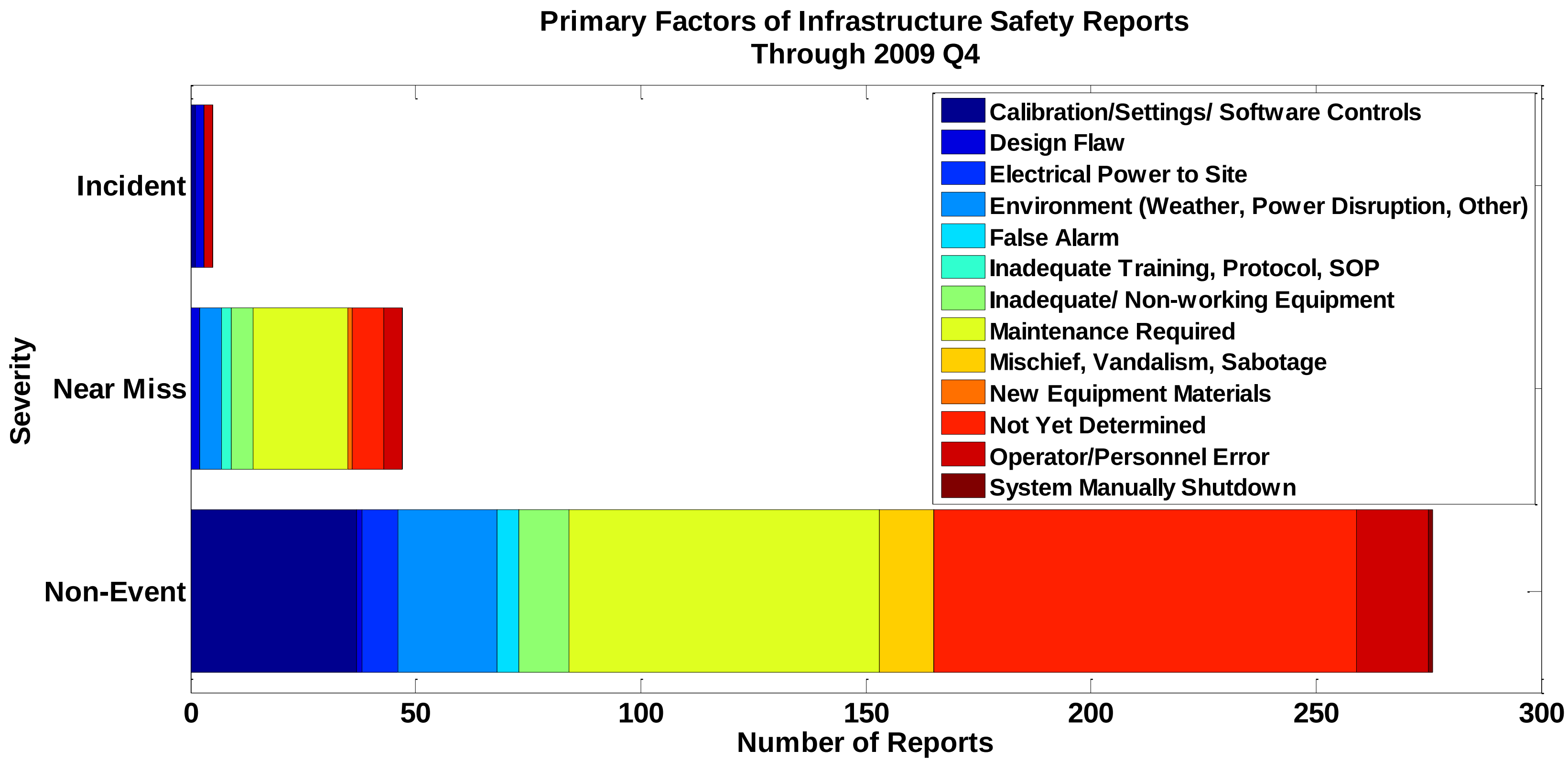
A NEAR-MISS is:

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

NREL CDP36

Created: Aug-23-10 10:02 AM

CDP#37: Primary Factors of Infrastructure Safety Reports



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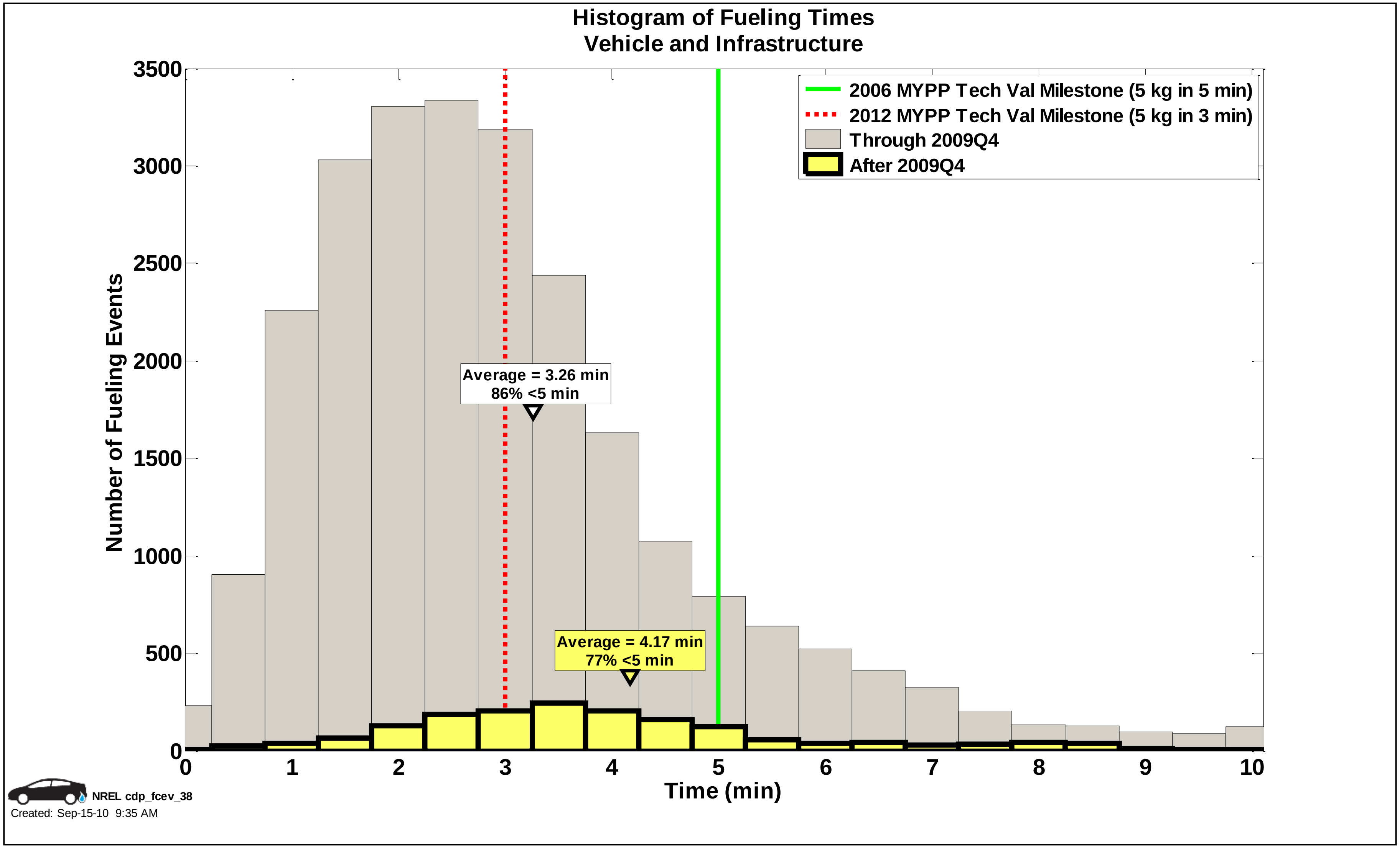
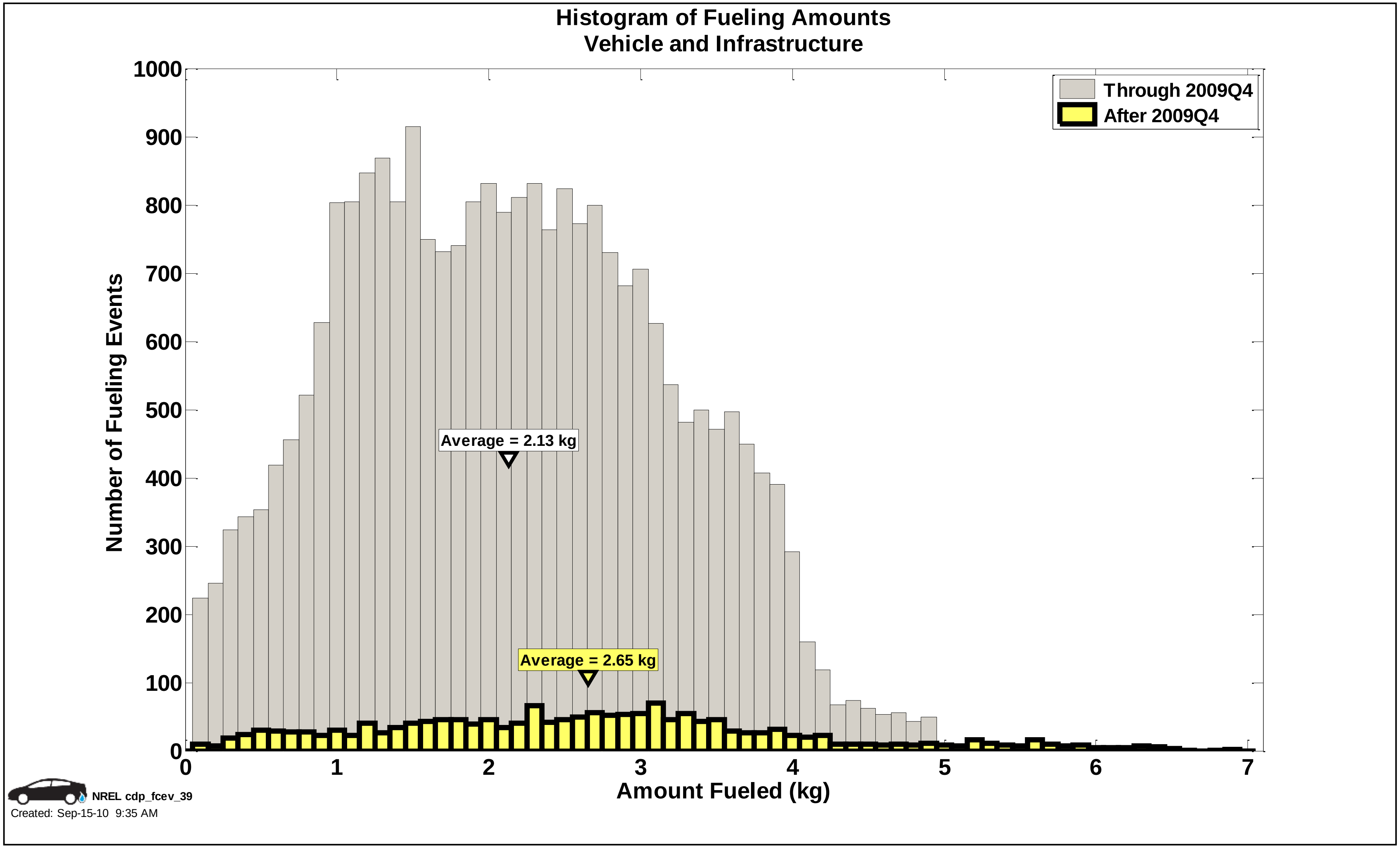
A NEAR-MISS is:
- an event that under slightly different circumstances could have become an incident
- unplanned H2 release insufficient to sustain a flame

NREL CDP37
Created: Mar-11-10 2:45 PM

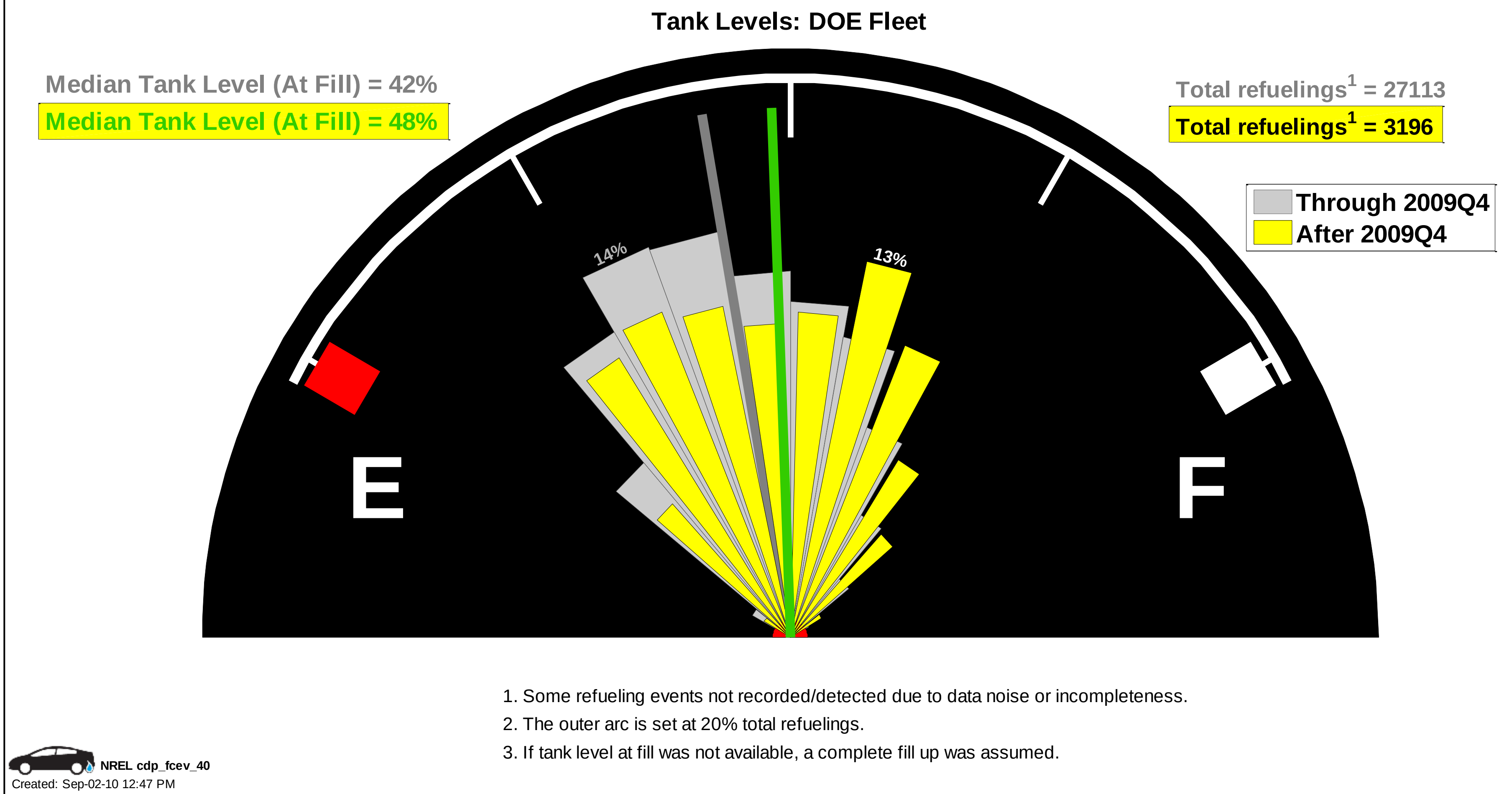
CDP#38: Refueling Times



CDP#39: Refueling Amounts



CDP#40: H2 Tank Level at Refueling

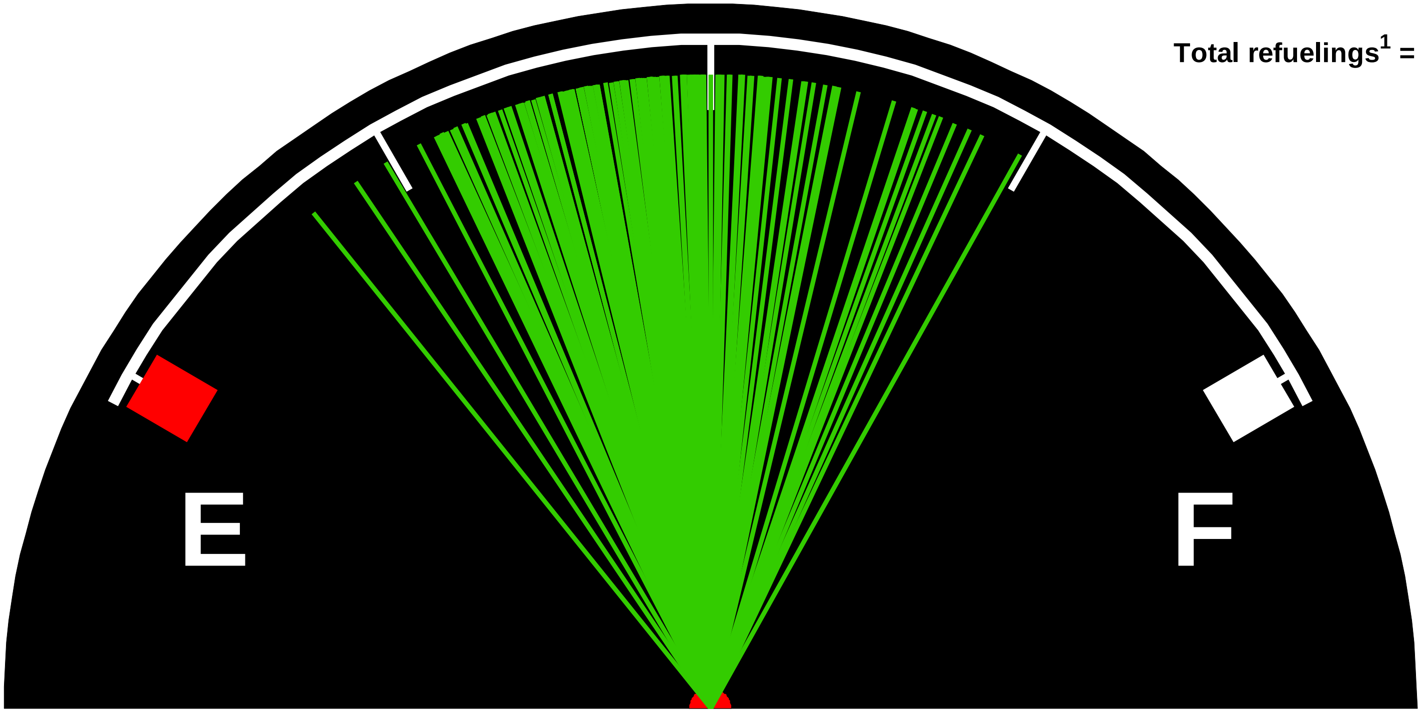


1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. The outer arc is set at 20% total refuelings.
3. If tank level at fill was not available, a complete fill up was assumed.

CDP#41: Refueling Tank Levels - Medians

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

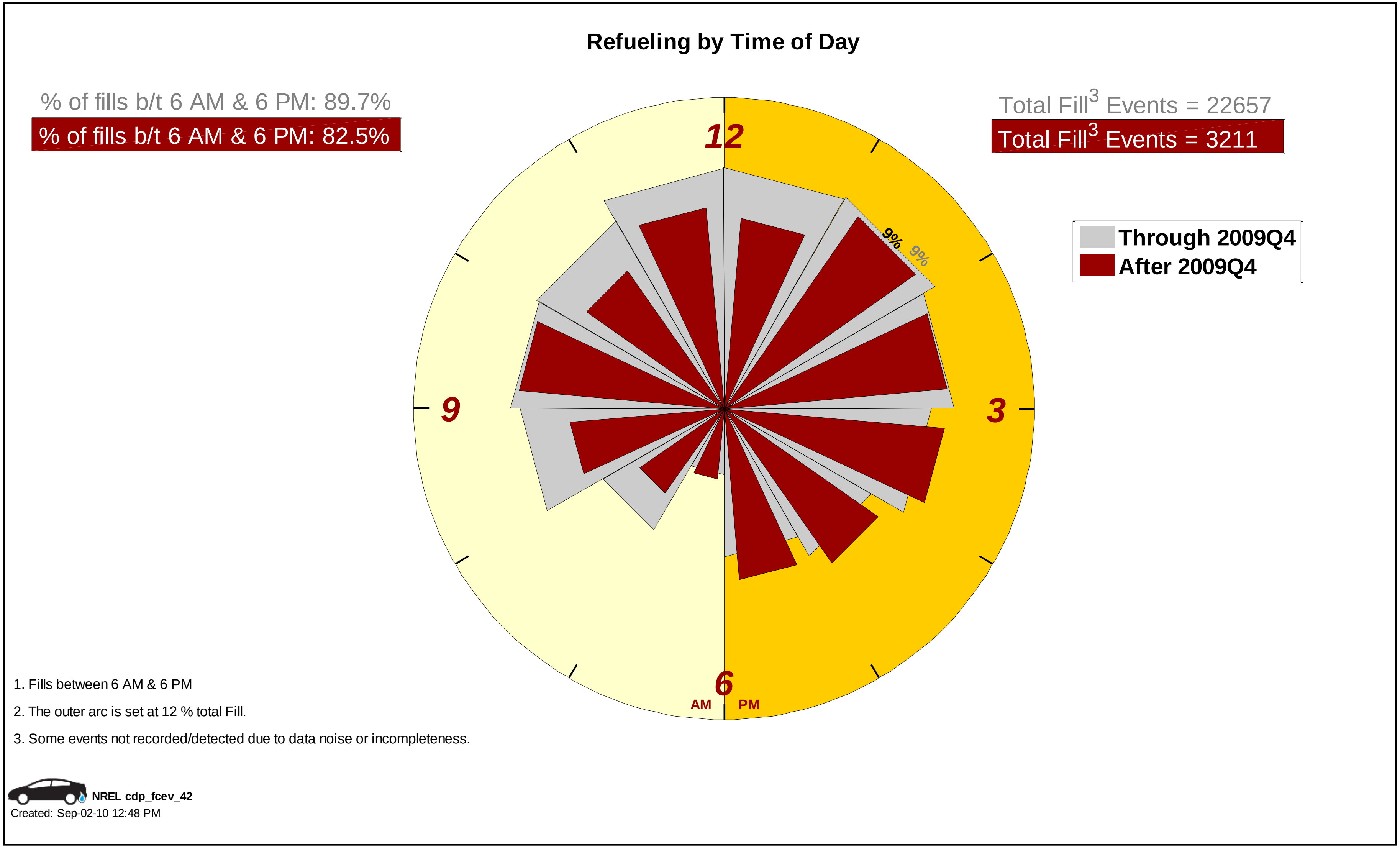
Total refuelings[1] = 27113



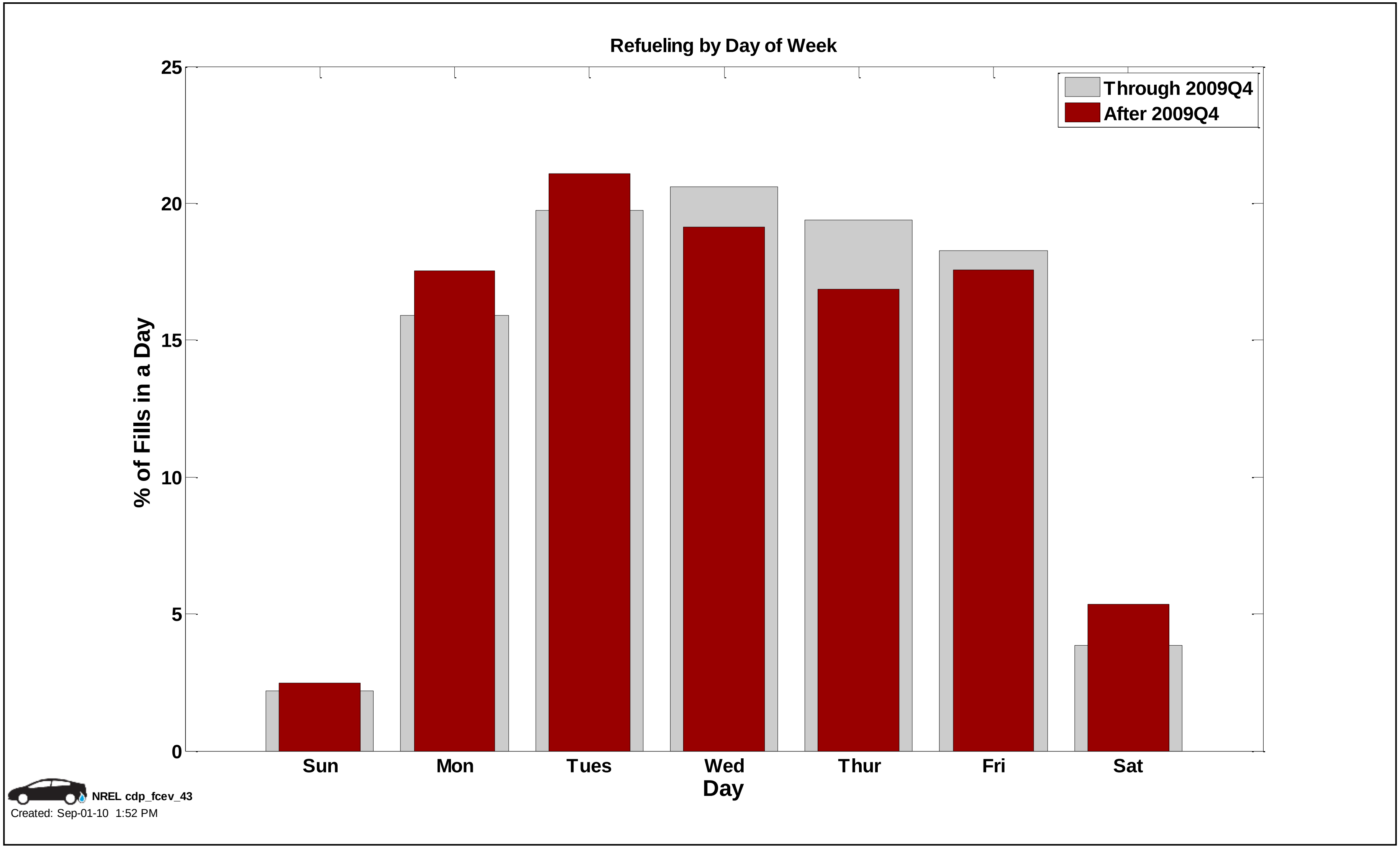
1. Some refueling events not recorded/detected due to data noise or incompleteness.
2. If tank level at fill was not available, a complete fill up was assumed.

NREL CDP41
Created: Mar-09-10 4:14 PM

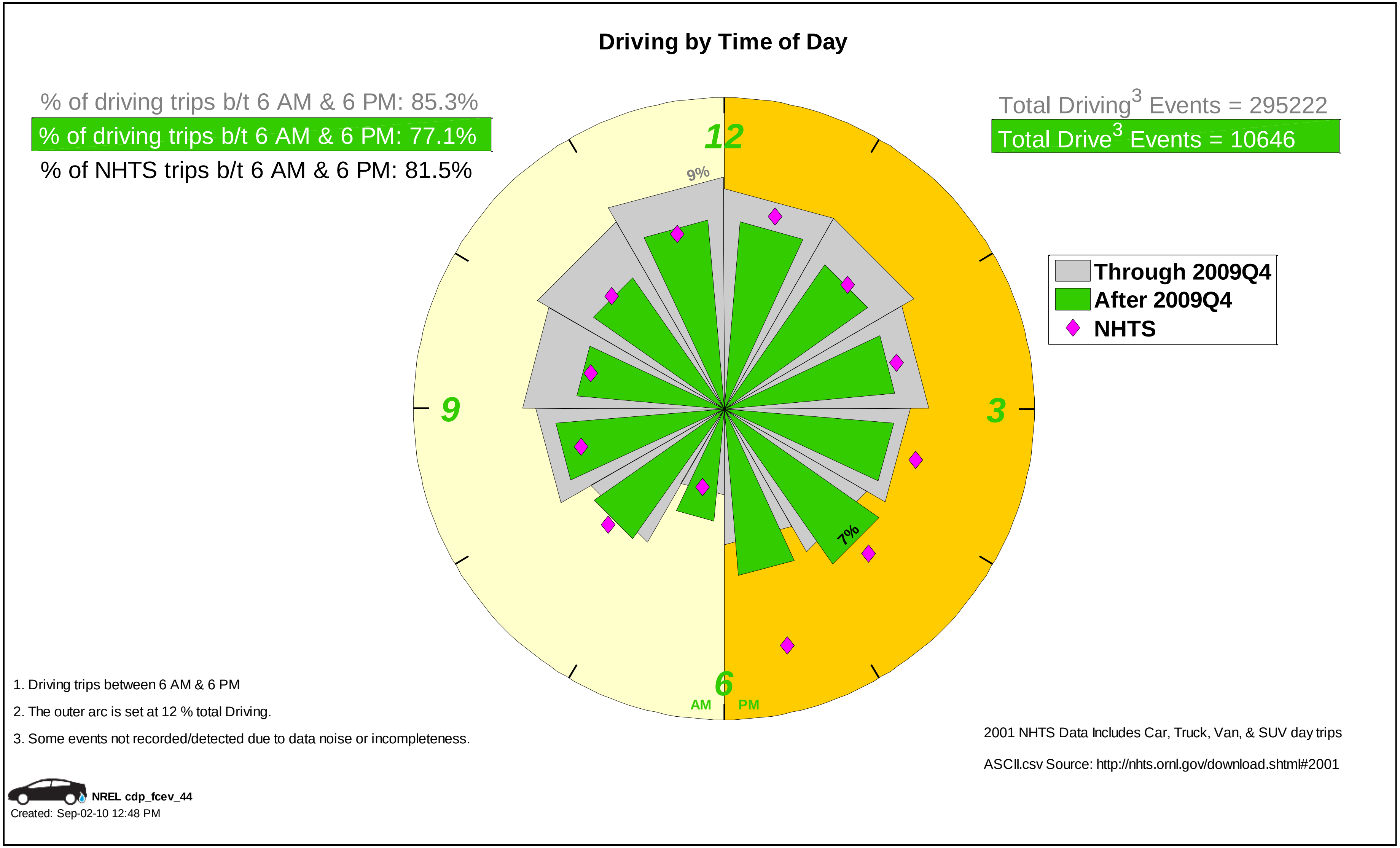
CDP#42: Refueling by Time of Day



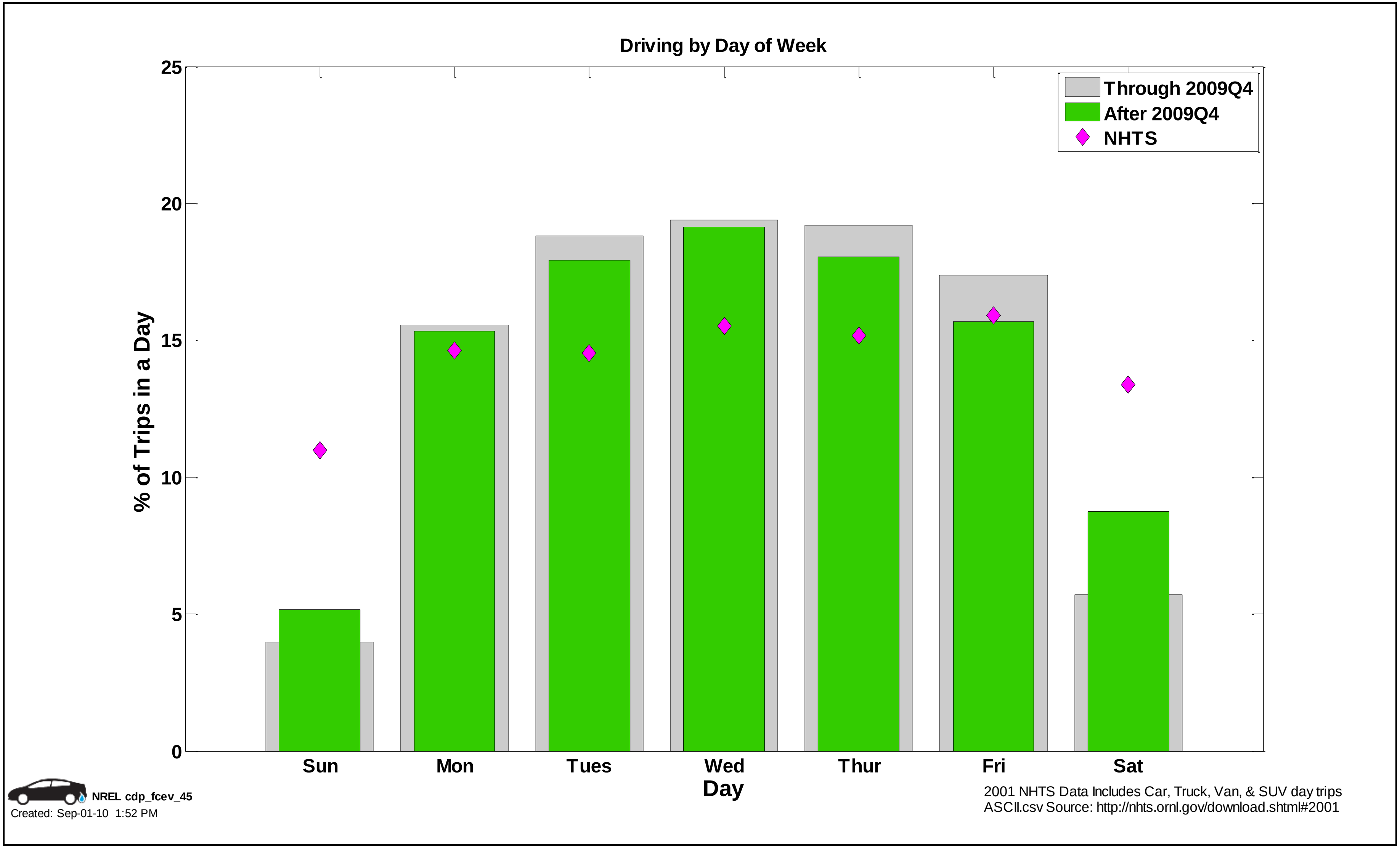
CDP#43: Refueling by Day of Week



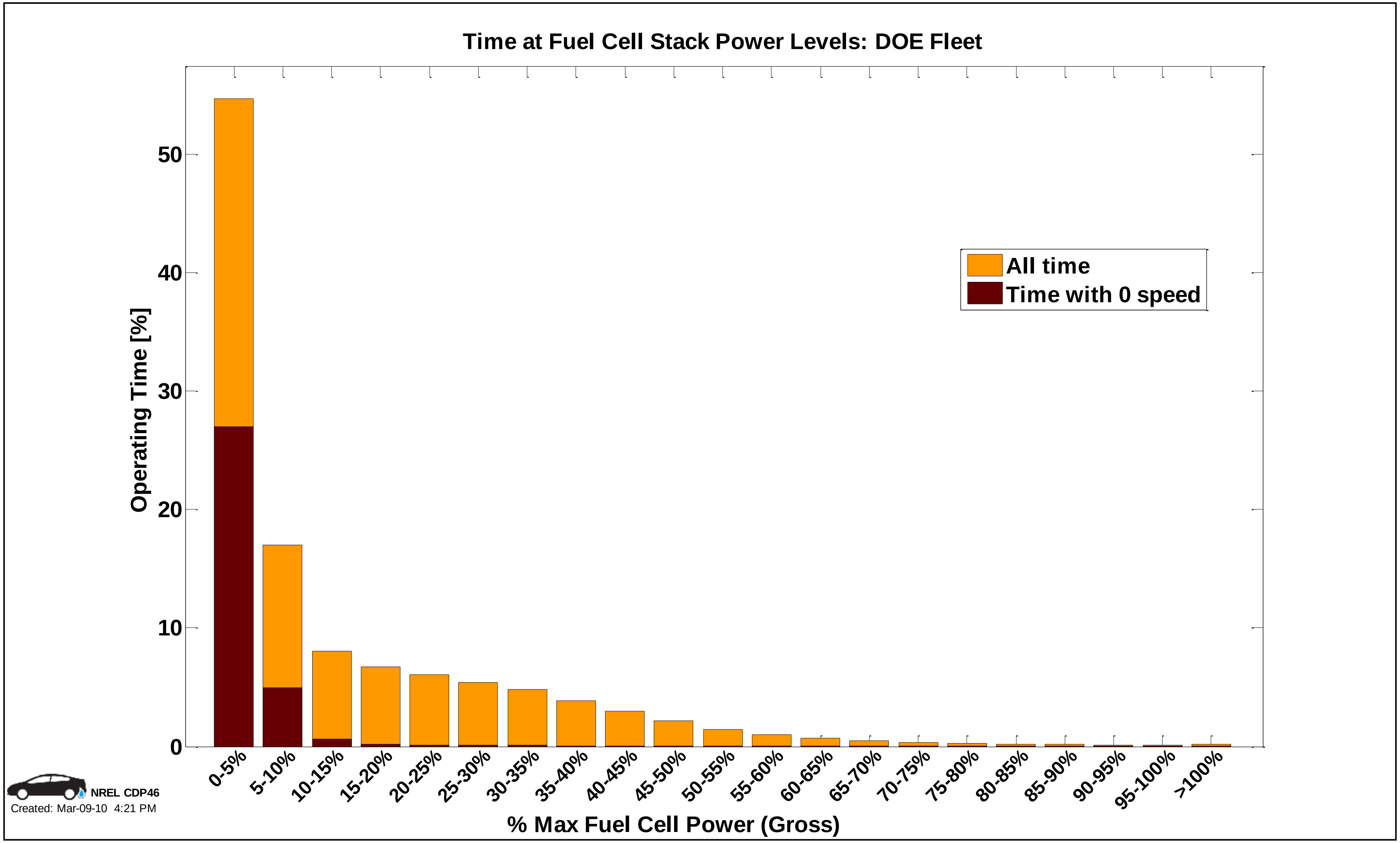
CDP#44: Driving Start Time – Day



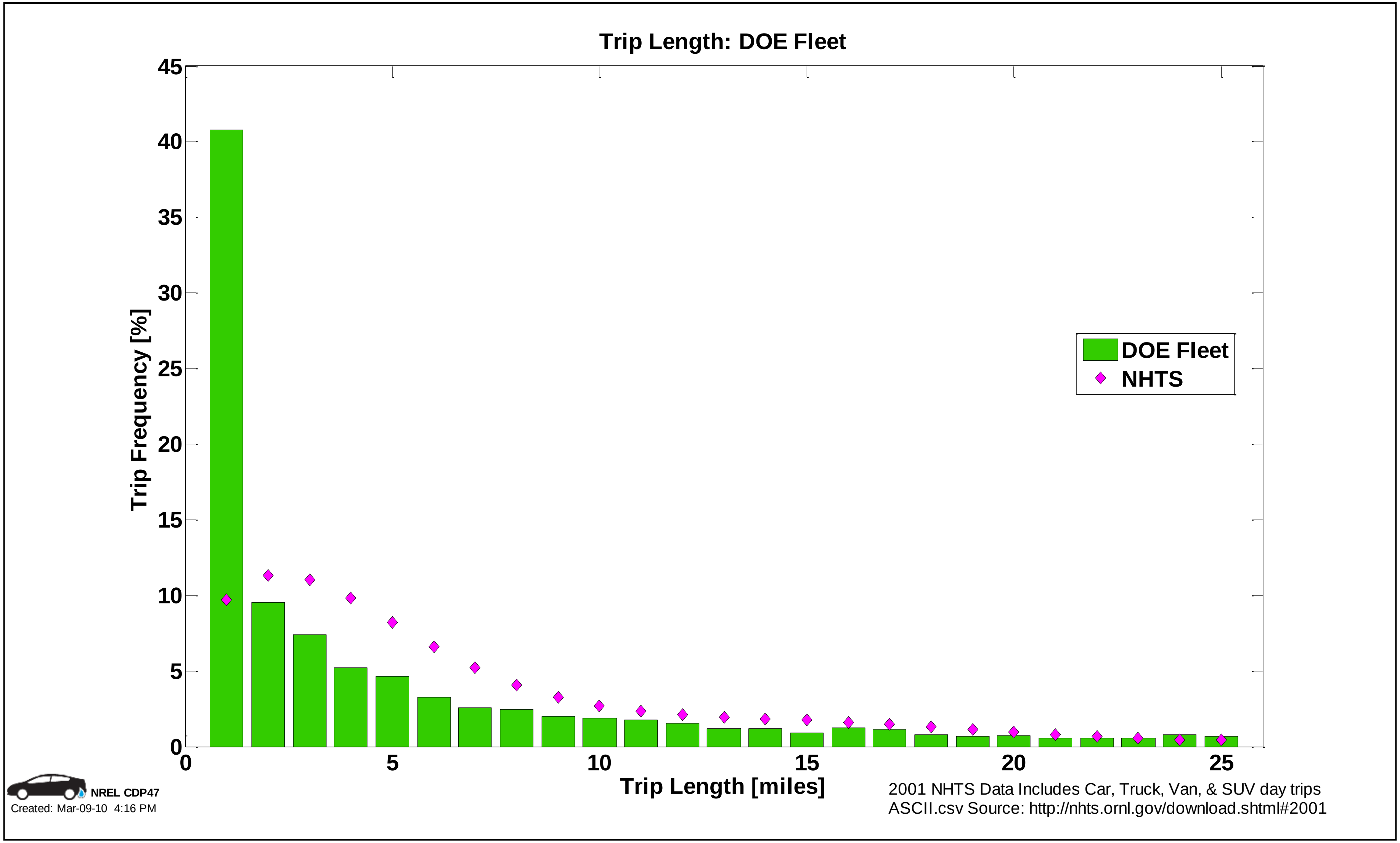
CDP#45: Driving by Day of Week



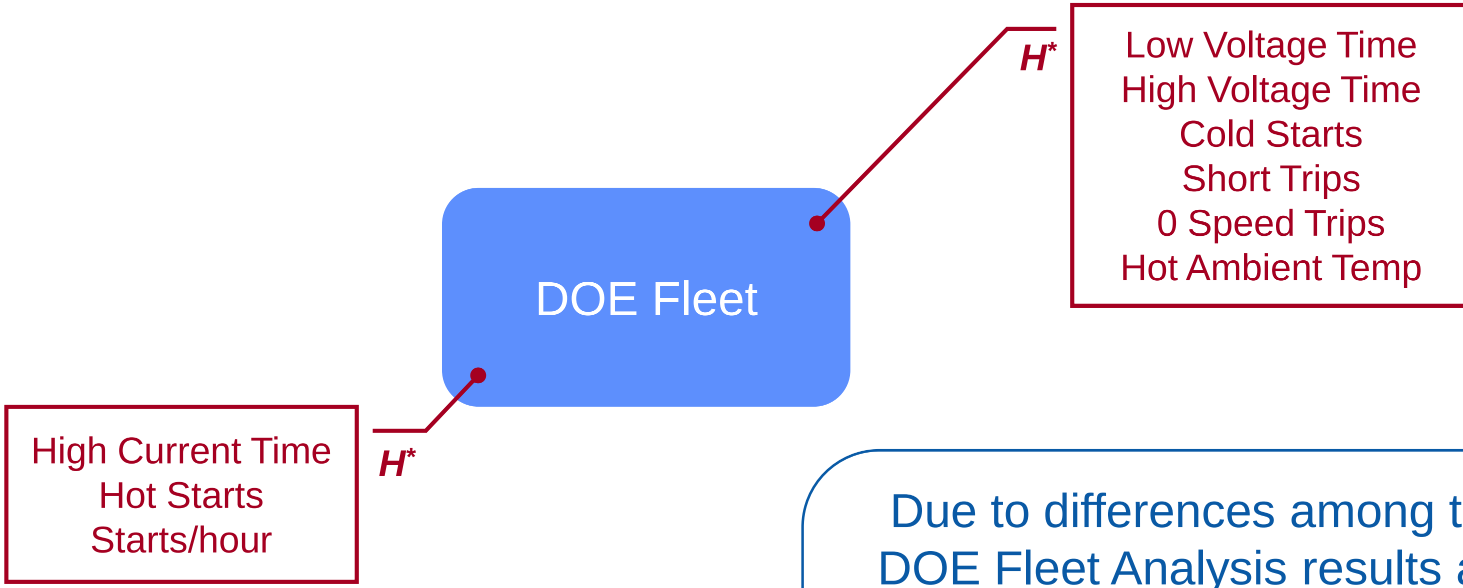
CDP#46: Fuel Cell System Operating Power



CDP#47: Trip Length



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



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

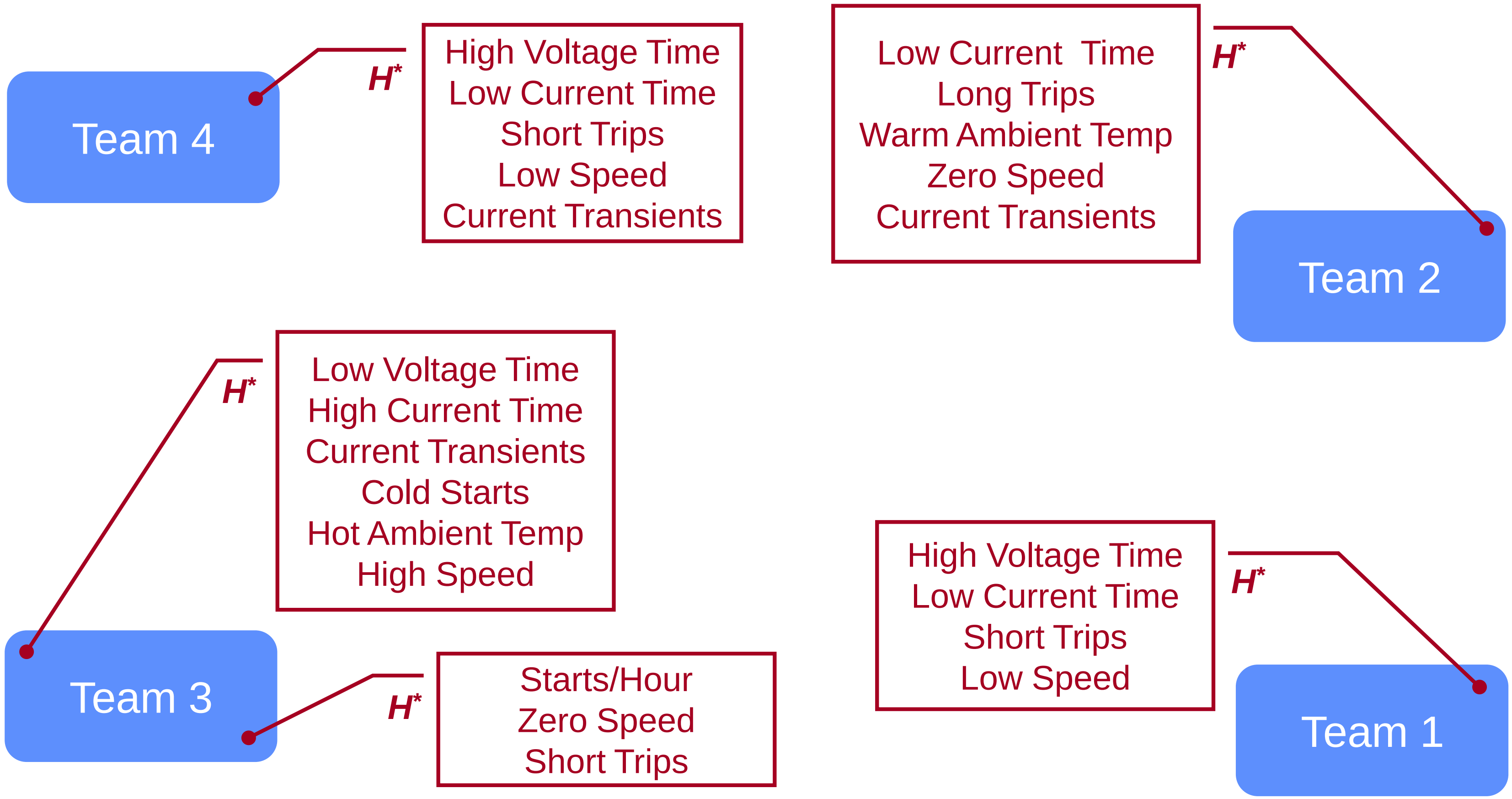
Individual team analyses (CDP#49) focused on patterns within a fleet.

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

NREL CDP48
Created: Feb-21-08 9:32 AM

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

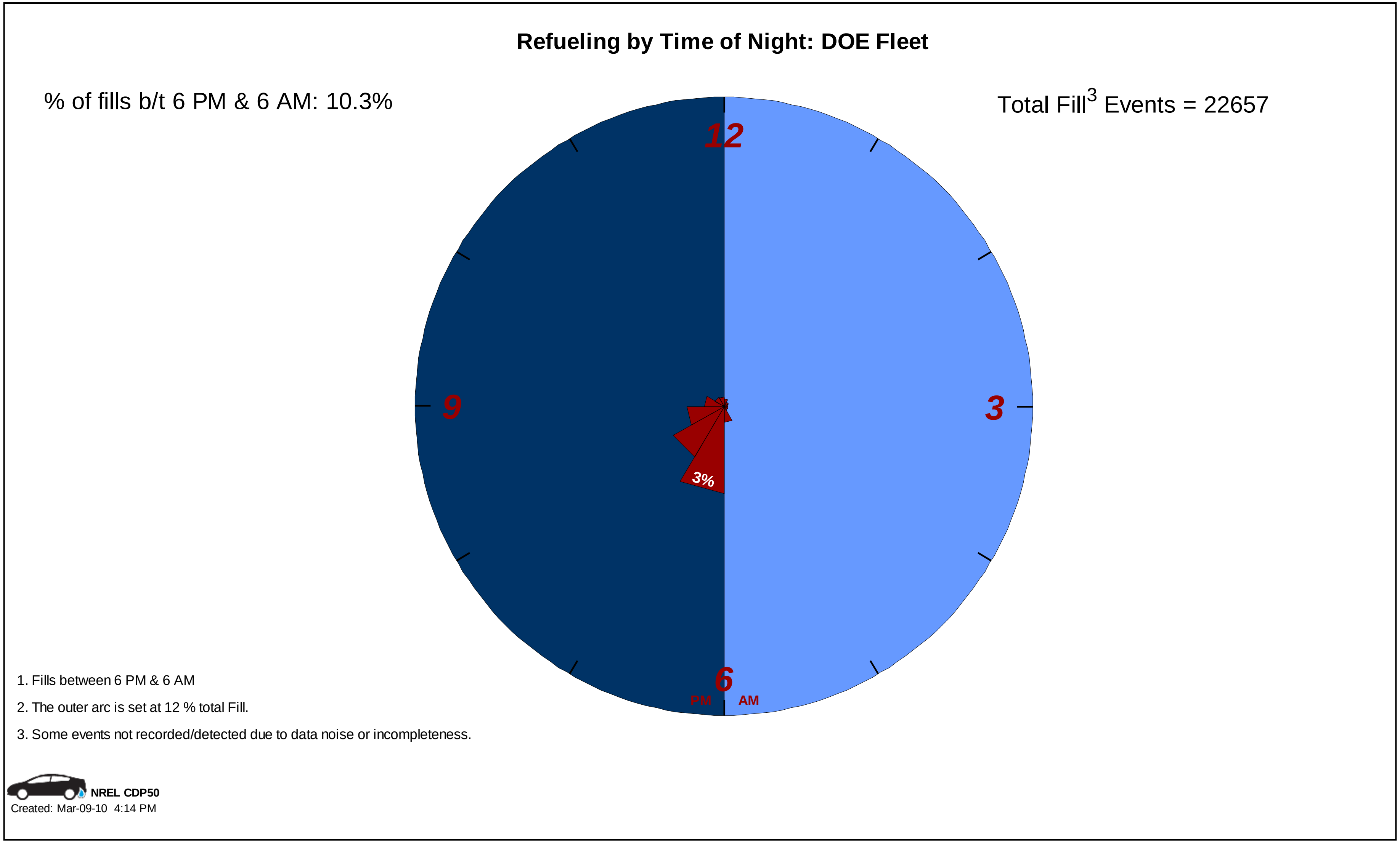


1) On-going fuel cell degradation study using Partial Least Squares (PLS) regression model for each team's Gen 1 fleet.
2) Teams' PLS models have a high percentage of explained decay rate variance, but the models are not robust and results are scattered.
3) Factor groups associated with stacks that are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

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

NREL CDP49
Created: Mar-09-09 9:06 AM

CDP#50: Refueling by Time of Night

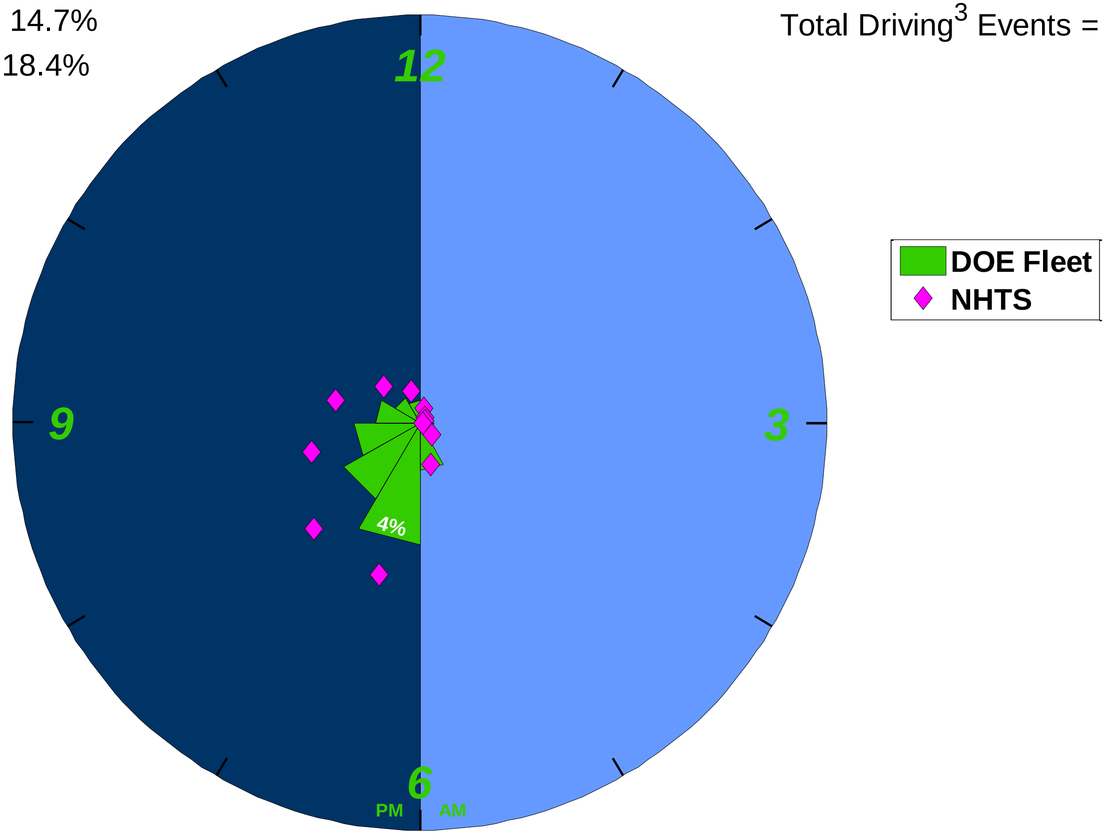


CDP#51: Driving Start Time – Night

Driving Start Time - Night: DOE Fleet

% of driving trips b/t 6 PM & 6 AM: 14.7%
% of NHTS trips b/t 6 PM & 6 AM: 18.4%

Total Driving[3] Events = 295222



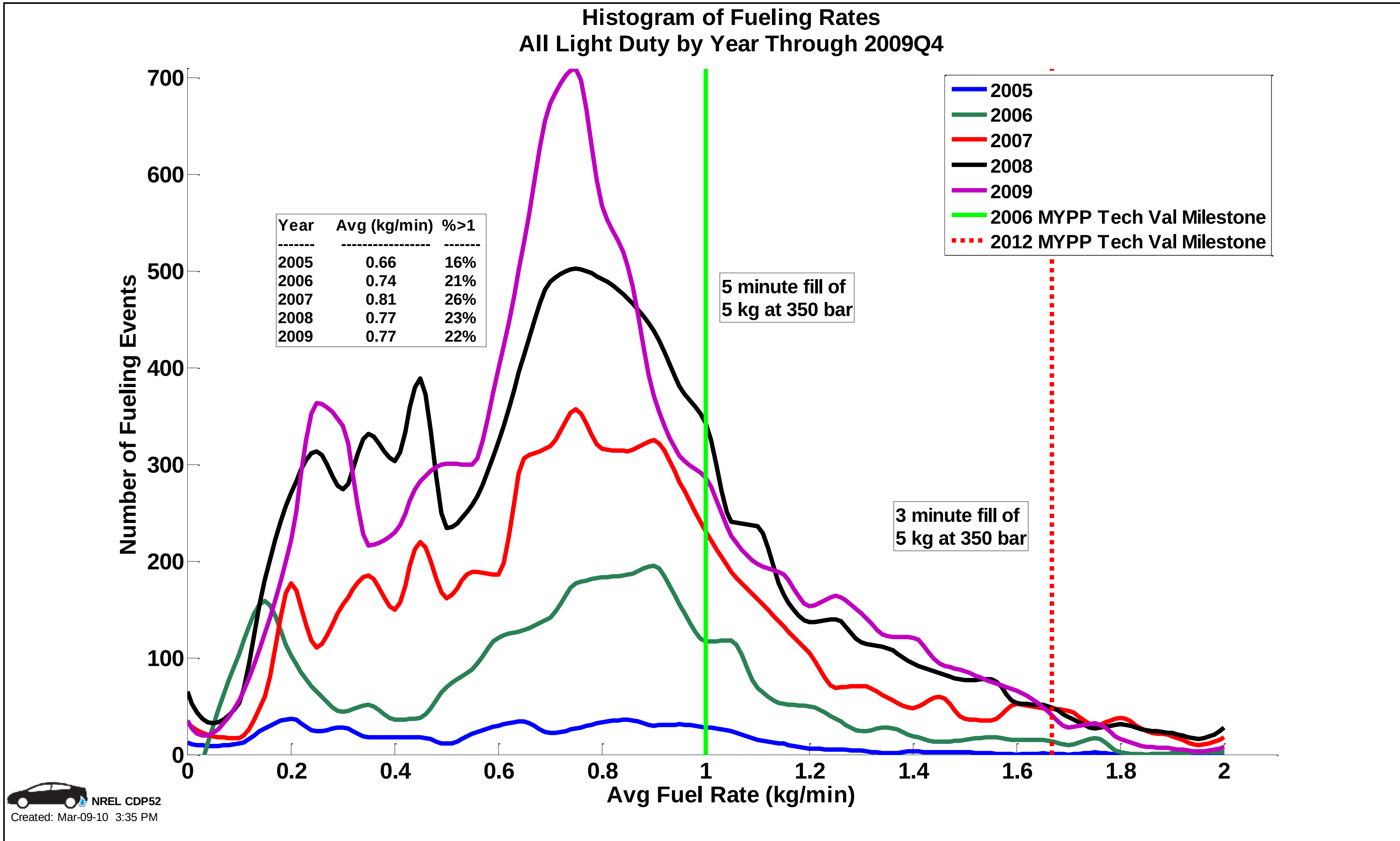
1. Driving trips between 6 PM & 6 AM
2. The outer arc is set at 12 % total Driving.
3. Some events not recorded/detected due to data noise or incompleteness.

2001 NHTS Data Includes Car, Truck, Van, & SUV day trips

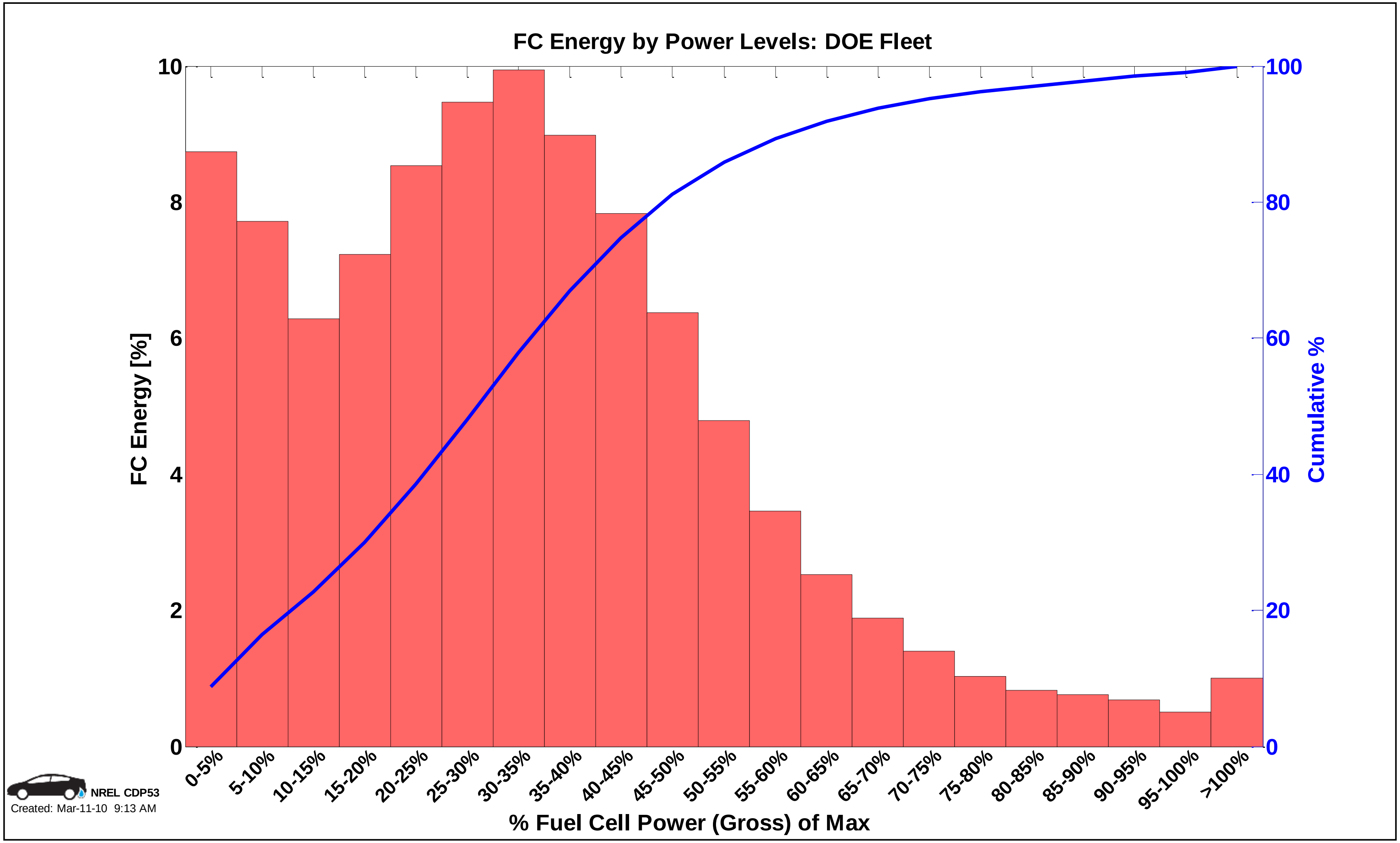
ASCII.csv Source: http://nhts.ornl.gov/download.shtml#2001

NREL CDP51
Created: Mar-09-10 4:15 PM

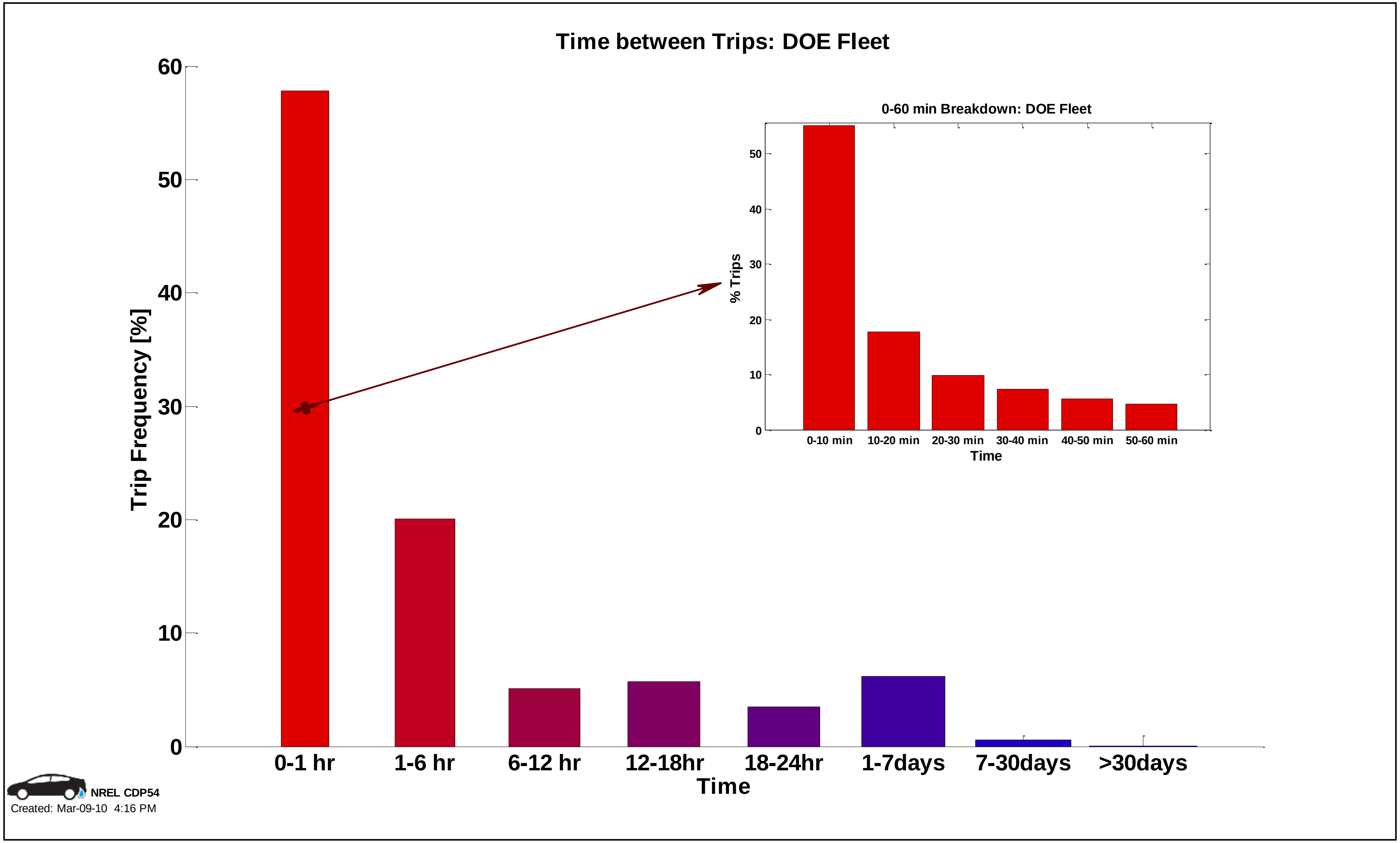
CDP#52: Refueling Data by Year



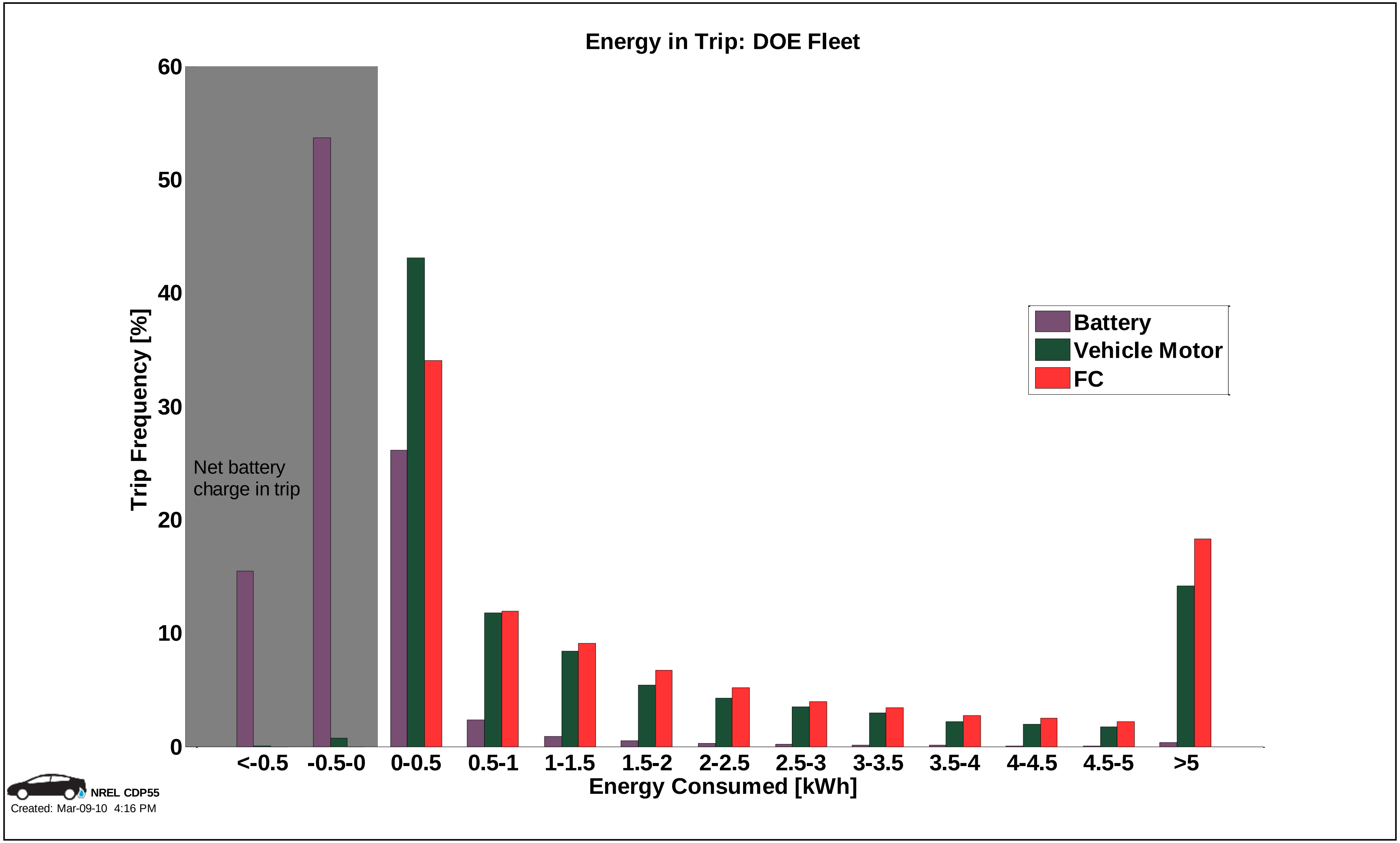
CDP#53: Fuel Cell System Energy within Power Levels



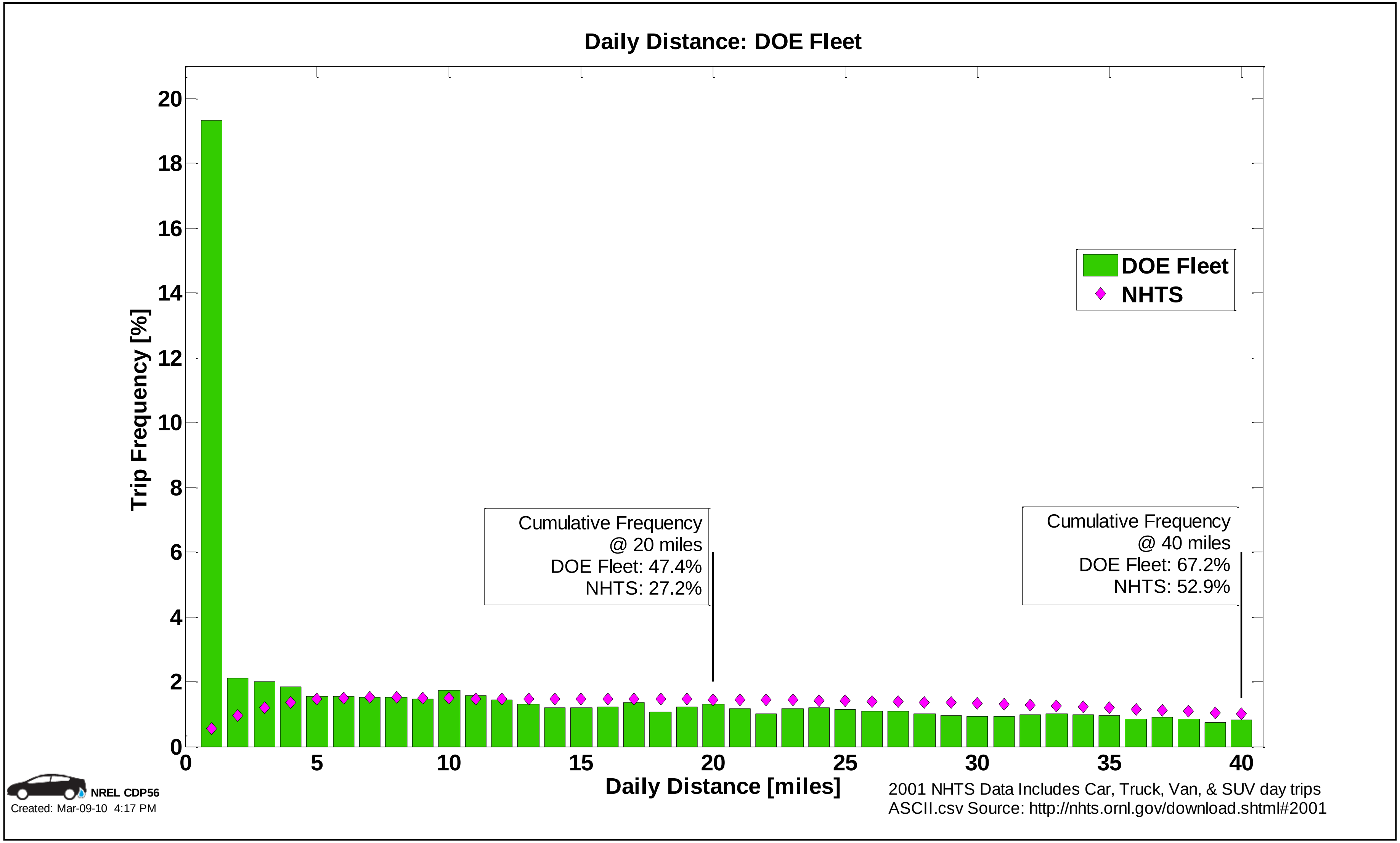
CDP#54: Time Between Trips



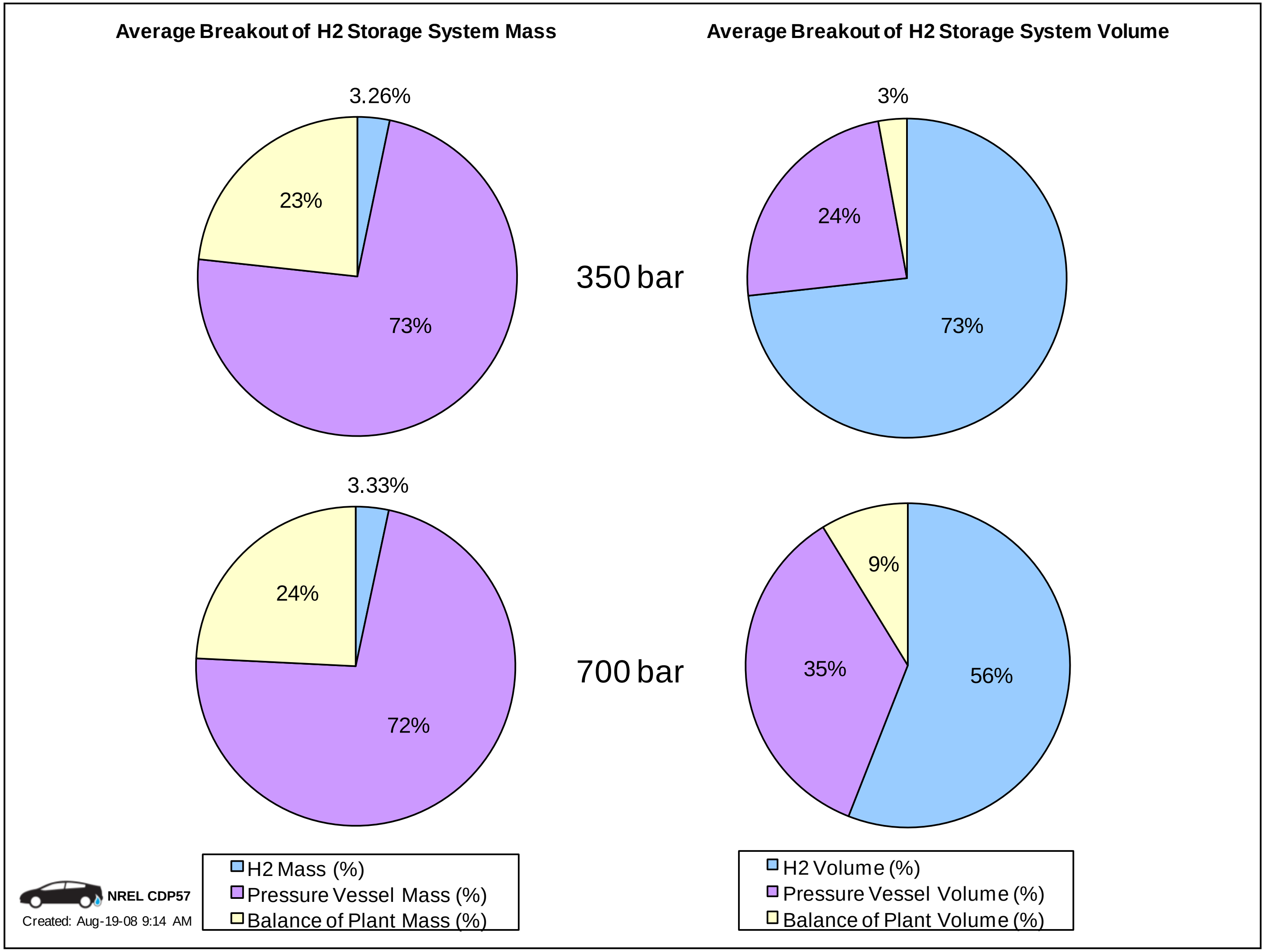
CDP#55: Fuel Cell System Energy



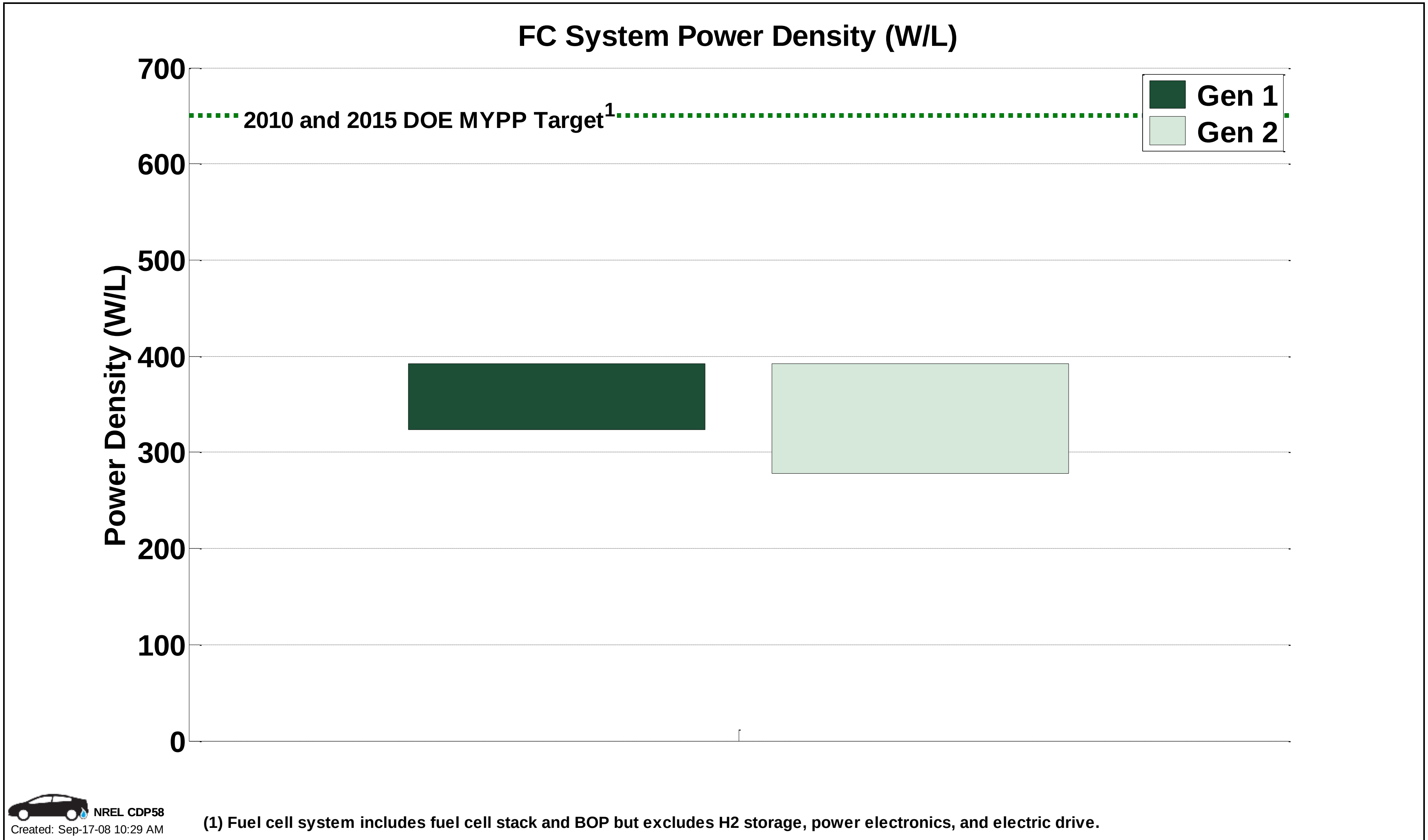
CDP#56: Daily Driving Distance



CDP#57: H2 Storage System Mass and Volume Breakdown

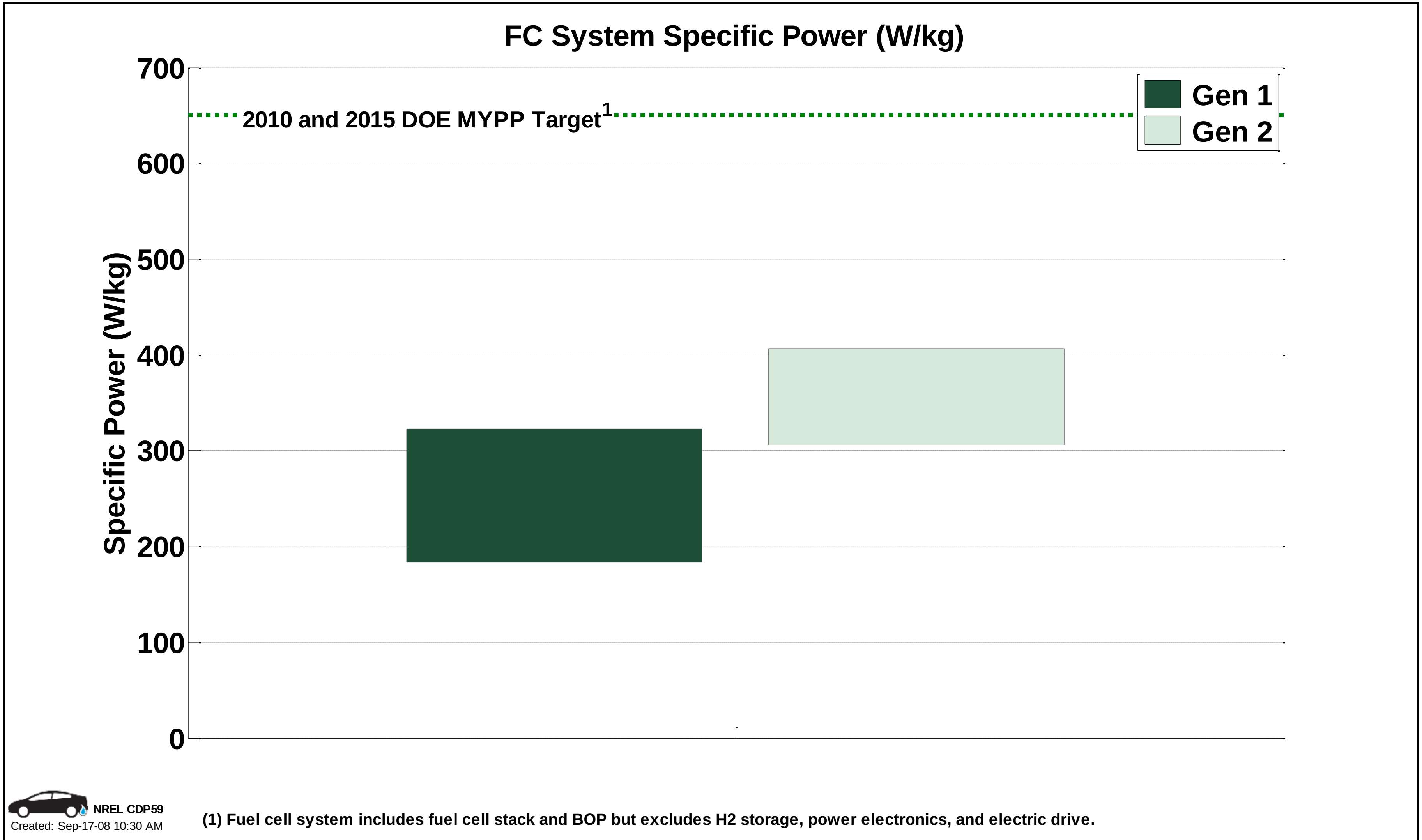


CDP#58: Fuel Cell System Power Density



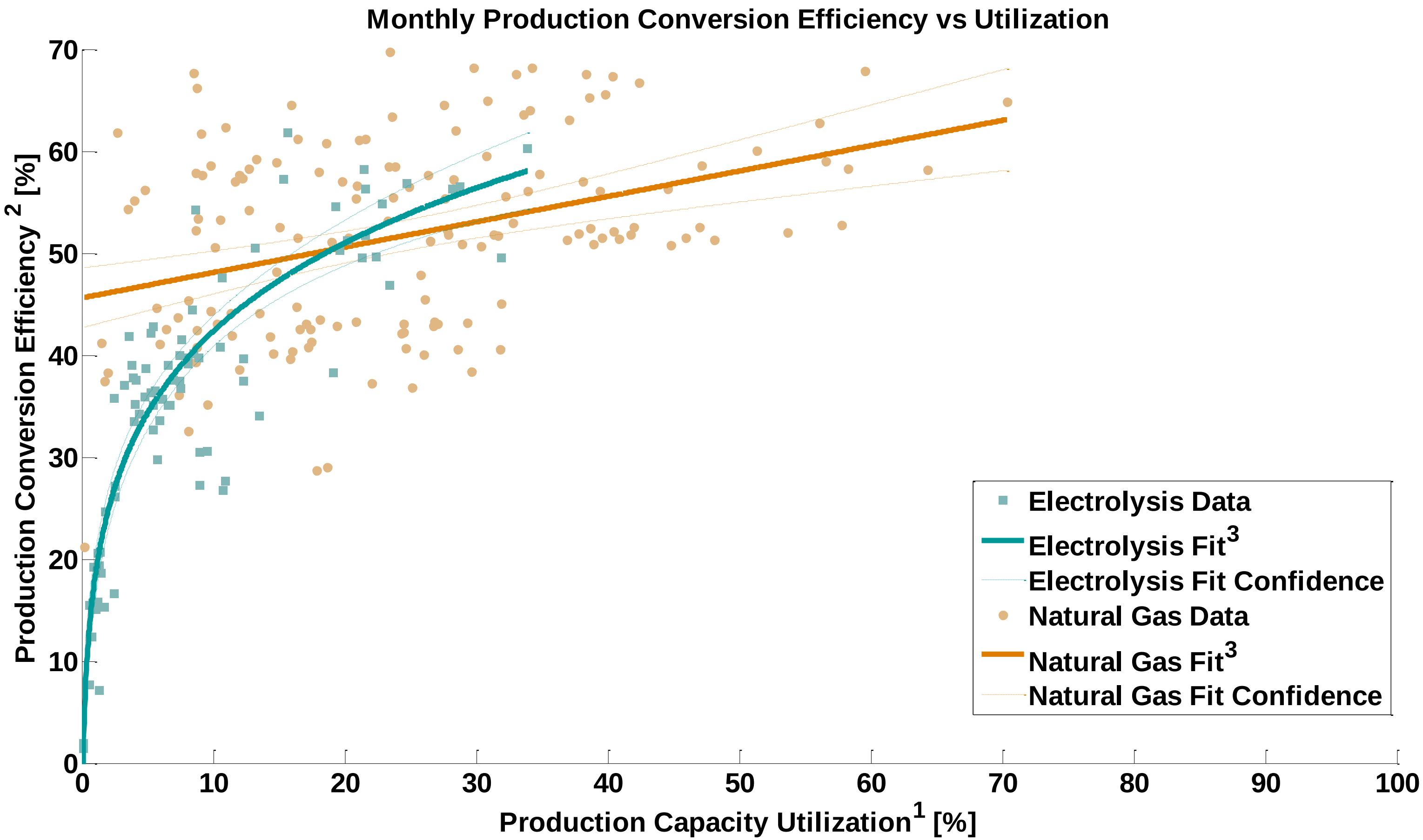
(1) Fuel cell system includes fuel cell stack and BOP but excludes H2 storage, power electronics, and electric drive.

CDP#59: Fuel Cell System Specific Power



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

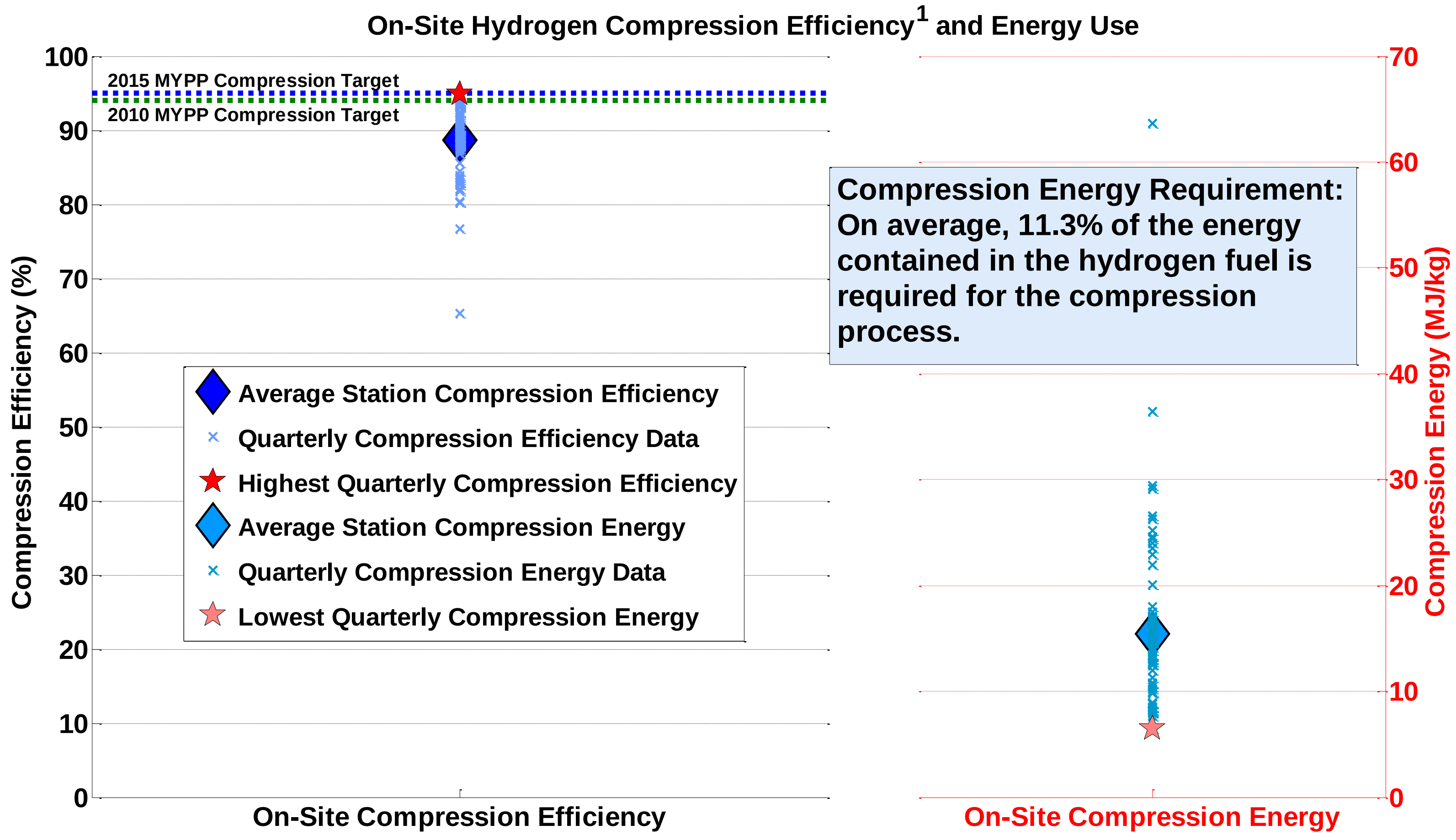
CDP#60: On-Site Hydrogen Production Efficiency vs. Capacity Utilization



1) 100% production utilization assumes operation 24 hrs a day, 7 days a week
2) Production conversion efficiency is defined as the energy of the hydrogen out of the process (on a LHV basis) divided by the sum of the energy into the production process from the feedstock and all other energy as needed. Conversion efficiency does not include energy used for compression, storage, and dispensing.
3) High correlation with electrolysis data (R^2 = 0.82) & low correlation with natural gas data (R^2 = 0.060)

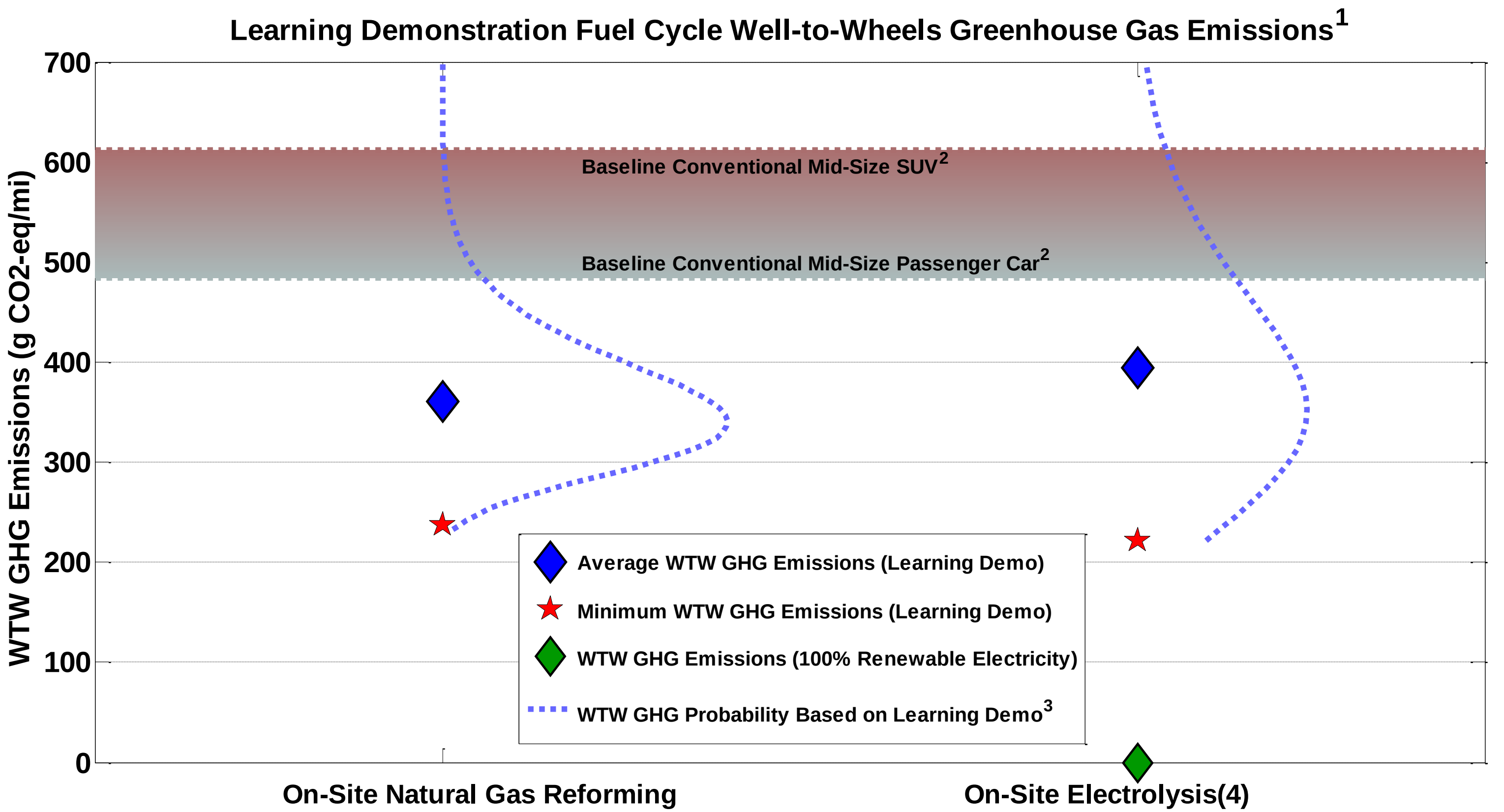
NREL CDP60
Created: Mar-09-10 3:34 PM

CDP#61: Refueling Station Compressor Efficiency



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

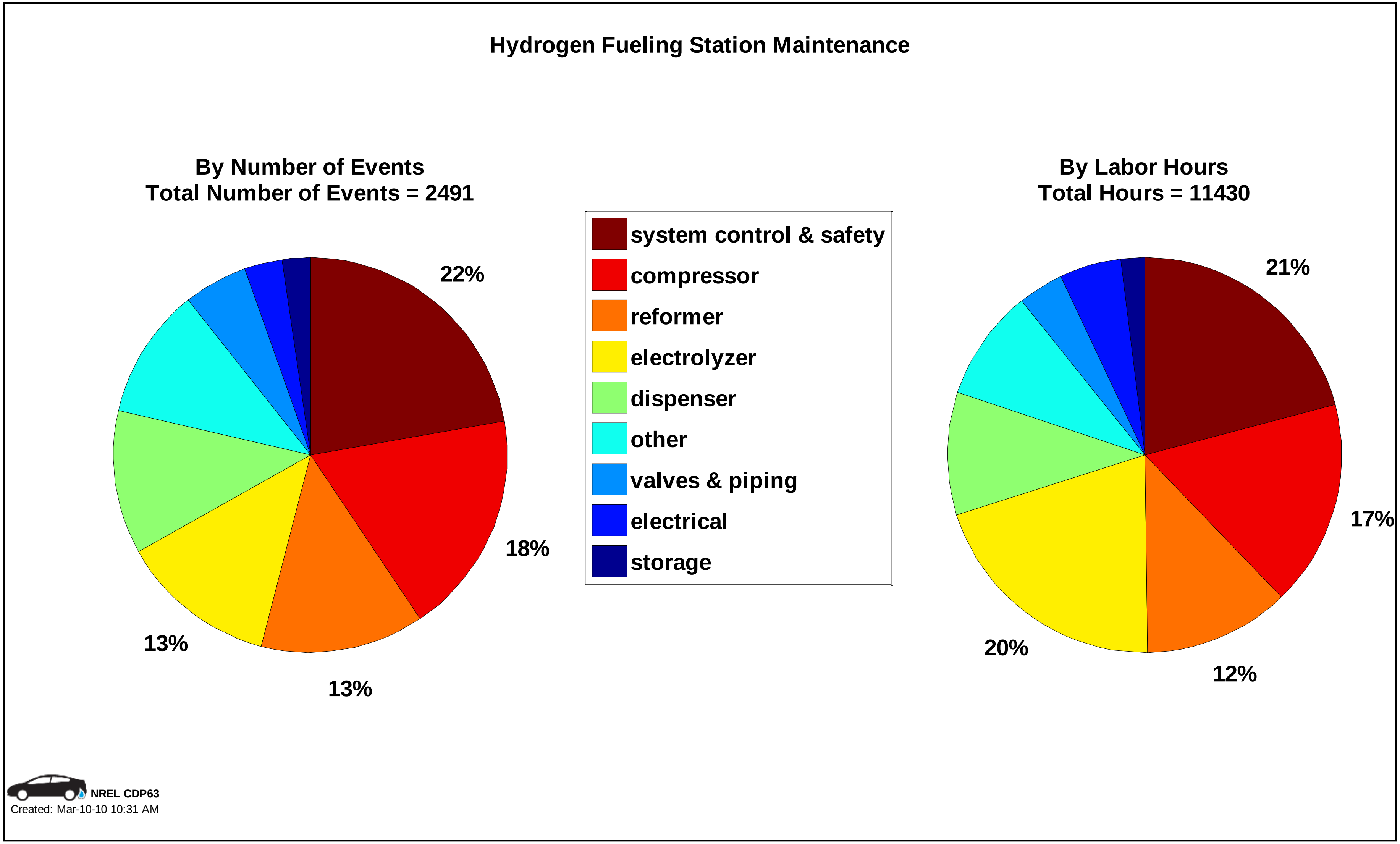
CDP#62: Learning Demonstration Vehicle Greenhouse Gas Emissions



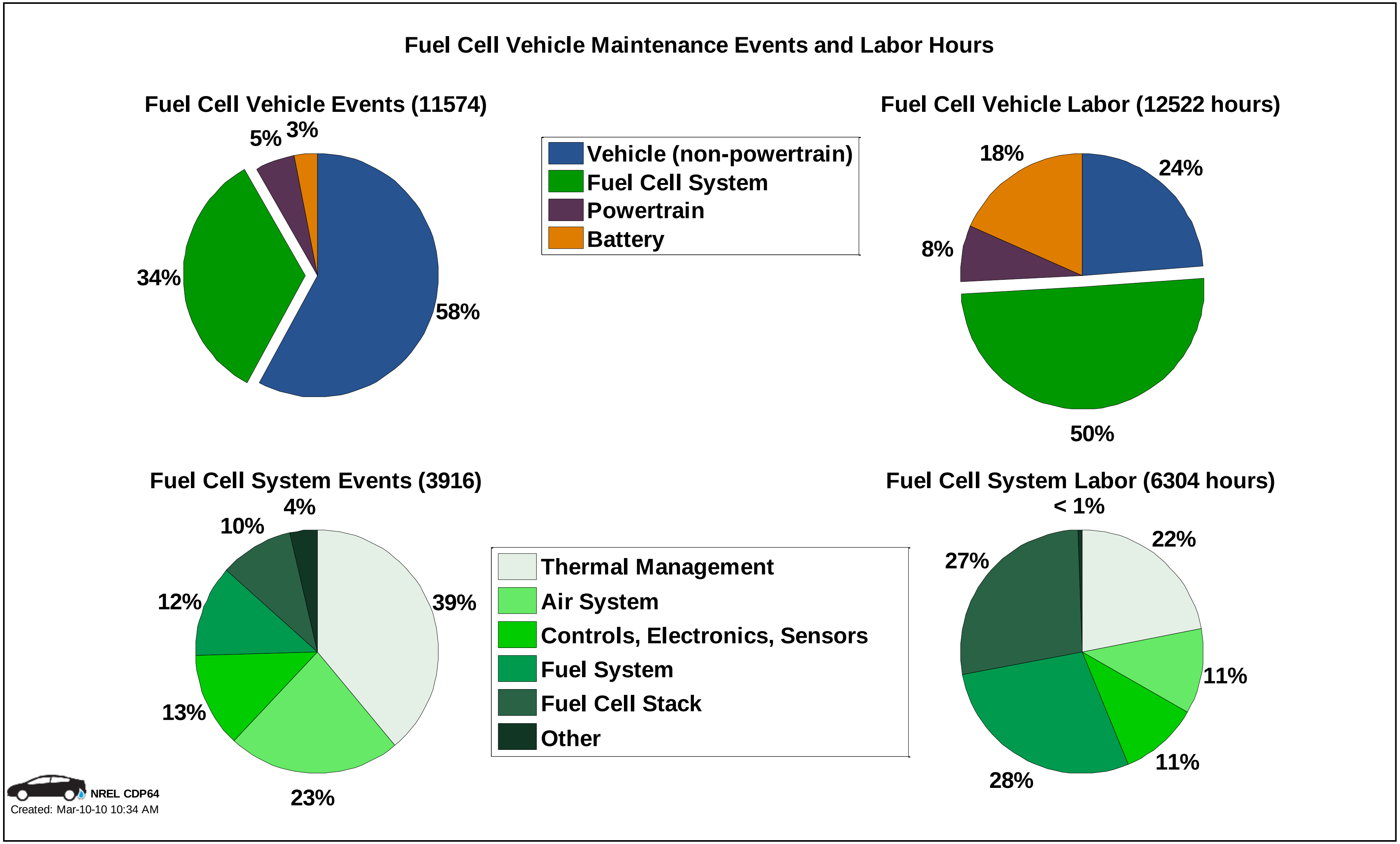
1. Well-to-Wheels greenhouse gas emissions based on DOE's GREET model, version 1.8b. Analysis uses default GREET values except for FCV fuel economy, hydrogen production conversion efficiency, and electricity grid mix. Fuel economy values are the Gen 1 and Gen 2 window-sticker fuel economy data for all 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 1330 g/mile.

NREL CDP62
Created: Mar-08-10 4:16 PM

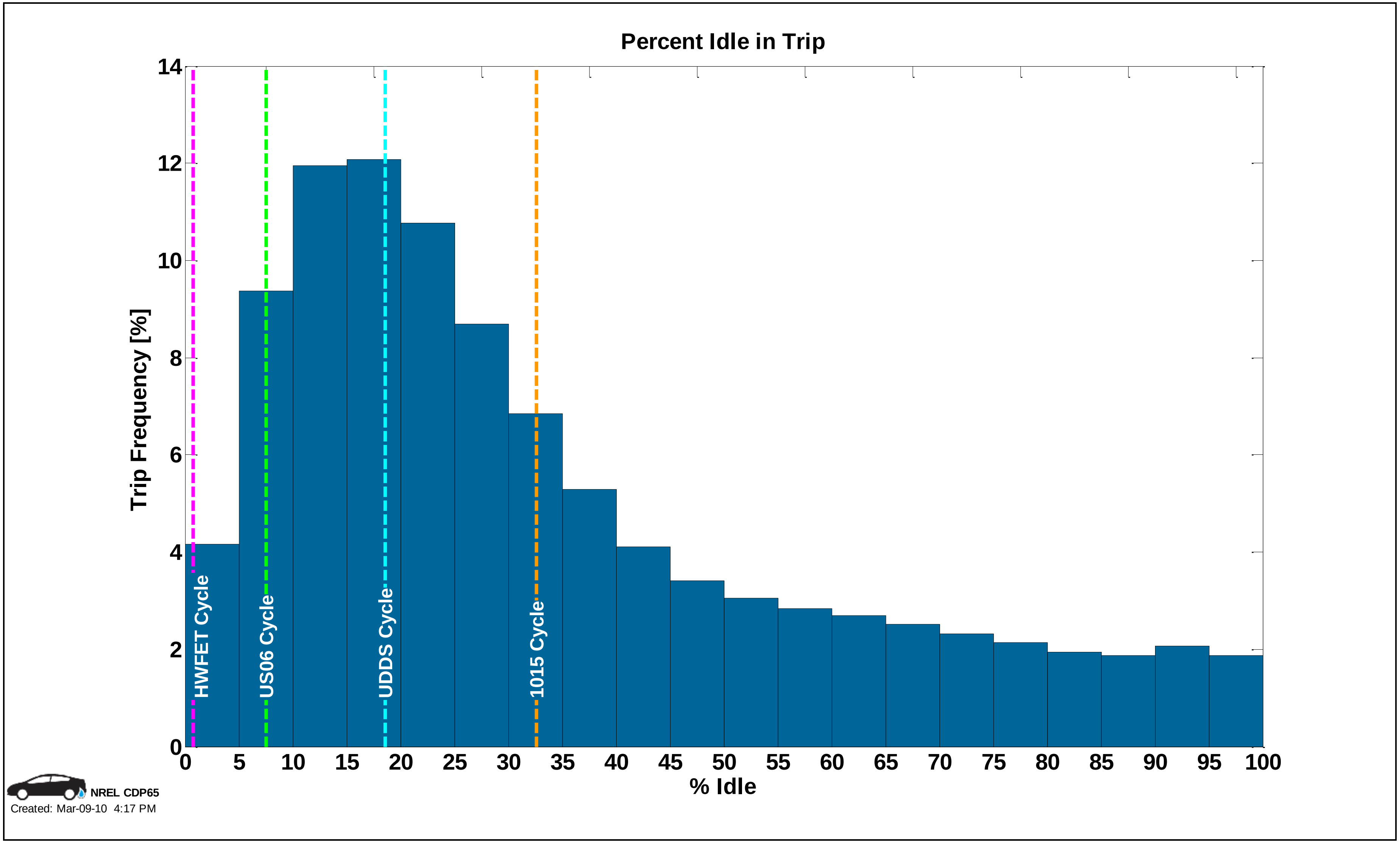
CDP#63: Hydrogen Fueling Station Maintenance by System



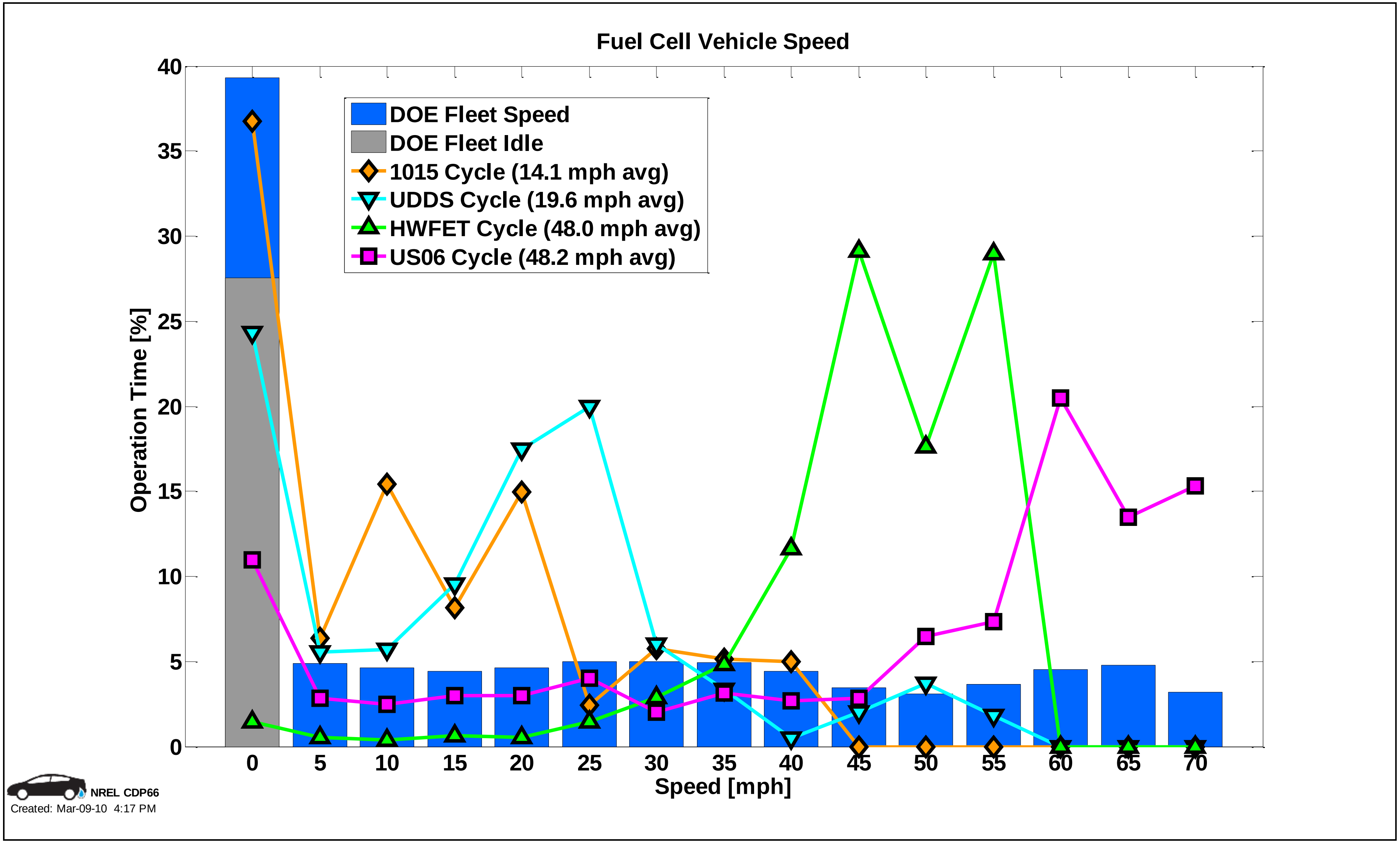
CDP#64: Fuel Cell Vehicle Maintenance by System



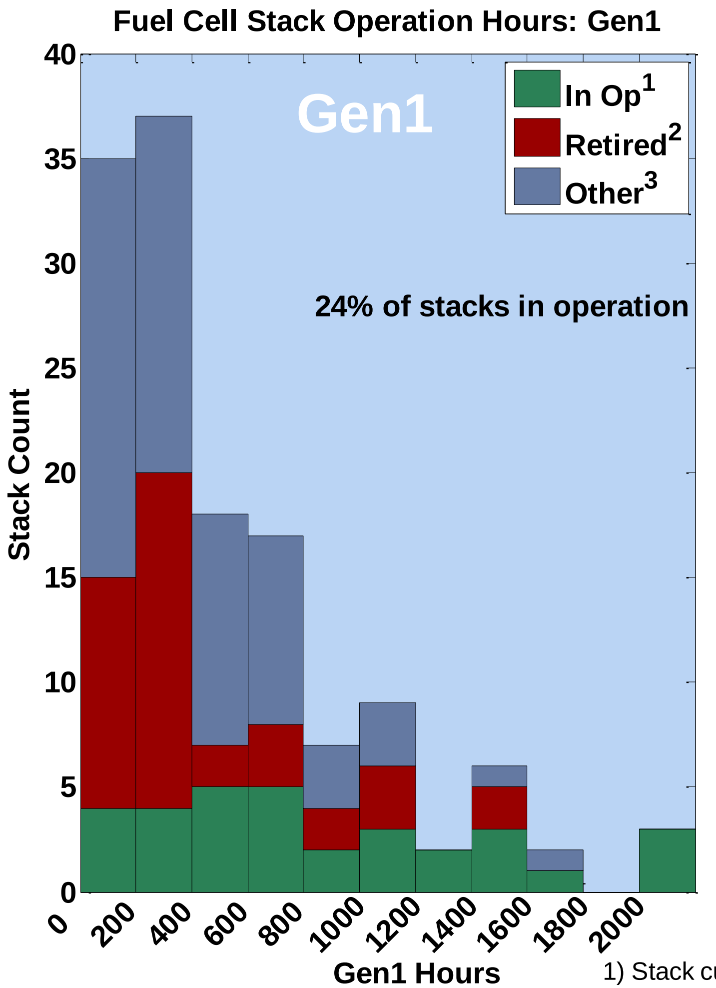
CDP#65: Percent Idle in Trip with Comparison to Standard Drive Cycles

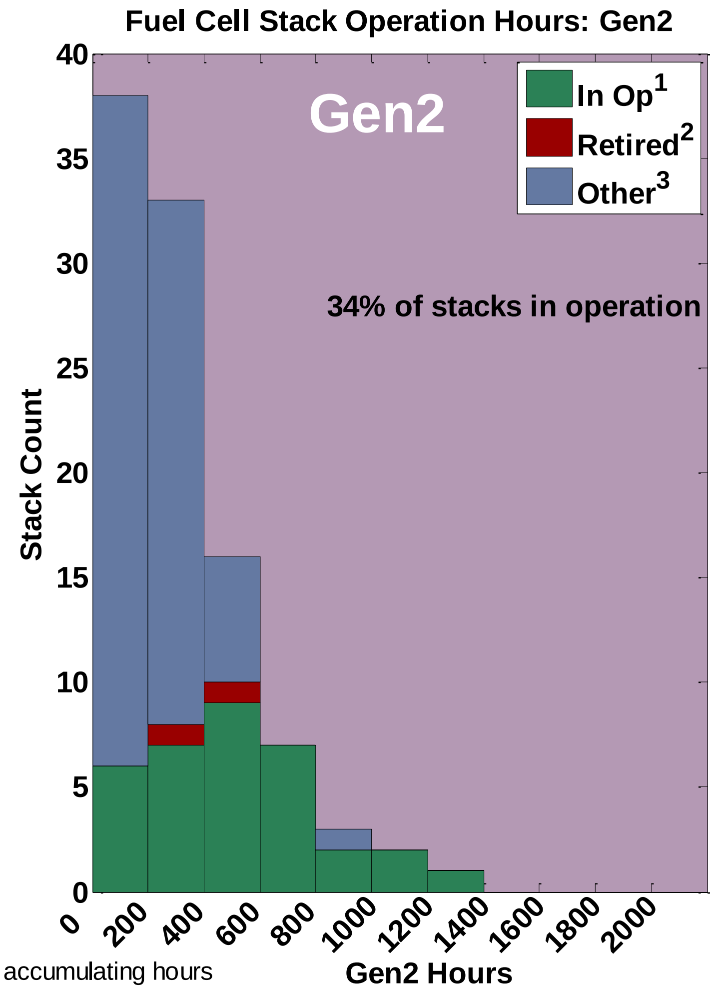


CDP#66: FCV Speed with Comparison to Standard Drive Cycles



CDP#67: Fuel Cell Stack Operation Hours

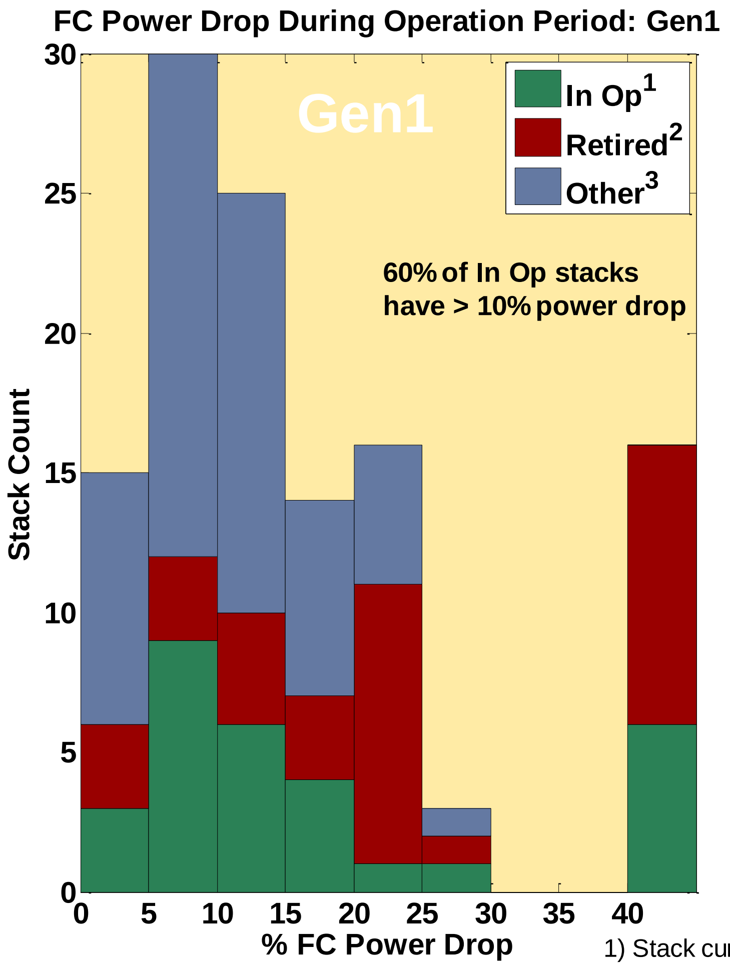


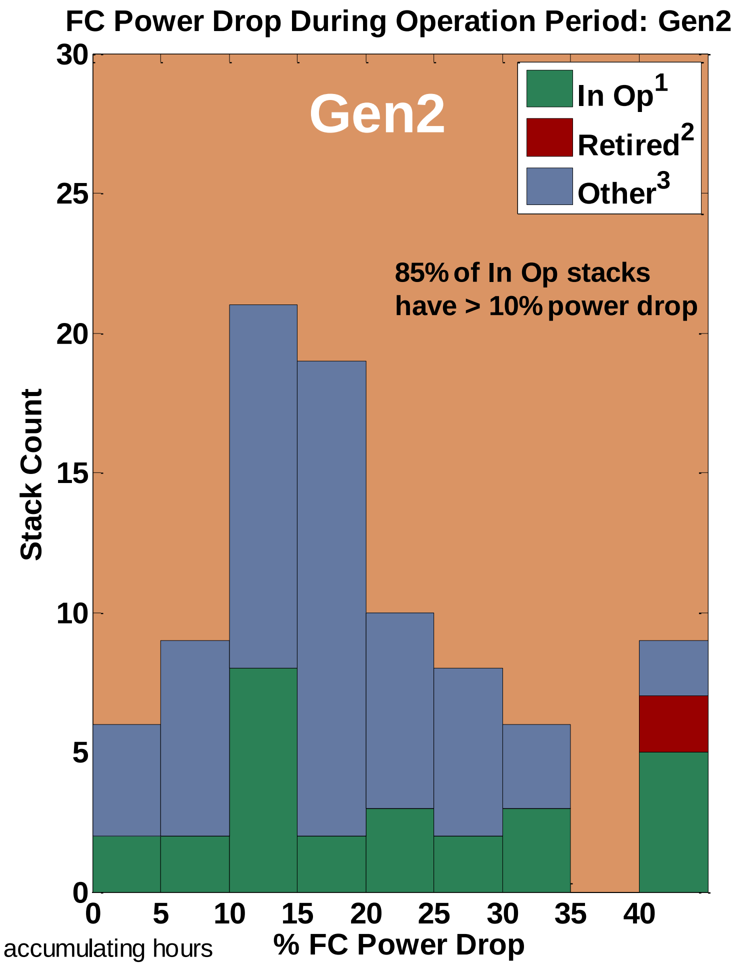


NREL CDP67
Created: Mar-23-10 10:39 AM

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

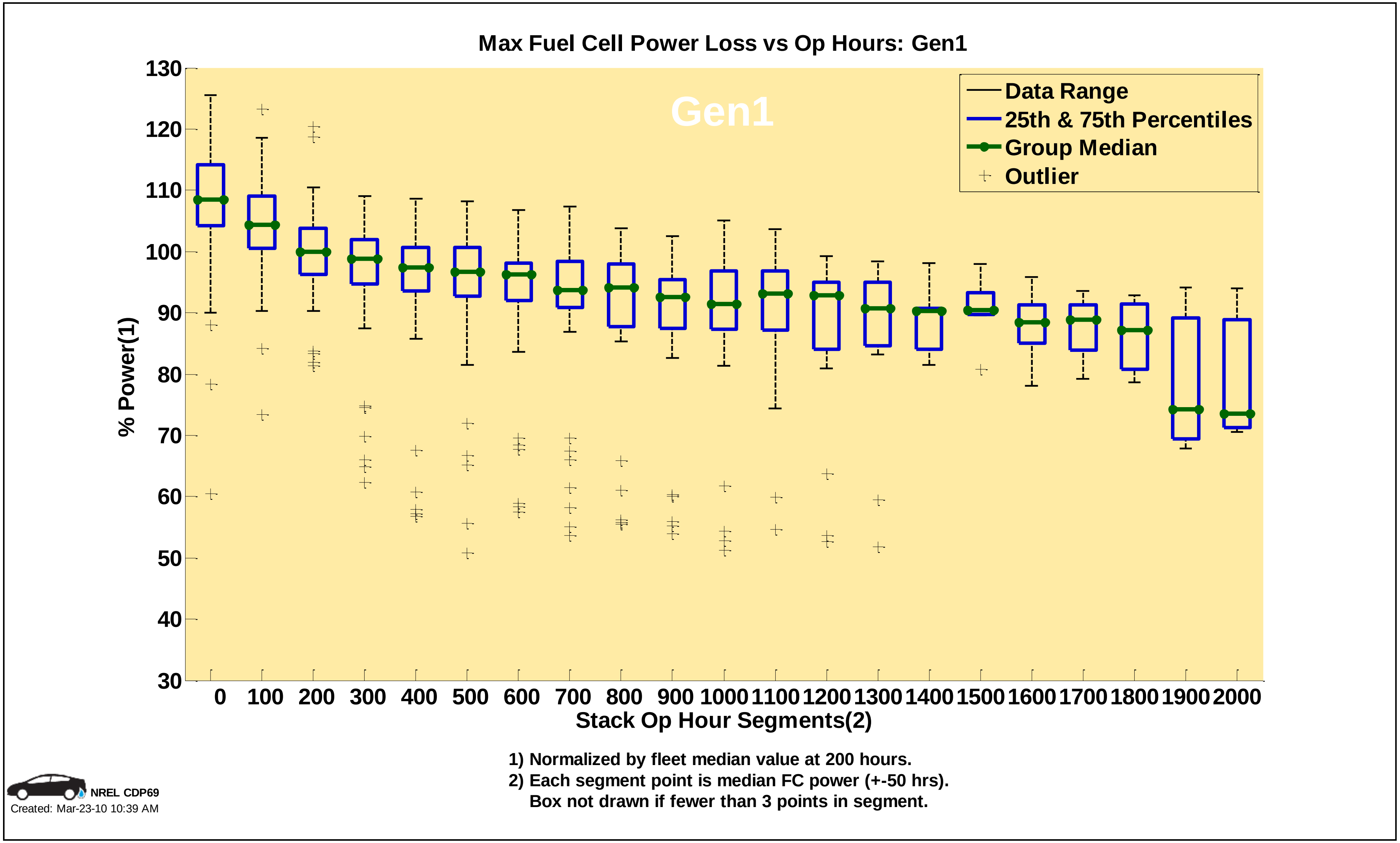




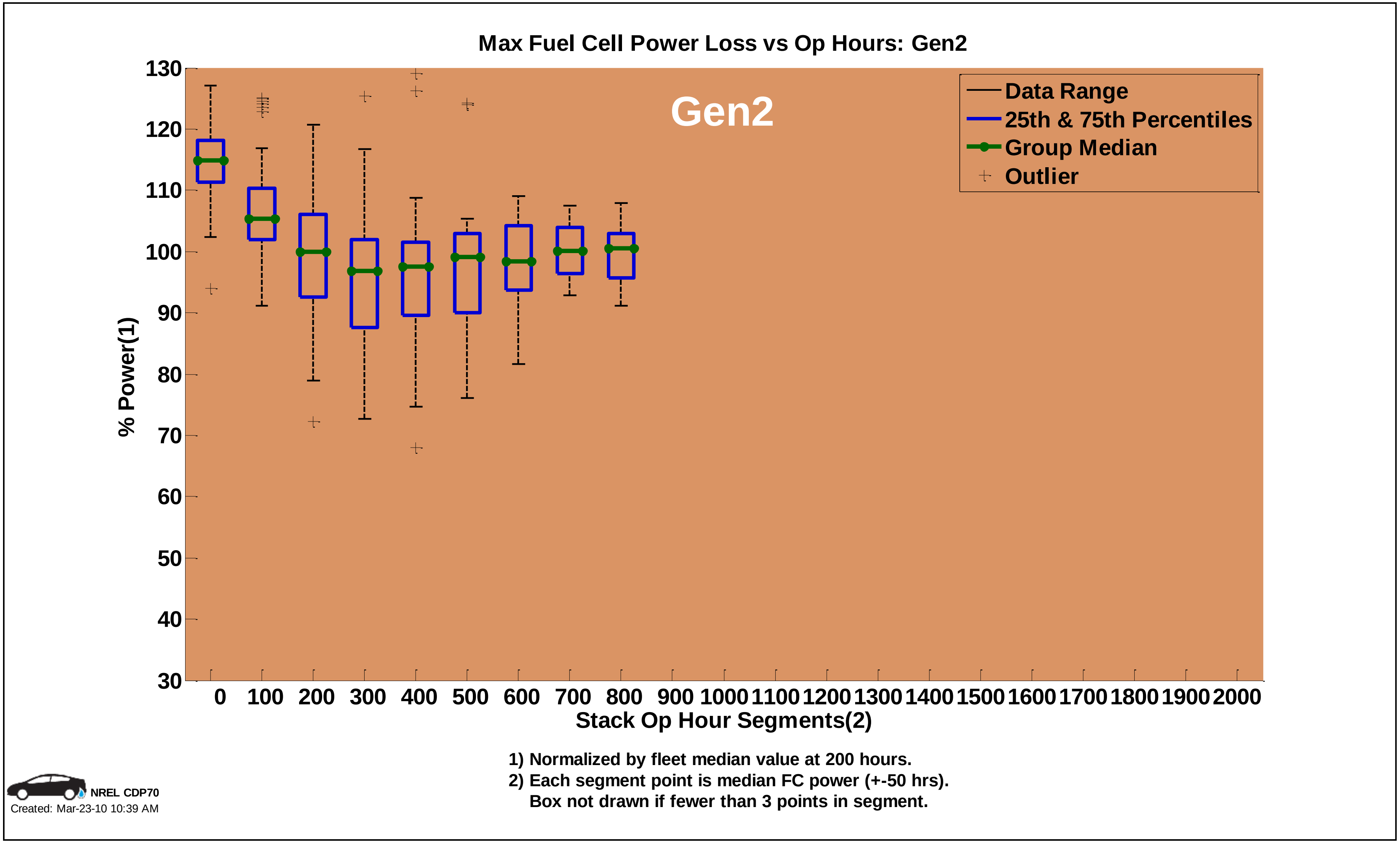
1) Stack currently accumulating hours
2) Stack removed for low performance
3) Stack not currently accumulating hours, but not removed because of low performance. Some project teams concluded in Fall/Winter 2009

NREL CDP68
Created: Mar-23-10 10:39 AM

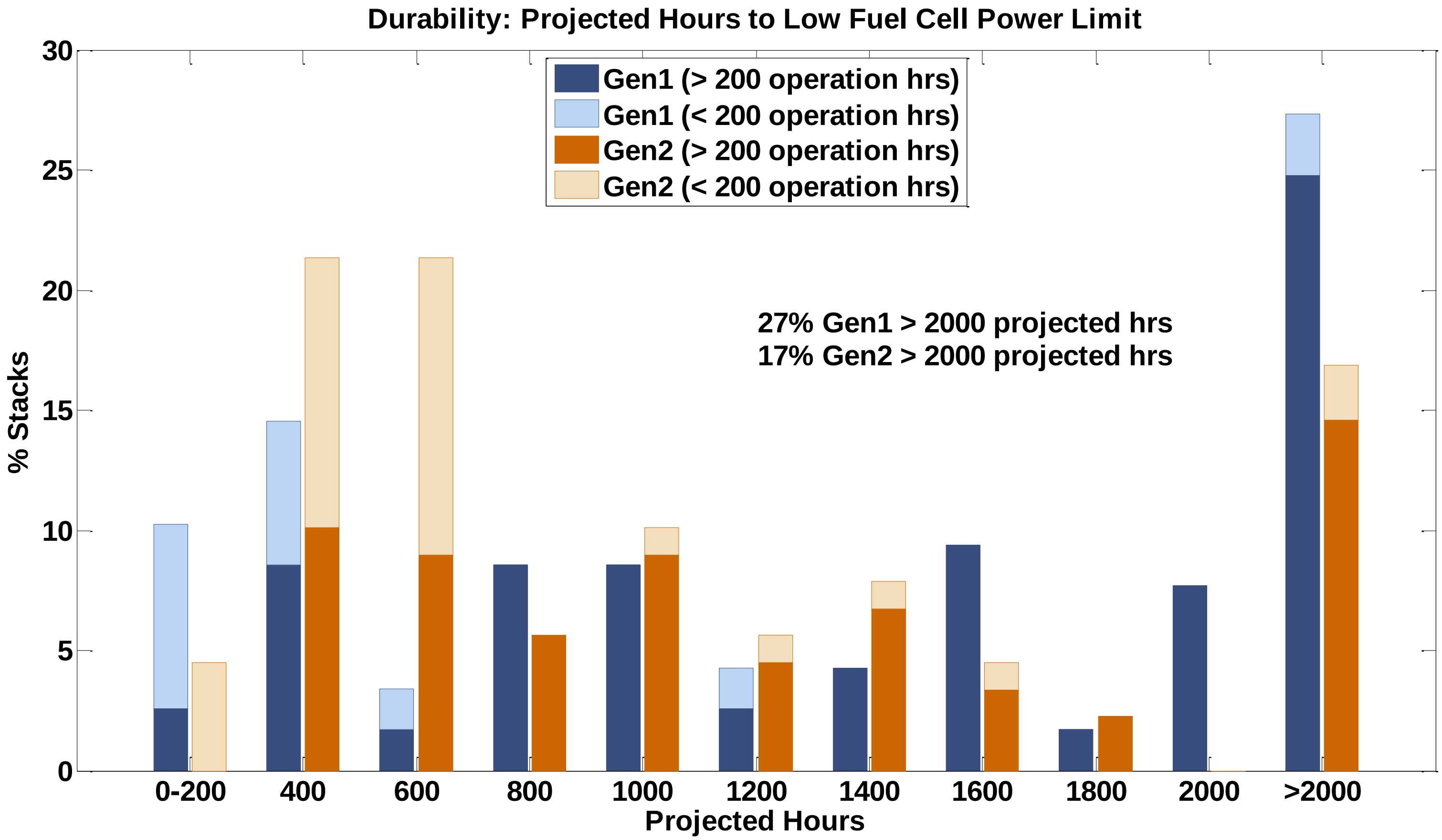
CDP#69: Max Fuel Cell Power Degradation – Gen 1



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



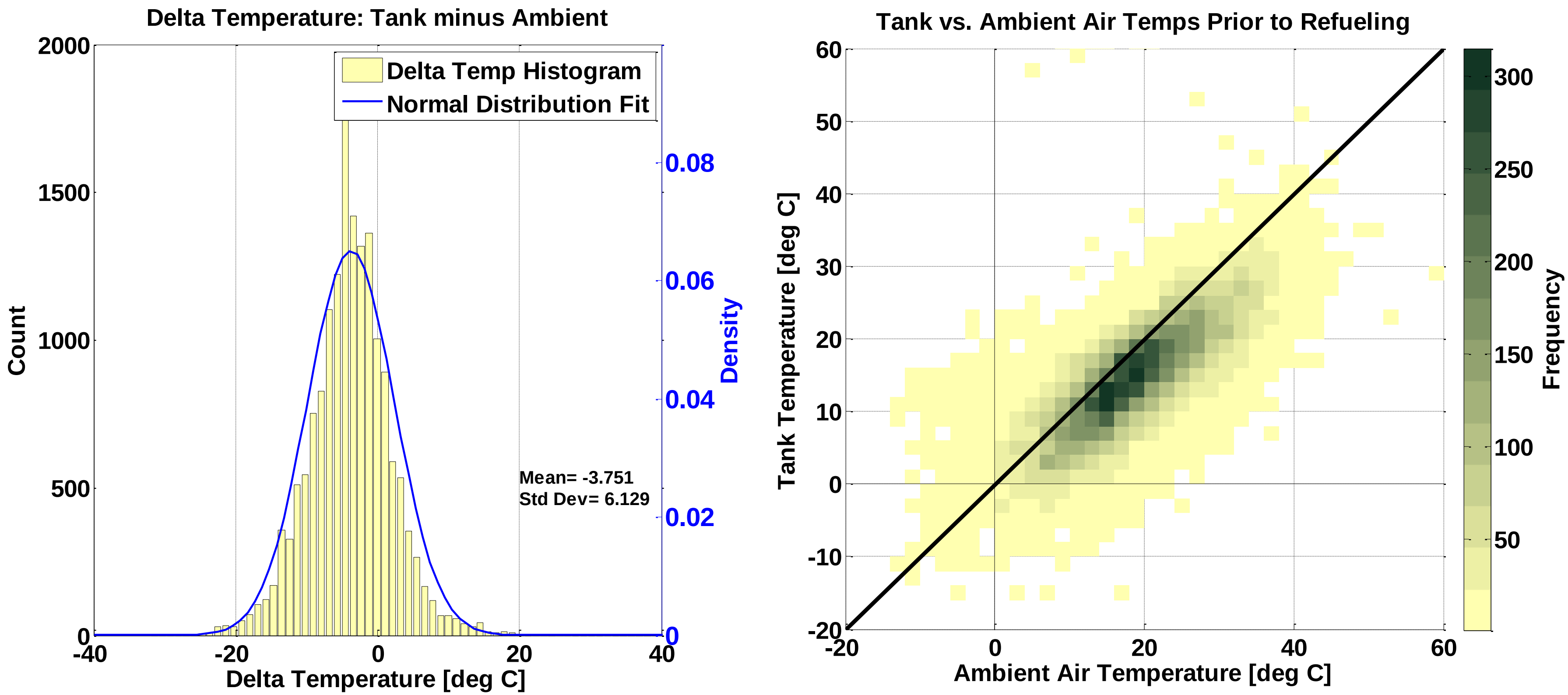
CDP#71: Projected Hours to OEM Low Power Operation Limit



1. Low fuel cell power limit is dependent on the fuel cell vehicle system and is unique to each company in this Learning Demonstration.
2. Acceptable low vehicle performance limit will be determined by retail customer expectations.
3. Power projection method based on the voltage degradation techniques, but uses max fuel cell power instead of voltage at a specific high current.
4. Stacks with less than 200 operation hours are in separate groups because the projection is based on operation data and with operation hours greater than 200 the degradation rate tends to flatten out.

NREL CDP71
Created: Mar-23-10 10:39 AM

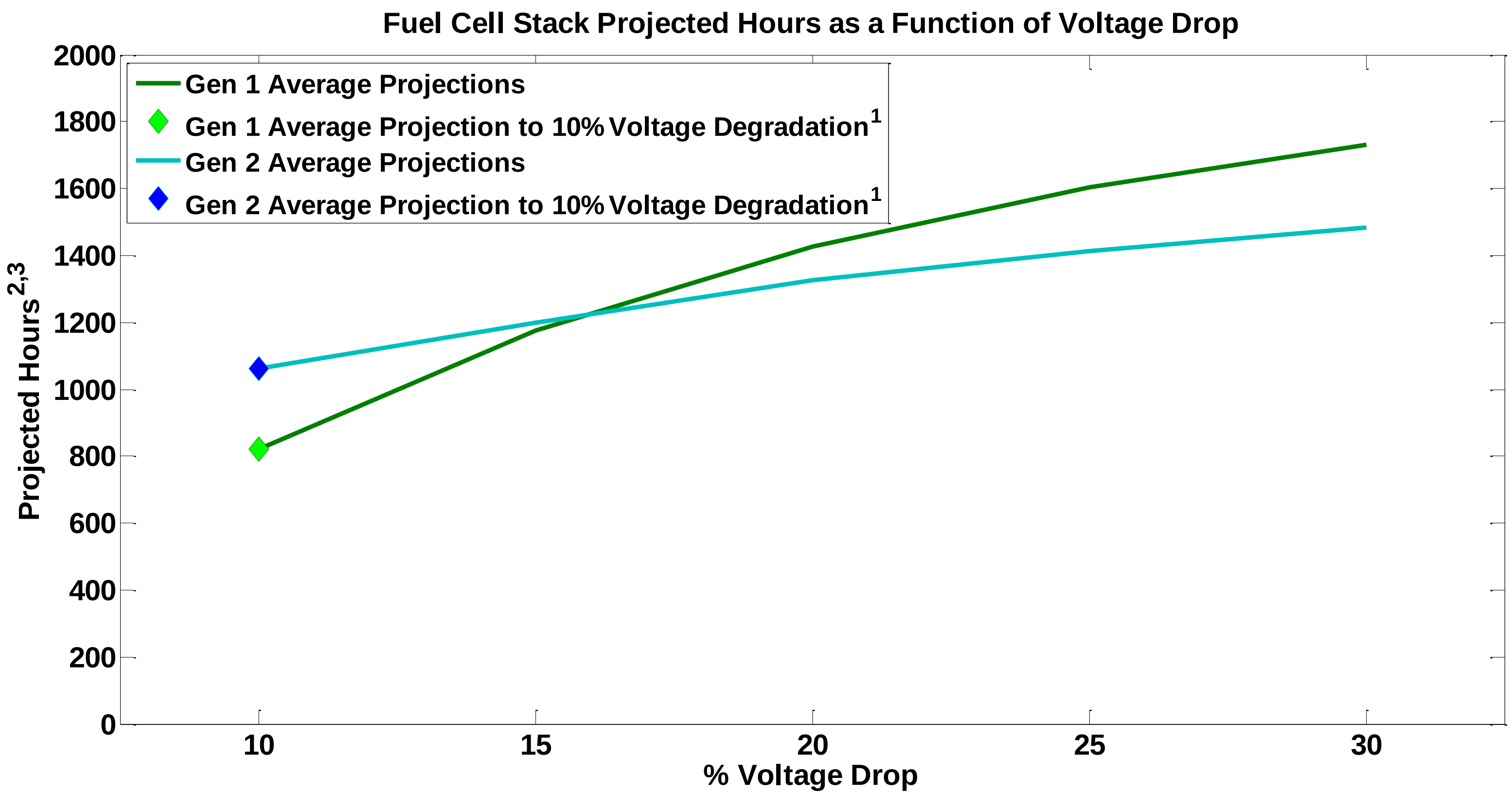
CDP#72: Difference Between Tank and Ambient Temperature Prior to Refueling



-This CDP created in support of SAE J2601 related to refueling
-Temperatures are prior to refueling and exclude data within 4 hours of a previous fill
-The plot to the left excludes ambient temperatures less than -5 deg C

NREL CDP72
Created: Mar-11-10 10:24 AM

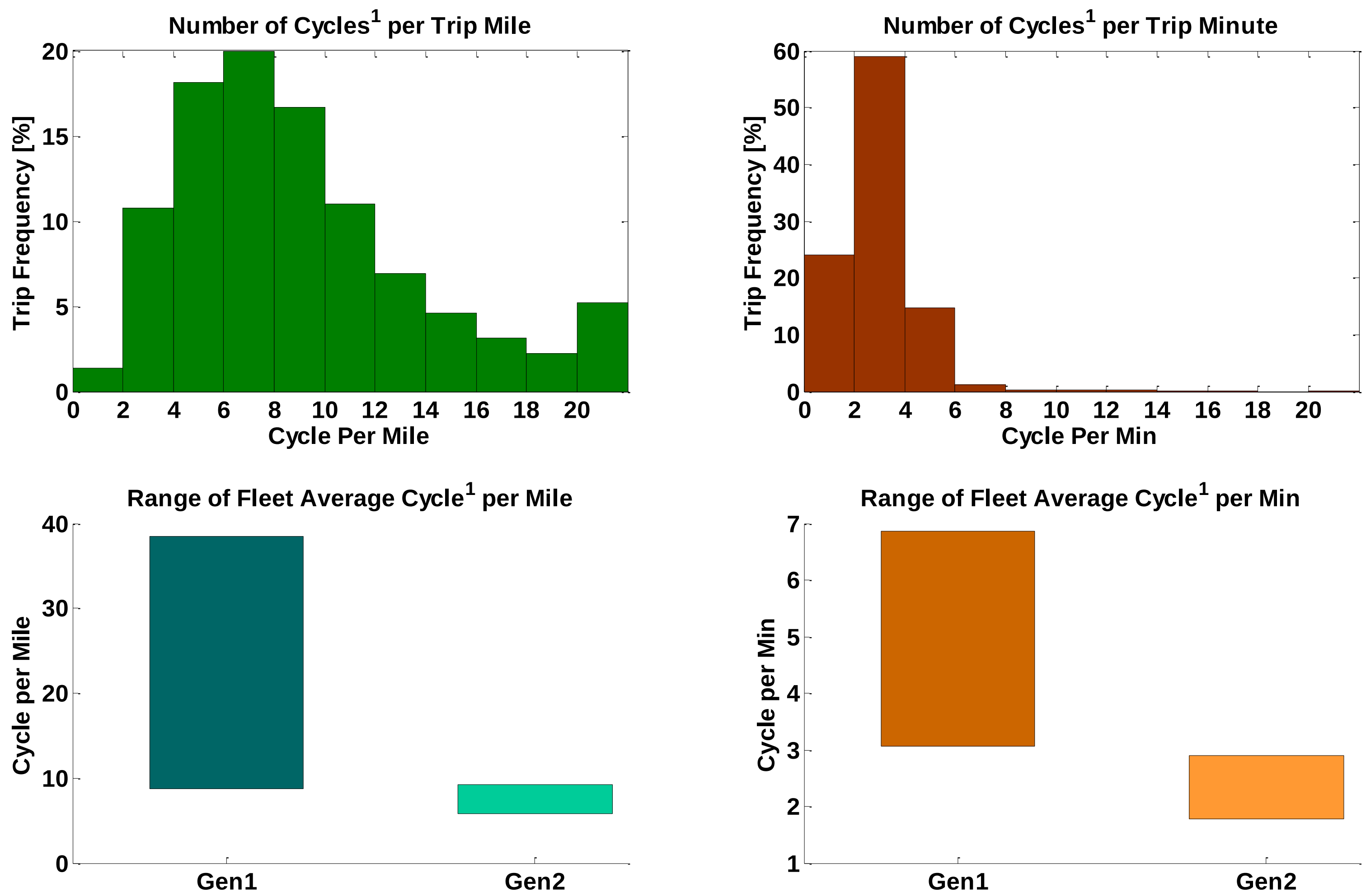
CDP#73: Fuel Cell Stack Projected Hours as a Function of Voltage Drop



(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.

NREL CDP73
Created: Mar-23-10 10:40 AM

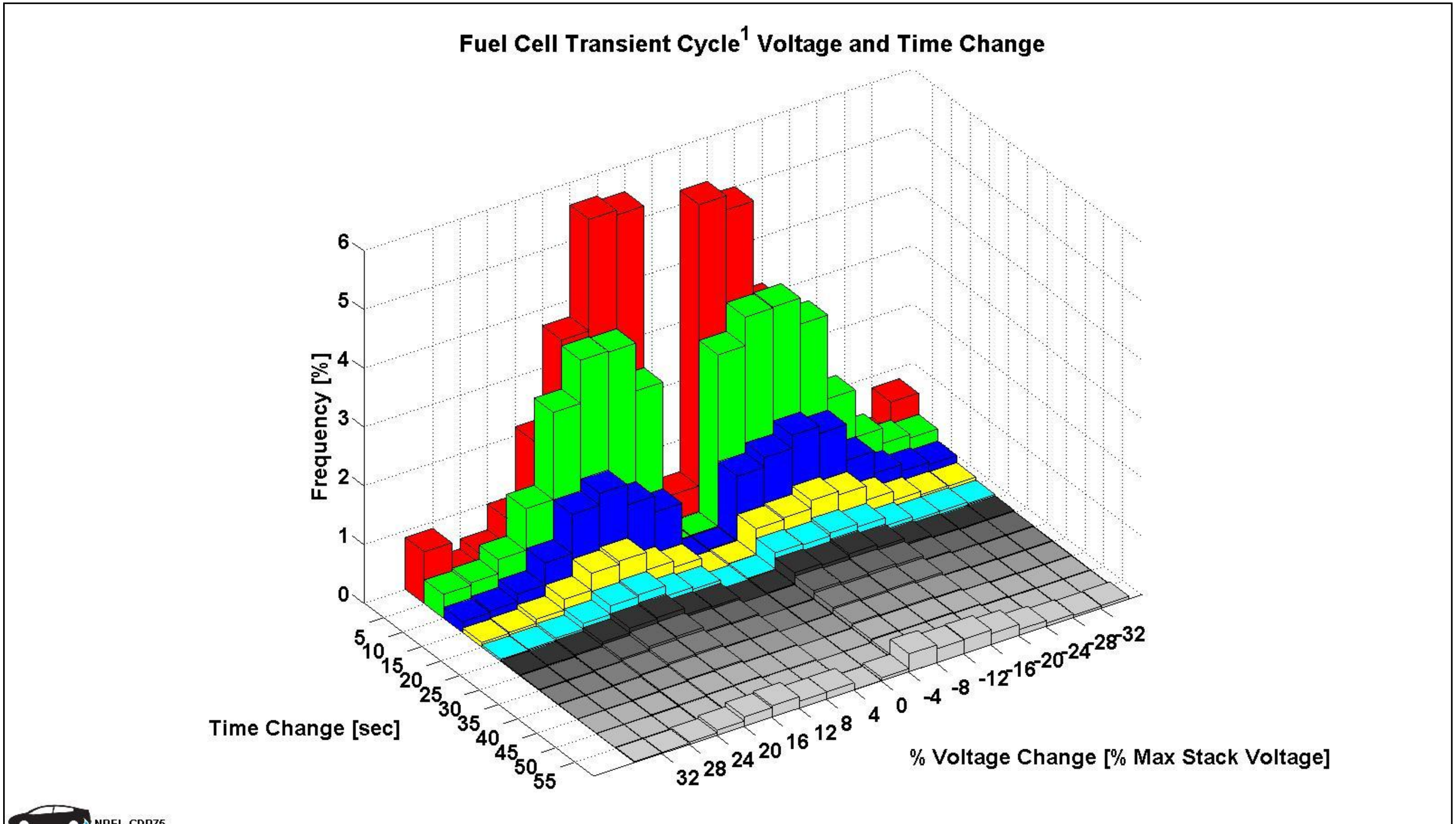
CDP#74: Fuel Cell Transient Cycle Count per Mile and per Minute



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

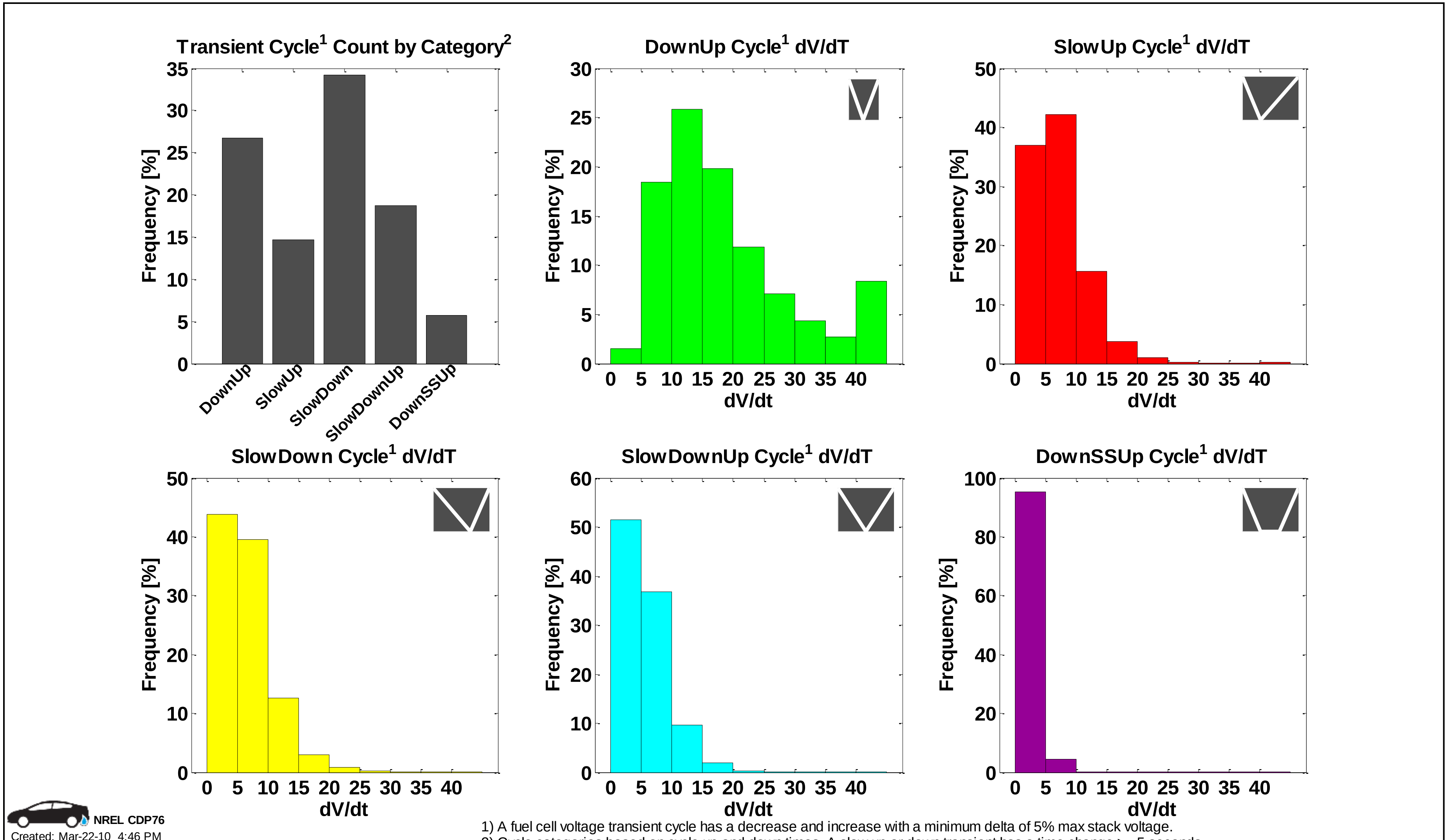
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

CDP#75: Fuel Cell Transient Voltage and Time Change



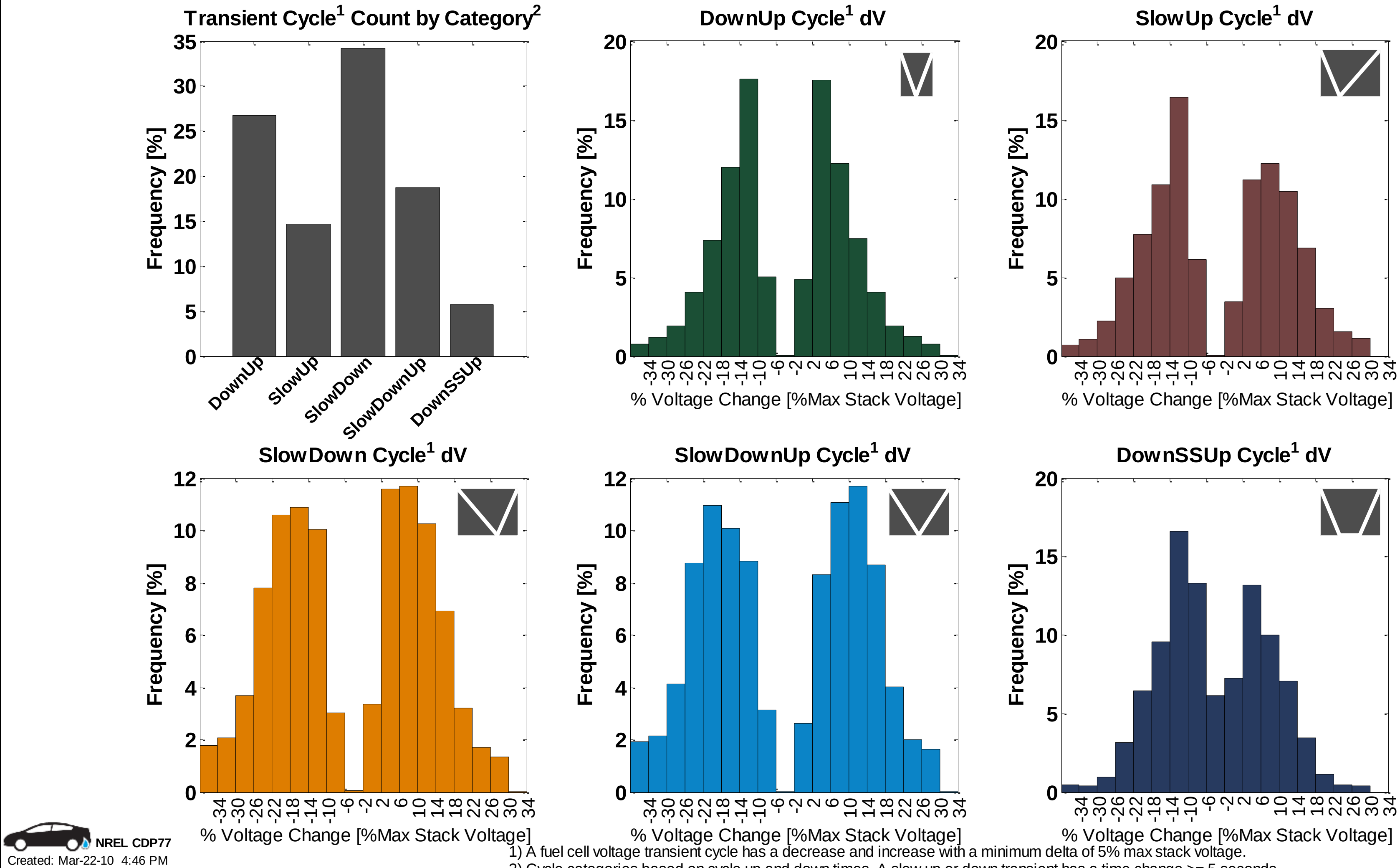
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.

CDP#76: Fuel Cell Transient Rate by Cycle Category



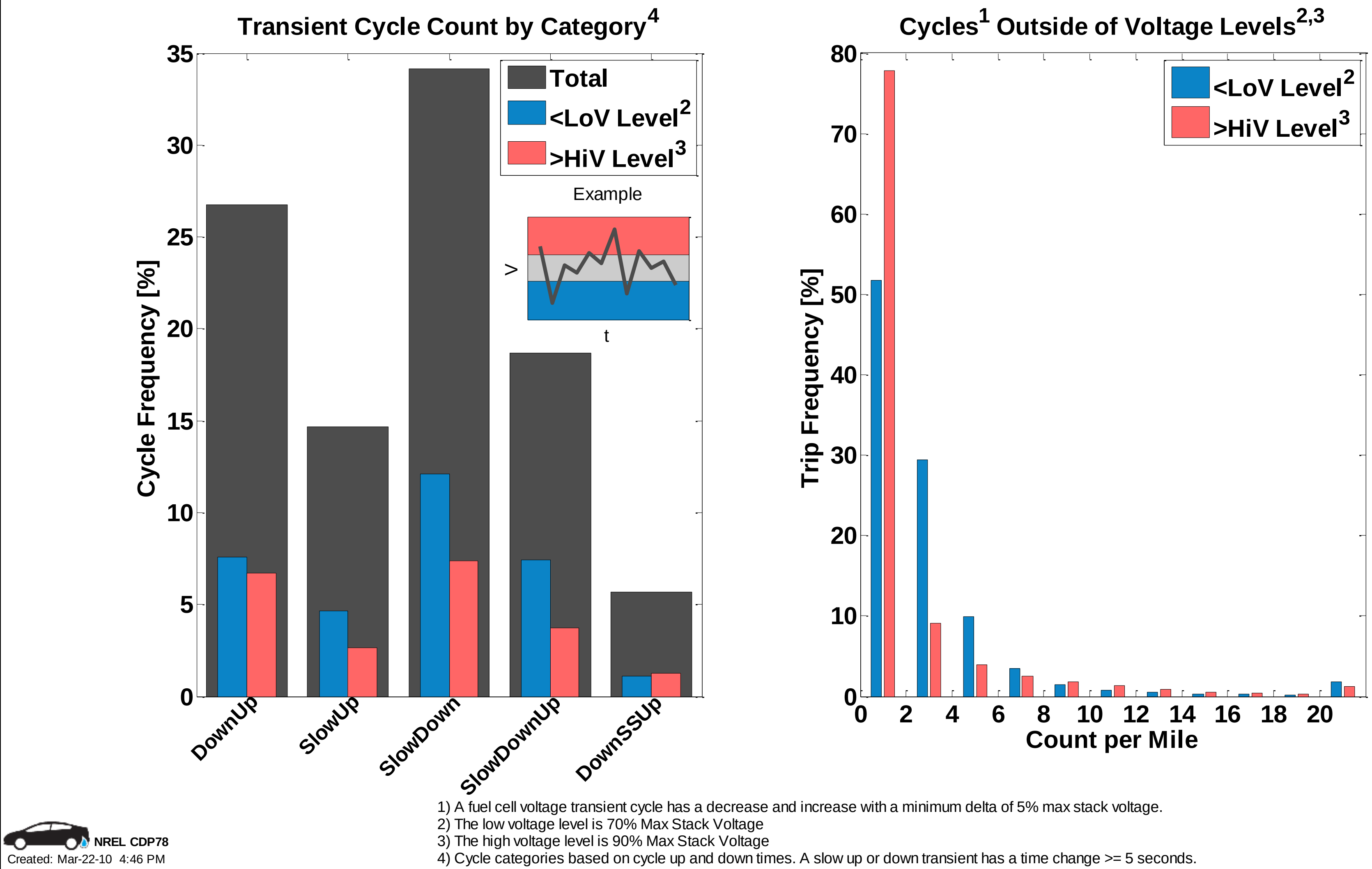
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change >= 5 seconds.
SS = Steady State, where the time change is >= 10 seconds and the voltage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

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



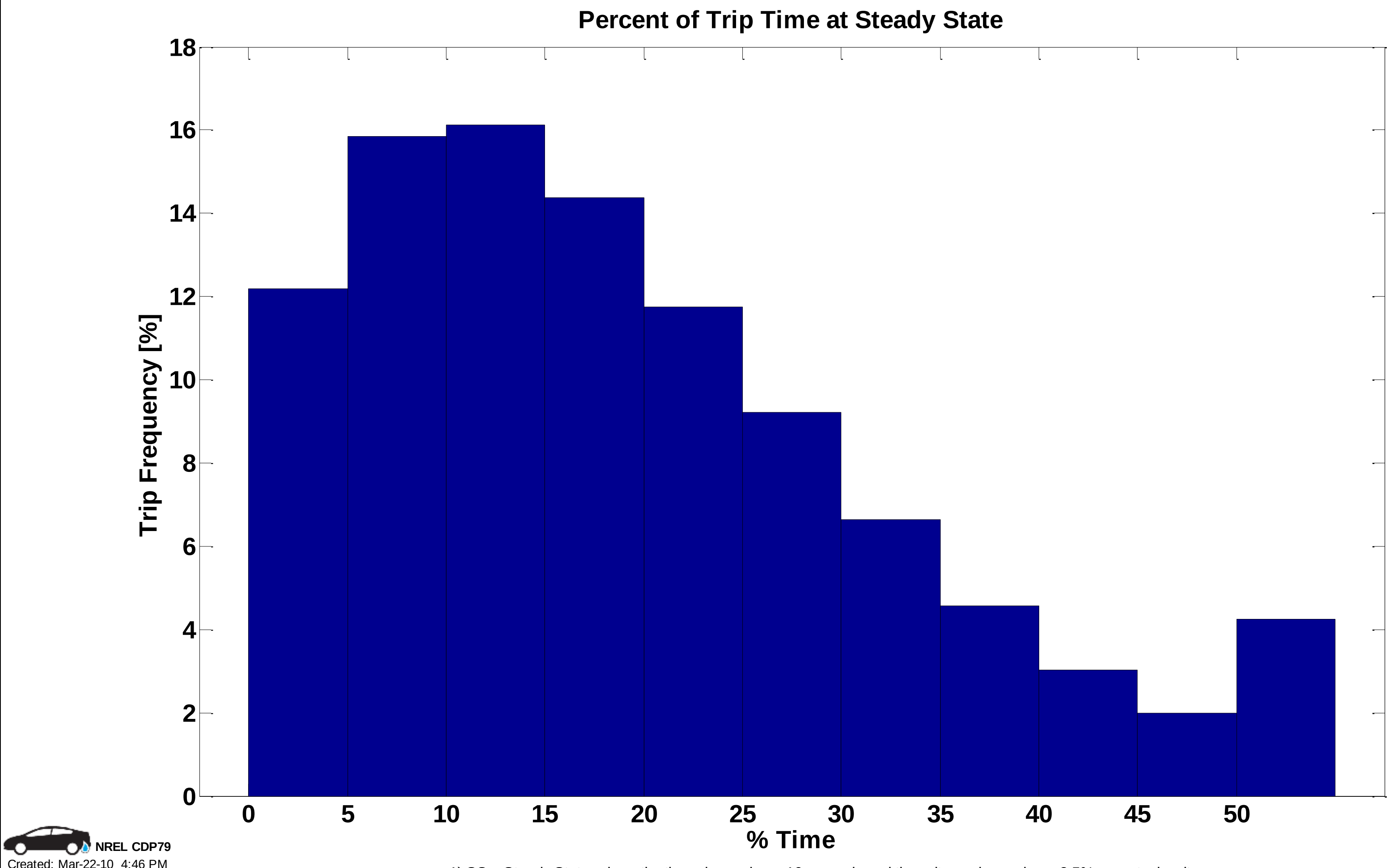
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) Cycle categories based on cycle up and down times. A slow up or down transient has a time change >= 5 seconds.
SS = Steady State, where the time change is >= 10 seconds and the voltage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

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



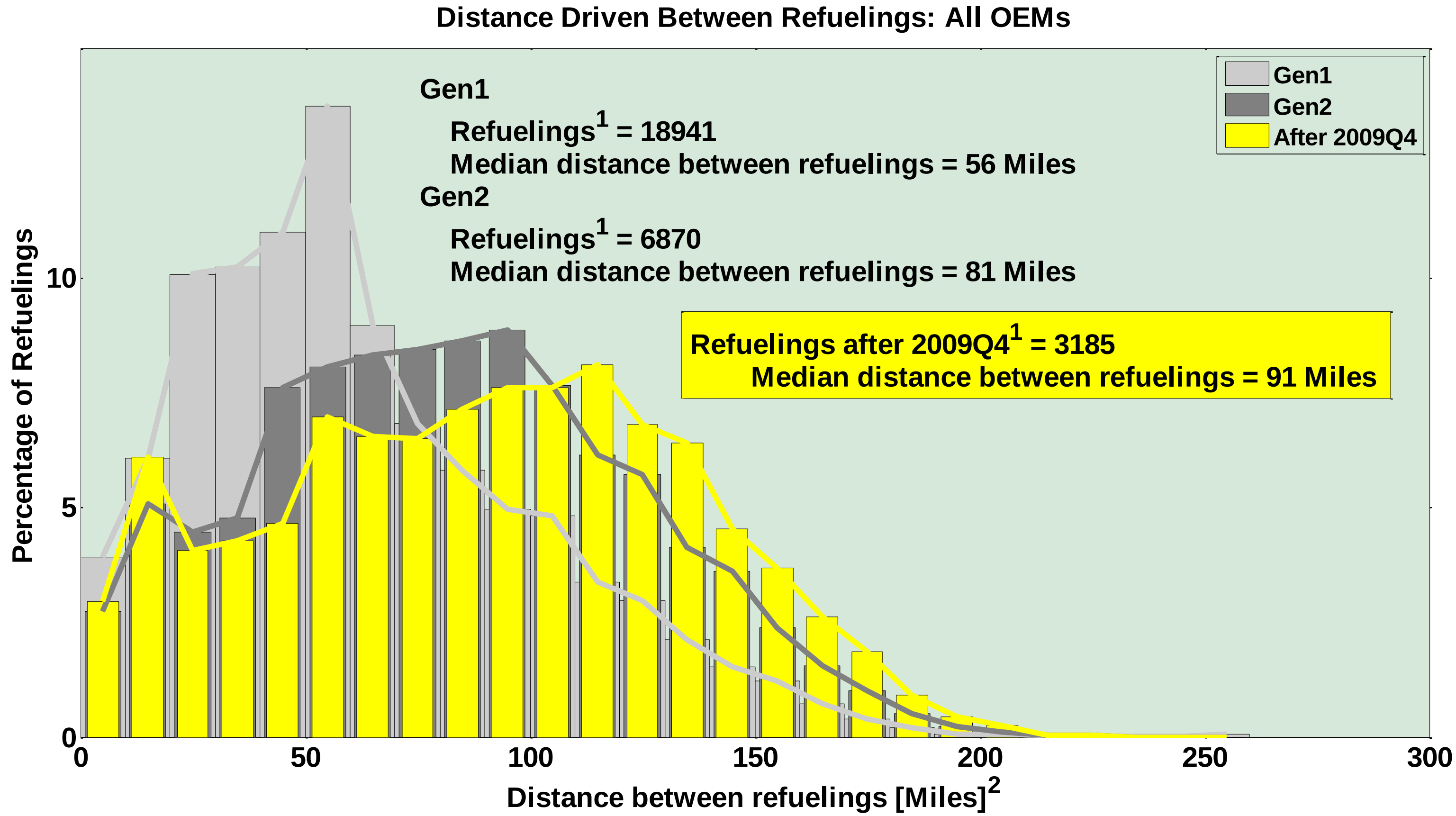
1) A fuel cell voltage transient cycle has a decrease and increase with a minimum delta of 5% max stack voltage.
2) The low voltage level is 70% Max Stack Voltage
3) The high voltage level is 90% Max Stack Voltage
4) Cycle categories based on cycle up and down times. A slow up or down transient has a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

CDP#79: Percentage of Trip Time at Steady State



1) SS = Steady State, where the time change is >= 10 seconds and the voltage change is <= 2.5% max stack voltage.

CDP#80: Miles Between Refuelings



1. Some refueling events are not detected/reported due to data noise or incompleteness.
2. Distance driven between refuelings is indicative of driver behavior and does not represent the full range of the vehicle.

NREL cdp_fcev_80
Created: Sep-07-10 9:16 AM