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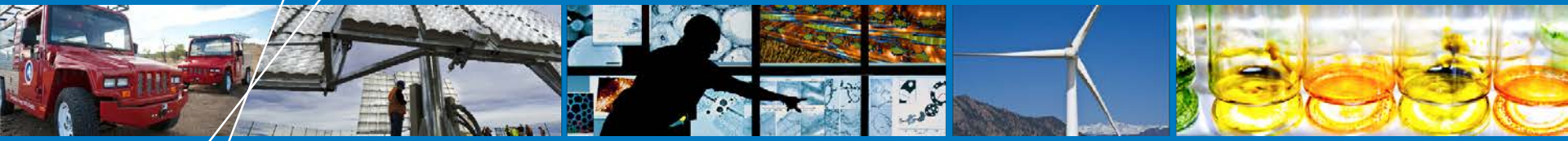
Fuel Cell Electric Vehicle Evaluation



Jennifer Kurtz (PI), Sam Sprik, Chris Ainscough, Genevieve Saur
National Renewable Energy Laboratory
June 10, 2015
DOE 2015 Annual Merit Review
Washington, DC

Project ID TV001

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline and Budget

- **Project start date: 10/2012***
- **Total DOE funds received to date: $1,265k**
- **FY14 DOE funding: $415k**
- **FY15 planned DOE funding: $365k**

Barriers

- Lack of current controlled and on-road hydrogen fuel cell vehicle data

Partners

- **Project partners supplying data include:**
  - **Daimler**
  - **GM**
  - **Honda**
  - **Hyundai**
  - **Nissan**
  - **Toyota**

*Project continuation determined annually by DOE

Project Objectives, Relevance, and Targets: Fuel Cell Electric Vehicle Evaluation

FY15 Objectives
Analysis and reporting on FCEV durability, fuel economy, range, vehicle specifications, and driving.

APC/Shell Pipeline station, Torrance, CA. Photo: NREL

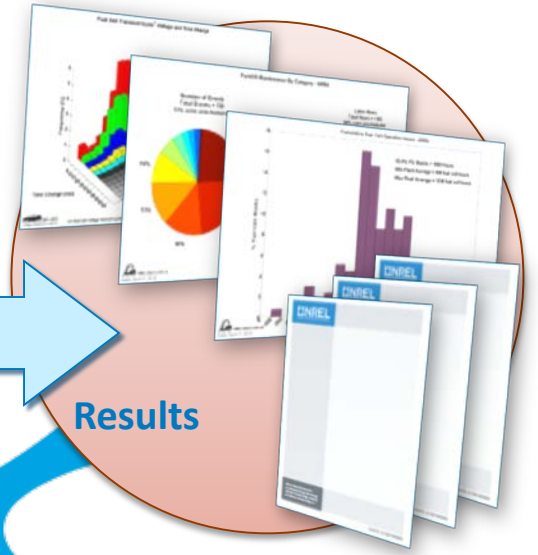
- **Objectives**
  - Validate hydrogen fuel cell electric vehicles (FCEV) in real-world setting
  - Identify current status and evolution of the technology
- **Relevance**
  - Objectively assess progress toward targets and market needs
  - Provide feedback to hydrogen research and development
  - Publish results for key stakeholder use and investment decisions

Approach: NFCTEC Analysis and Reporting of Real-World Operation Data

Bundled data (operation and maintenance/safety) delivered to NREL quarterly

Internal analysis completed quarterly in NFCTEC

National Fuel Cell Technology Evaluation Center



Results

DDPs

Confidential

Public

CDPs

Detailed Data Products (DDPs)

- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data

Composite Data Products (CDPs)

- Aggregated data across multiple systems, sites, and teams
- Publish analysis results every six months without revealing proprietary data

www.nrel.gov/hydrogen/proj_tech_validation.html

Approach: FCEVs

Six Data Providers[1]

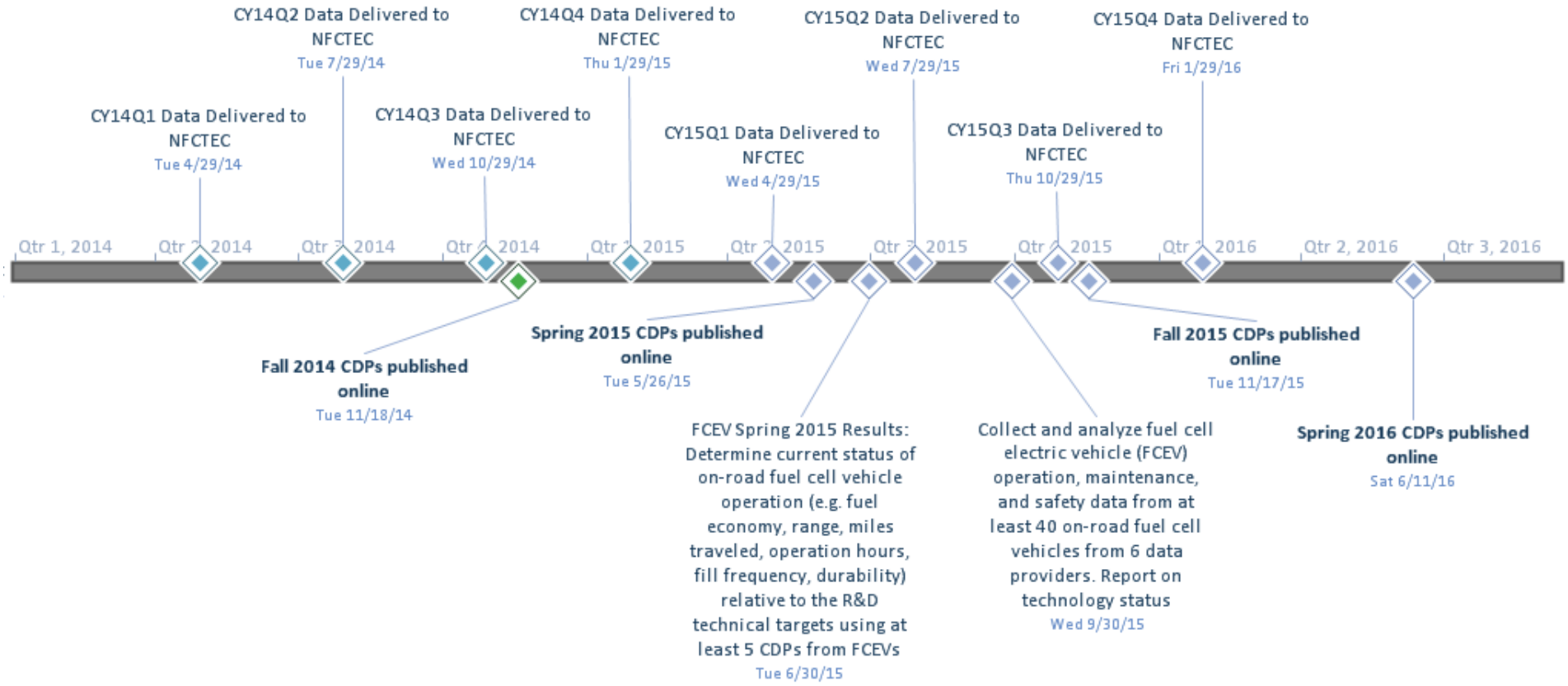
Range of FCEV Model Years

[1]DOE project overview:

- $5.5 million DOE funding
- Data to be collected from up to ~90 vehicles

[2]Project managed by Electricore

Approach: Milestones



Regular project activities include:

Quarterly analysis

Bi-annual technical CDPs

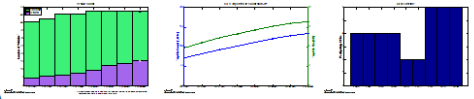
Detailed data and analysis reviews with project partners

Publishing and presenting results

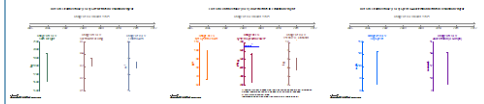
Collaborating with infrastructure evaluation

Accomplishment: 32 FCEV CDPs—Count and Category

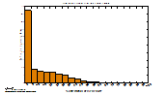
Deployment
(# 01, 10, 33)



Specifications
(#11, 12, 13)

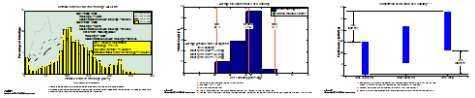


Fuel Cell Operation
(# 24)

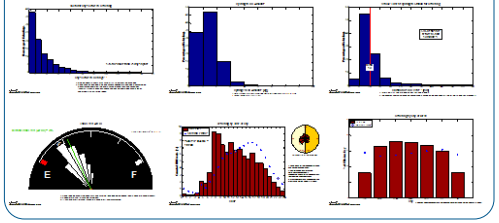


Data included through 12/2014

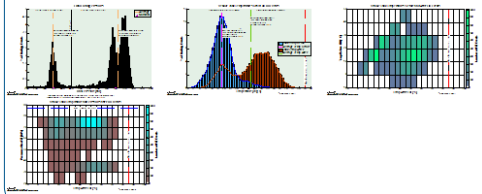
Fuel Economy & Range
(# 7, 14, 32)



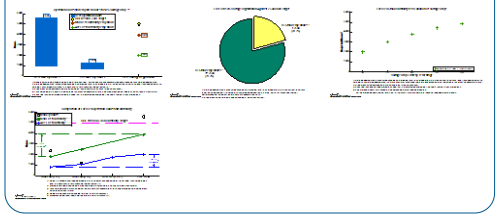
Fueling
(# 6, 8, 9, 16, 16, 17)



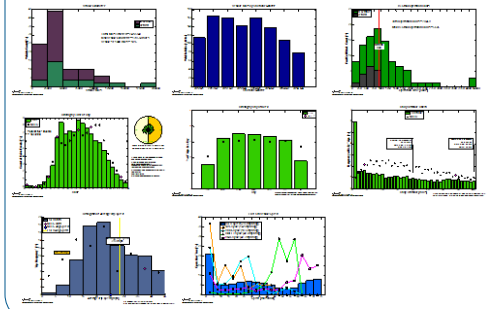
H2 Performance
(# 25, 28, 29, 30)



Fuel Cell Durability
(# 21, 22, 23, 31)



Driving
(# 2, 3, 4, 18, 19, 20, 26, 27)



Results are not all presented here but are available online at www.nrel.gov/hydrogen/proj_tech_validation.html

Accomplishment: FCEV Deployment and Operation Summary through 2014CYQ4

48
FCEVs

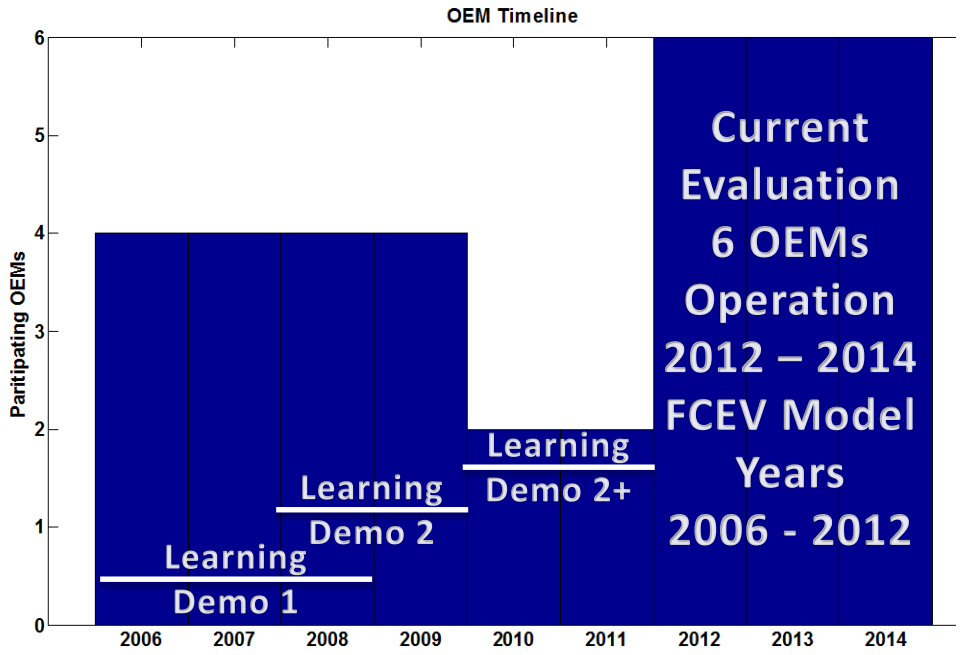
51
Average on-road fuel economy miles/kg

3,930
Average fleet voltage durability (Hours to 10% degradation metric)

20
FCEVs retired

> 2,400,000
miles traveled

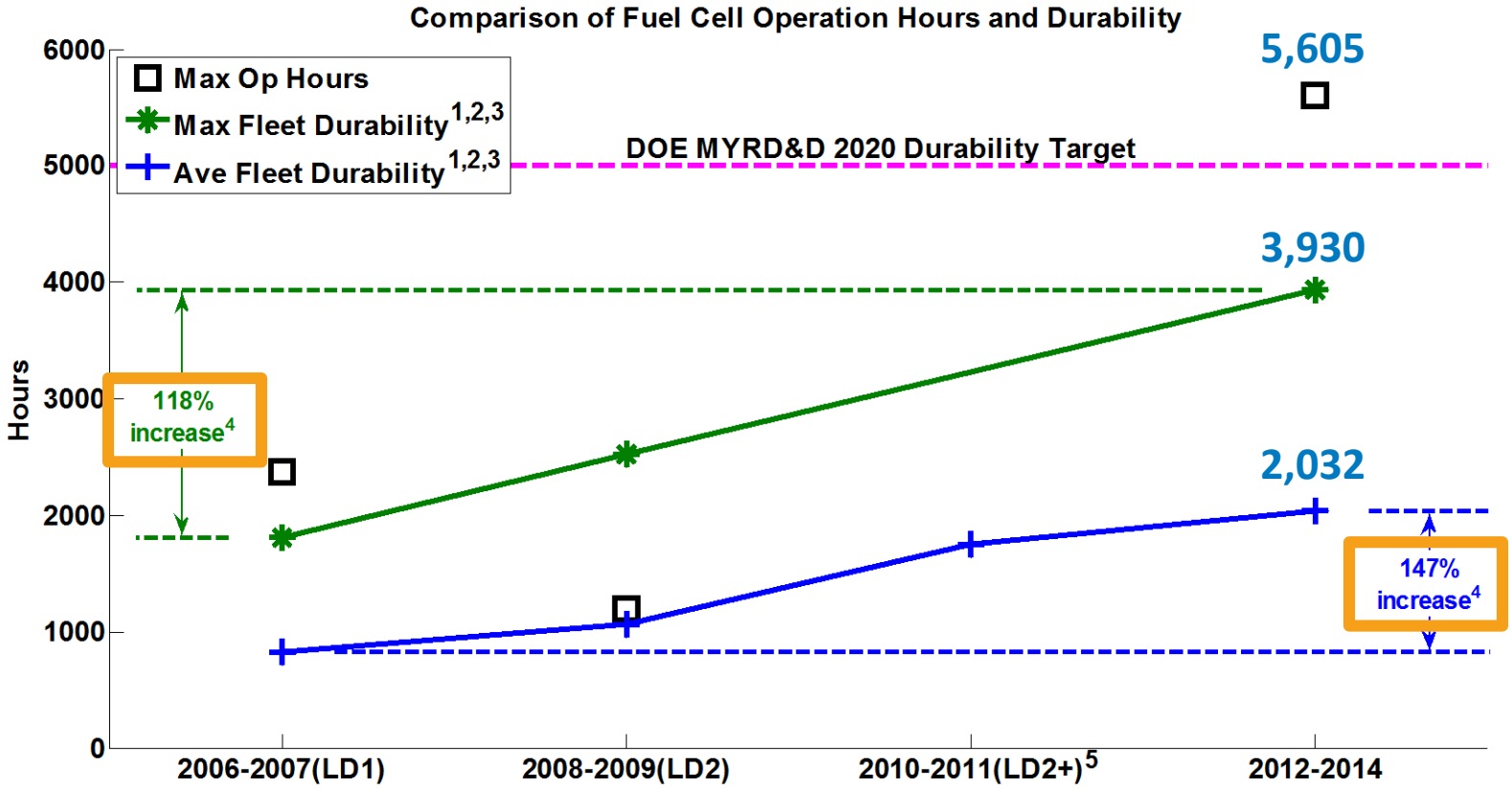
> 178,000
Max FCEV odometer miles



> 79,000
Fuel cell operation hours

5,600
Max fuel cell operation hours

Accomplishment: FCEV Durability Trend

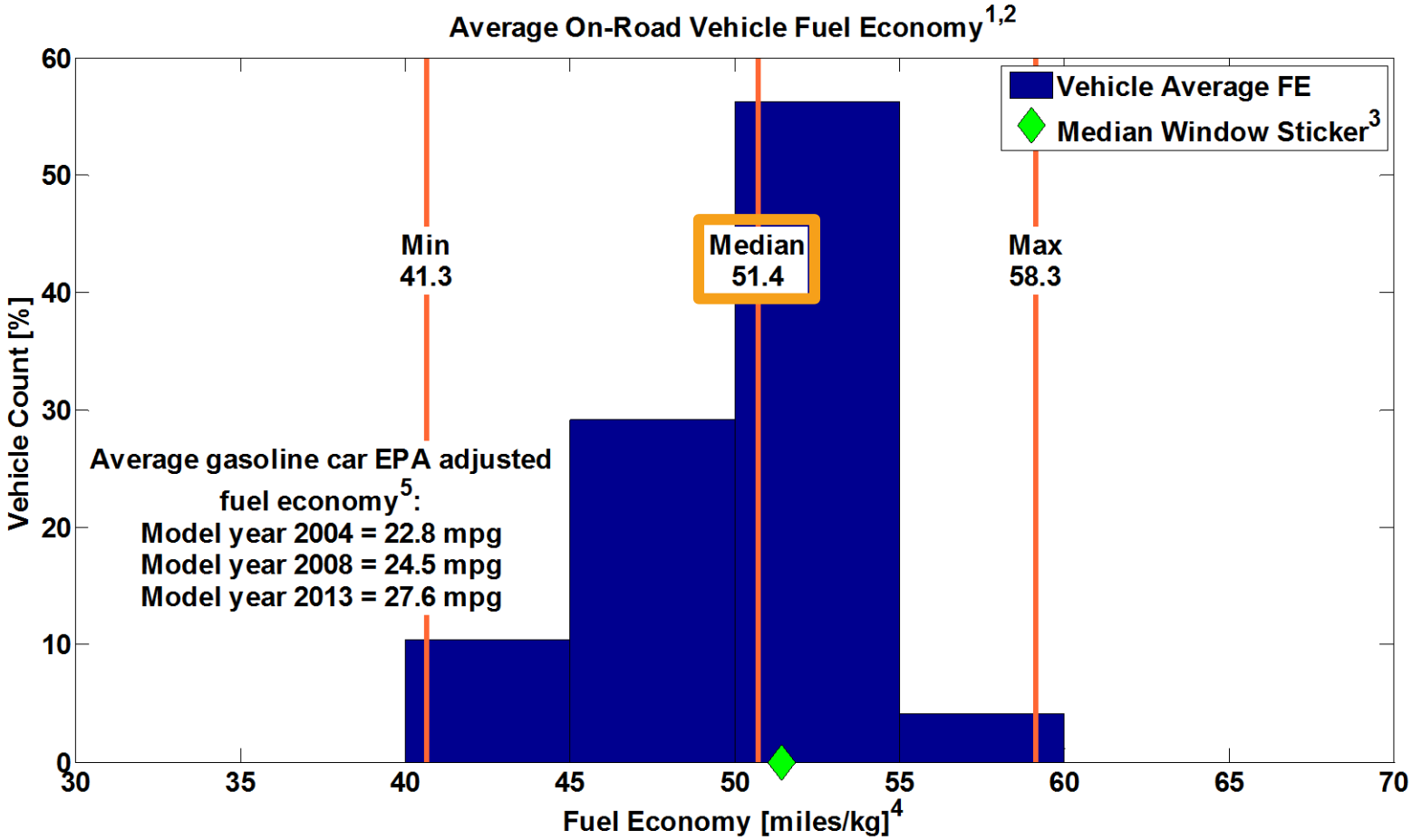


1) Durability based on voltage degradation to 10% lower than beginning of life voltage. 10% voltage drop level is a DOE metric for assessing fuel cell durability.
2) Projections using on-road data are calculated at approximately 55 - 65% rated stack current.
3) 10% voltage drop is NOT an indication of an OEM's end-of-life criteria and projections do not address catastrophic stack failure.
4) Percent increases are calculated relative to LD1 (2006-2007).
5) Maximum operational hours not reported in LD2+ (2010-2011).

NREL cdp_fcev_31
Created: Apr-30-15 4:16 PM | Data Through: 2014Q4

FCEV voltage durability has continually improved over time.

Accomplishment: On-Road Fuel Economy

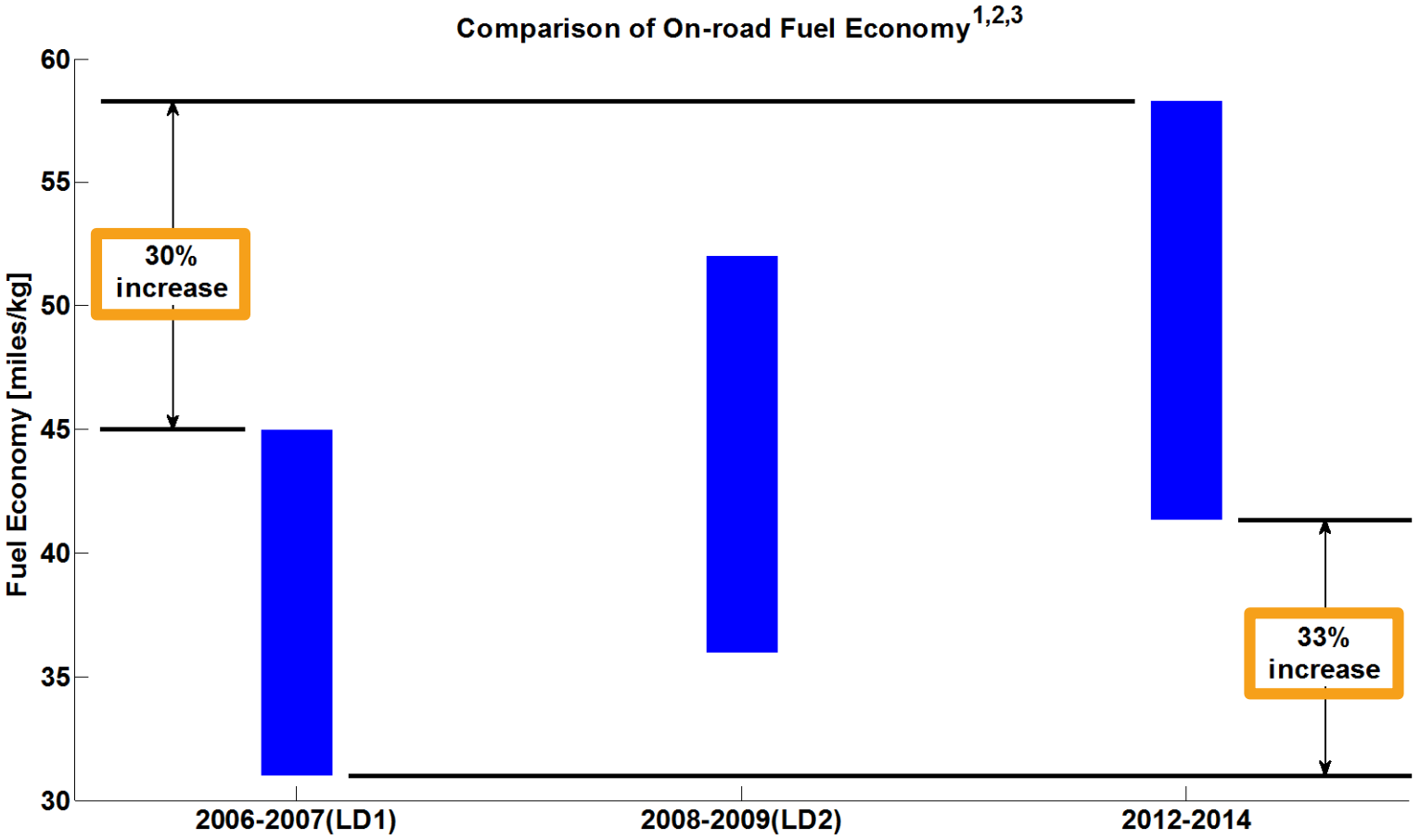


1) Calculated from on-road fuel cell stack current.
2) Excludes trips < 1 mile.
3) EPA Combined Rating.
4) 1 kg of hydrogen has the same energy content as 1 gallon (3.2 kg) of gasoline.
5) Source: EPA Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Eocnomy Trends: 1975 - 2014.

NREL cdp_fcev_14
Created: Apr-30-15 11:47 AM | Data Through: 2014Q4

The median on-road vehicle fuel economy is ~51 miles per kg, nearly twice the 2013 EPA adjusted fuel economy for gasoline.

Accomplishment: On-Road Fuel Economy Trends



1) Range bars in the learning demo (LD) represented one data point for OEM's fleet mean. 2012-2014 analysis represents the spread of all vehicles.
2) Percent increases are calculated relative to LD1 (2006-2007).
3) Refer to NREL cdp_fcev_14 for more detailed information on current analysis.

NREL cdp_fcev_32
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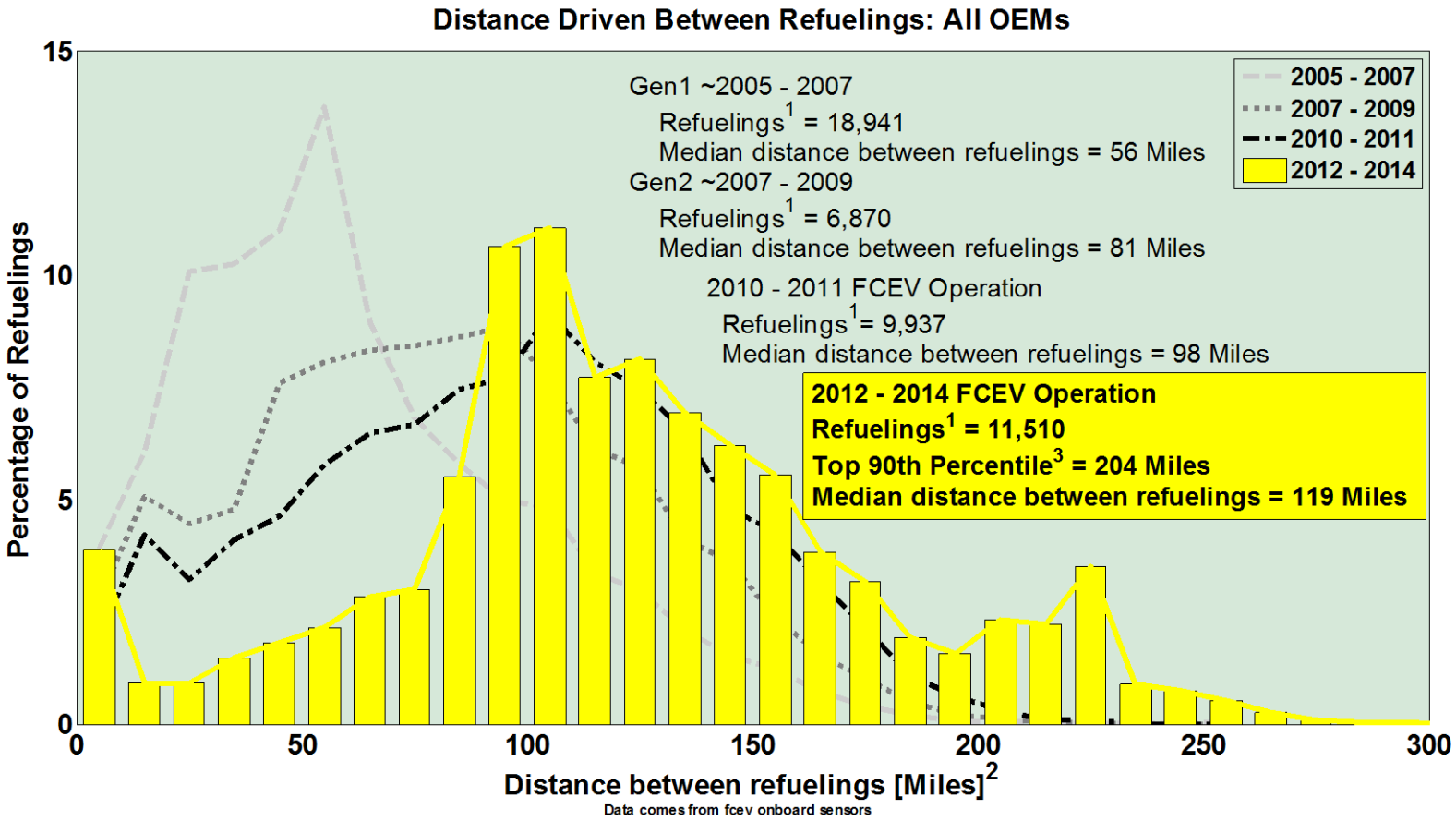
The on-road fuel economy has consistently increased over the last 10 years.

Accomplishment: Driving Distance 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.
3. Events with over 400 miles between refueling are filtered out.

NREL cdp_fcev_07
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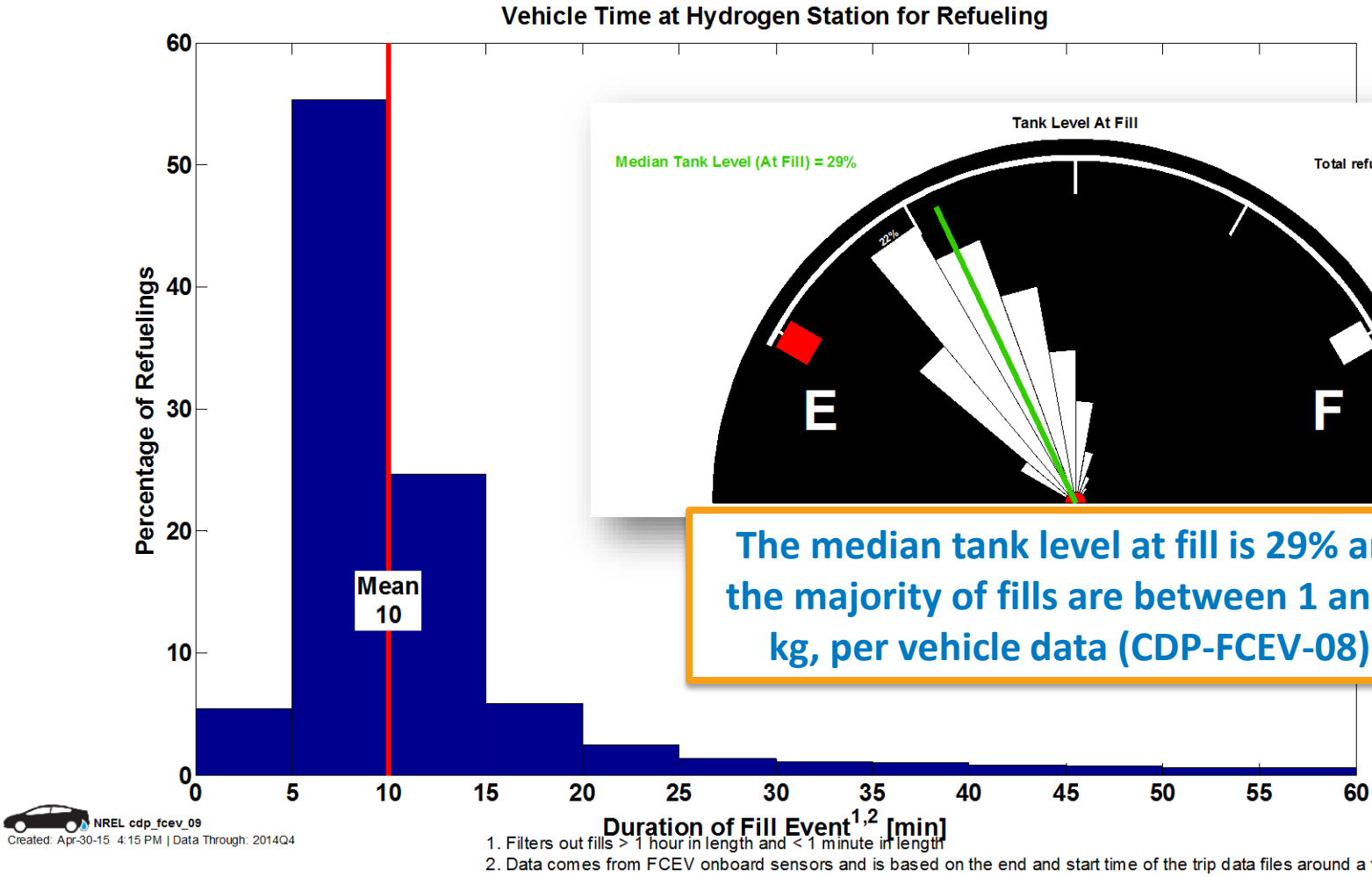
The median distance between refuelings is 119 miles. Distance is based on actual driving and not the full vehicle range.

Accomplishment: Fueling

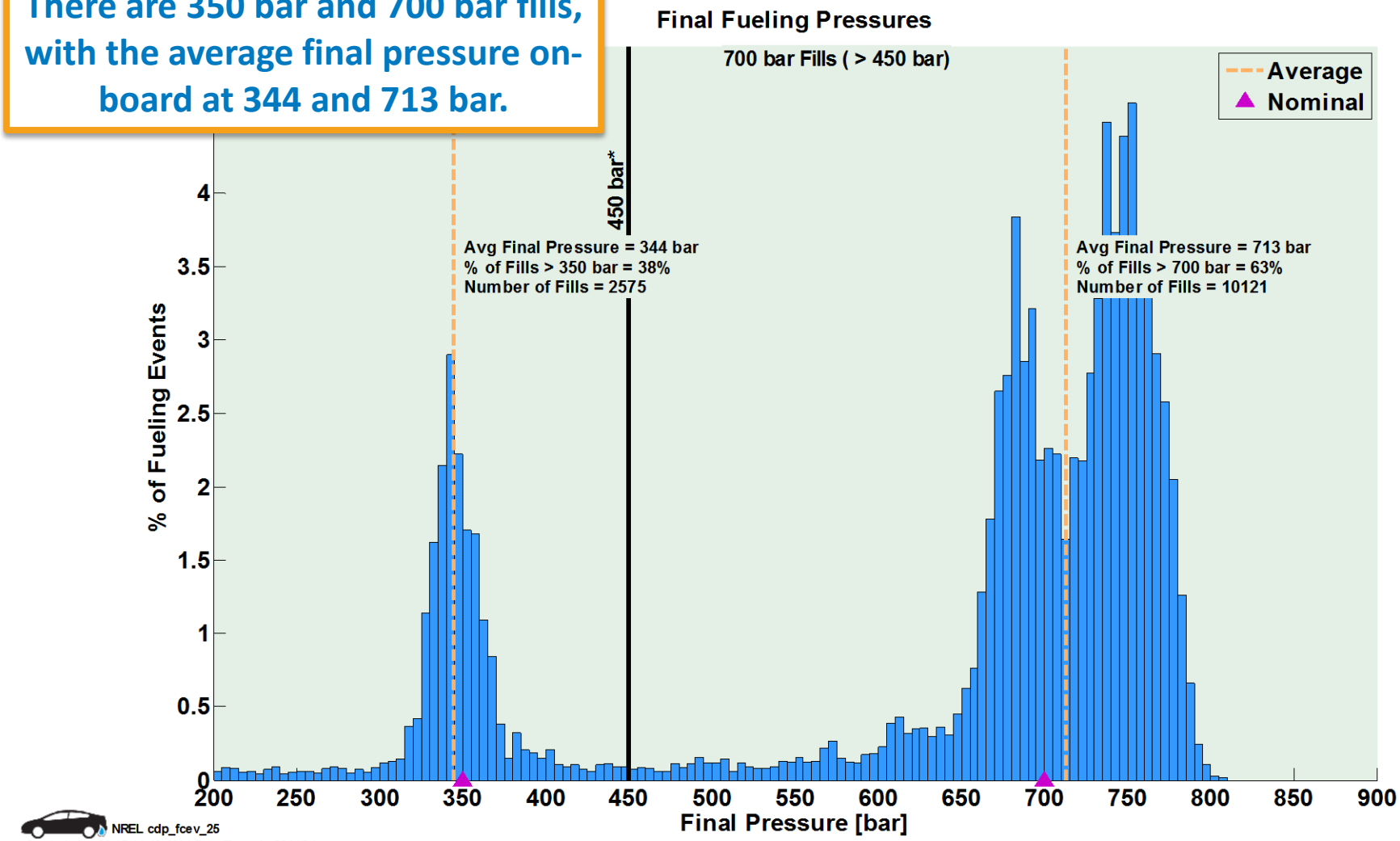


The median tank level at fill is 29% and the majority of fills are between 1 and 2 kg, per vehicle data (CDP-FCEV-08).

The average time spent at station is 10 minutes. The average fill time (gas flowing) from the station data is 5.6 minutes. The remaining time at the station is for connection, point-of-sale, and other (CDP-FCEV-09).

Accomplishment: On-Board Hydrogen Tank Pressures

There are 350 bar and 700 bar fills, with the average final pressure on-board at 344 and 713 bar.



NREL cdp_fcev_25
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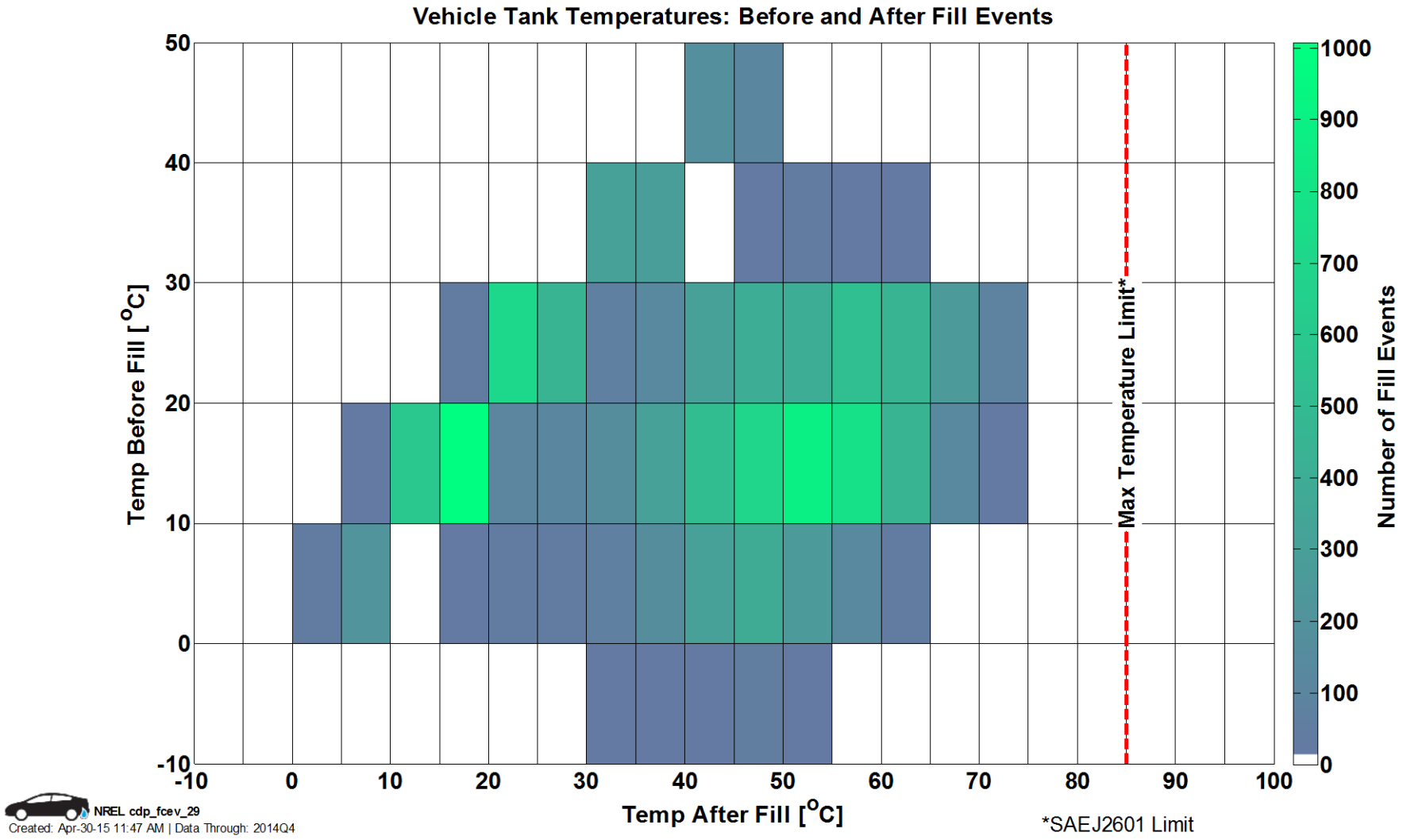
*The line at 450 bar separates 350 bar fills from 700 bar fills. It is slightly over the allowable 125% of nominal pressure (437.5 bar) from SAE J2601.

Accomplishment: On-Board Hydrogen Tank Temperatures



The tank temperature is typically 10° to 30°C (approximately ambient) before a fill and 45° to 65°C after a fill. The tank temperature after a fill has not exceeded 85°C.

Accomplishments: Status Against Technical Targets

Vehicle Performance Metrics	DOE Target (Year 2020)[b]	Current[a]	LD2+[c]	LD2[c]	LD1[c]
Durability					
Max Fuel Cell Durability Projection (hours)	5,000	3,930	--	2,521	1,807
Average Fuel Cell Durability Projection (hours)		2,032	1,748	1,062	821
Max Fuel Cell Operation (hours)		5,605	1,582	1,261	2,375
Efficiency					
Adjusted Dyno (Window Sticker) Range		No Update Planned	--	196-254 miles	103-190 miles
Median On-Road Distance Between Fuelings		119 miles	98 miles	81 miles	56 miles
Fuel Economy (Window Sticker)		51 mi/kg (median)	--	43 – 58 mi/kg	42 – 57 mi/kg
Fuel Cell Efficiency at ¼ Power	60%	No Update Planned	--	53% – 59%	51% – 58%
Fuel Cell Efficiency at Full Power		No Update Planned	--	42% – 53%	30% – 54%
Specification					
Specific Power (W/kg)	650	Planned 2015		306-406	183-323
Power Density (W/L)	850	Planned 2015		300-400	300-400

a) Current results are available at http://www.nrel.gov/hydrogen/proj_fc_vehicle_evaluation.html (Updated 10/2014)

b) Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22)

c) National Fuel Cell Vehicle Learning Demonstration Final Report (http://www.nrel.gov/hydrogen/pdfs/54860.pdf)

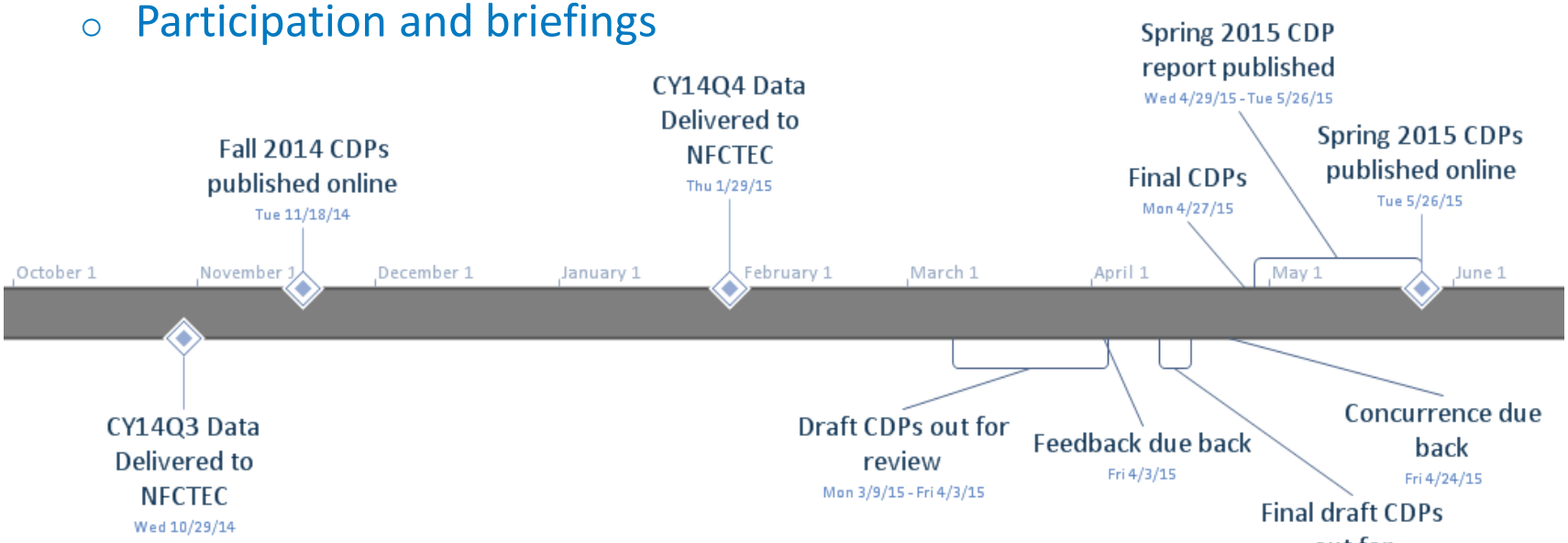
Steady progress has been demonstrated over the four evaluation periods with FCEV technology improvements especially in key technical areas like fuel cell durability, range, and fuel economy.

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **This project was not reviewed last year.**

Collaborations

- **Six participating OEMs – Daimler, GM, Honda, Hyundai, Nissan, Toyota. These OEMs:**
  - Supply data
  - Review detailed data analysis and approve published results
  - Review current and future analysis topics.
- **Industry working groups (CaFCP, H2USA, and FCHEA)**
  - Participation and briefings



Detailed view of a typical data cycle with OEMs

Remaining Challenges and Barriers

- **Validation of technical targets**
  - Durability
  - Fuel economy
  - Range
  - Efficiency
  - Reliability & Safety
  - Power specifications
  - Refueling performance
- **Relationship between FCEV and new stations coming online**
- **Impacts of hydrogen demand increasing over time**

Proposed Future Work

- **Fall 2015**
  - Complete quarterly analysis of CY15 Q1 and Q2 data
  - Publish analysis results (10/2015)
- **Spring 2016**
  - Complete quarterly analysis of CY15 Q3 and Q4 data
  - Publish analysis results (4/2016)
- **Identify new opportunities to document fuel cell and hydrogen progress publicly**
- **Future analysis topics include**
  - the validation of technical targets for durability, fuel economy, range, reliability and safety, transient performance, power management and specifications, and refueling performance
  - Relationship between FCEVs and new stations coming online
  - Impacts of hydrogen demand increasing over time
  - Identify technology gaps and needs based on the on-road performance data

Summary

- **Relevance**
  - Independent validation of FCEV on-road performance against DOE and industry targets
- **Approach**
  - Collaborate with industry partners
  - Continue to develop core NFCTEC and analysis capability and tools
  - Leverage 7+ years of analysis and experience from the Learning Demonstration
- **Technical Accomplishments and Progress**
  - Analyzed data from six OEMs
  - Performed detailed reviews of individual OEM data results
  - Published results via 32 CDPs that cover topics such as deployment, fuel cell performance, durability, fuel economy, range, and driving.
- **Collaborations**
  - Working closely with industry partners to validate methodology and with other key stakeholders to ensure relevance and accuracy of results
- **Future Work**
  - Analyze on-road FCEVs and publish updated results in Fall 2015, and add new analysis topics
  - Identify new opportunities to document fuel cell and hydrogen progress publicly
  - Identify technology gaps

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Technical Back-Up Slides

Key Analysis Topics

Critical

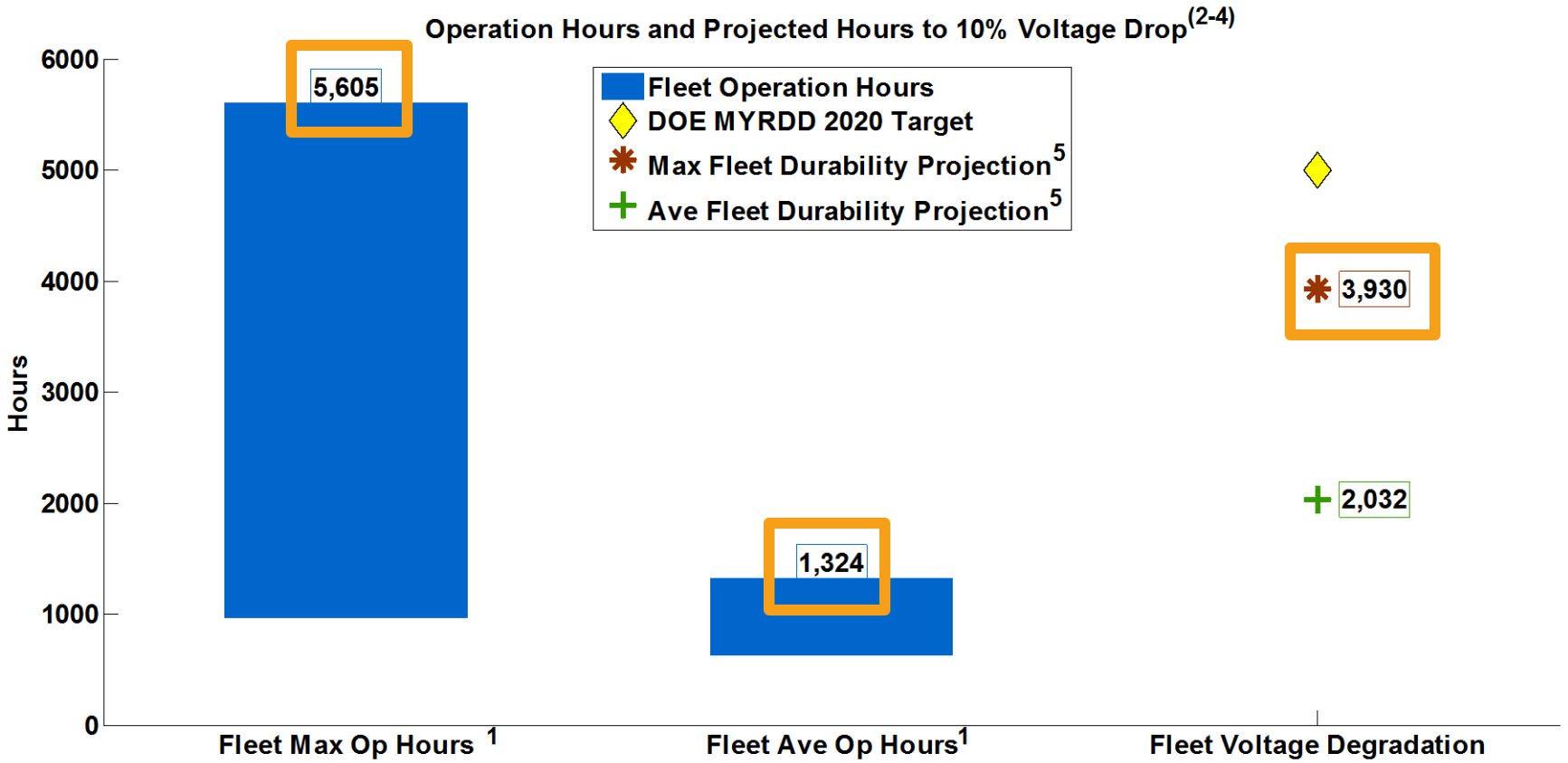
- Fuel cell durability
- Vehicle operation (hours, miles)
- Specs (power density, specific power)
- Range, fuel economy, and efficiency
- Fill performance
- Reliability

Important

- Drive behaviors
- Fill behaviors
- Power management
- Energy
- Transients
- Comparisons to conventional vehicles

These key topics were selected based on review of past CDPs, targets, most commonly referenced topics, and DOE feedback.

Accomplishment: FCEV Operation Hours and Durability

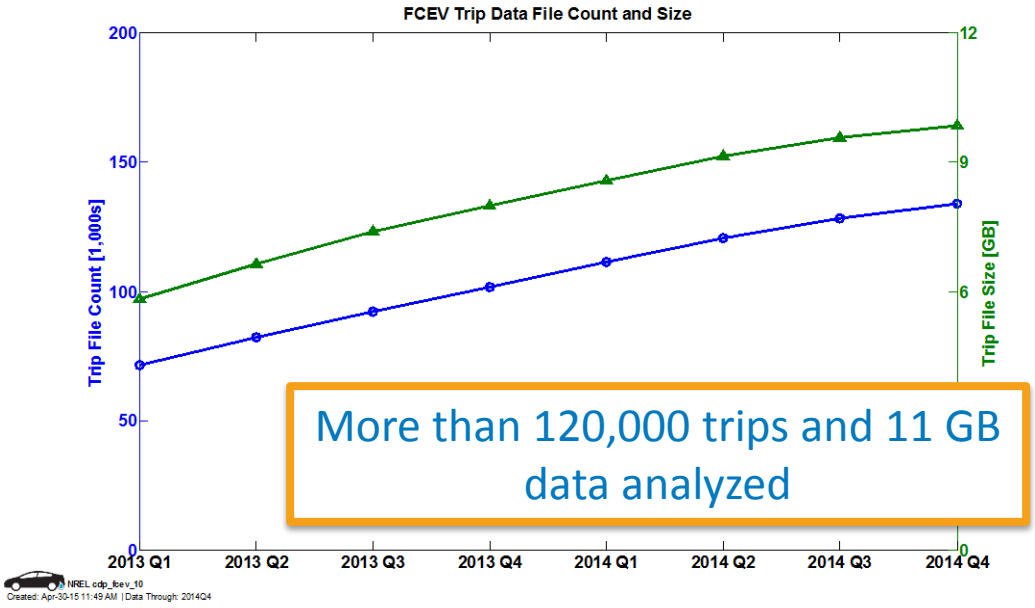


1) Range bars created using one data point for each fleet. Some stacks have accumulated hours beyond 10% voltage degradation.
2) Voltage degradation is measured based on a projected time to a voltage drop, at a high current, level 10% lower than beginning of life voltage. 10% voltage drop level is a DOE metric for assessing fuel cell durability.
3) Projections using on-road data are calculated at approximately 55 - 65% rated stack current.
4) 10% voltage drop is NOT an indication of an OEM's end-of-life criteria and projections do not address catastrophic stack failure.
5) Each fleet has one voltage projection value that is the weighted average of the fleet's fuel cell stack projections.

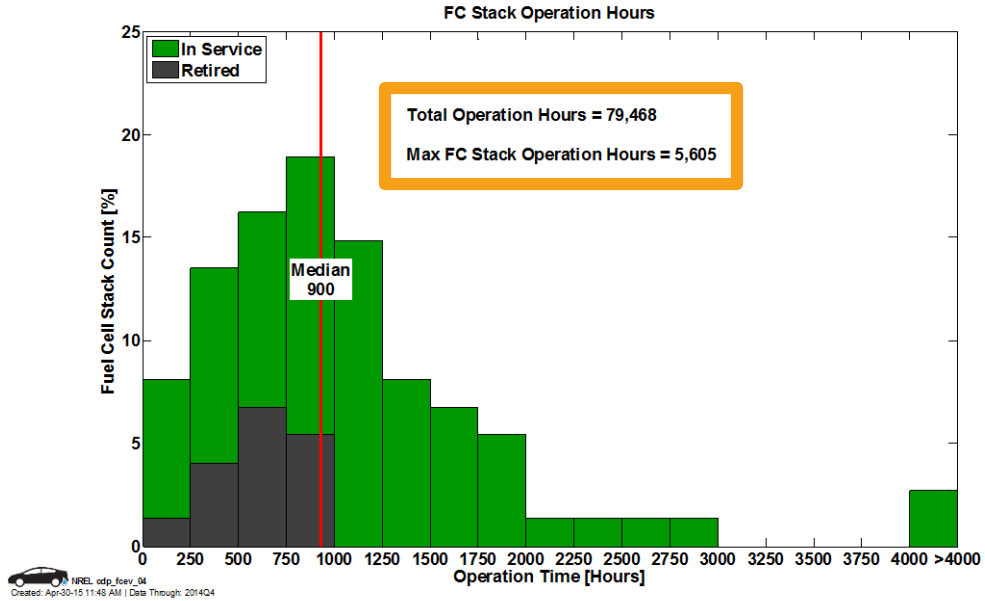
NREL cdp_fcev_21
Created: Apr

FCEV operation hours and durability projections to 10% voltage degradation. Each fleet has a max and average FC operation hours value and a weighted average hours to 10% voltage degradation.

On-Road Data Processing



More than 120,000 trips and 11 GB data analyzed



CDP List

#	Description	Category	Date Updated	First Publication	updated #
01	Vehicle Count	Deployment	4/30/15	4/30/15	1
02	Vehicle Odometer	Driving Behavior	4/30/15	10/15/14	2
03	Vehicle Miles Driven by Calendar Quarter	Driving Behavior	4/30/15	4/30/15	1
04	Fuel Cell Stack Operation Hours	Driving Behavior	4/30/15	10/15/14	1
06	Average Calendar Days Between Refueling per Vehicle	Fueling Behavior	4/30/15	4/30/15	1
07	Distance Driven Between Refueling	Range	4/30/15	4/30/15	1
08	Vehicle Fill Amounts	Fuel Economy	4/30/15	4/30/15	1
09	Vehicle Dwell Time at Station	Fueling Behavior	4/30/15	4/30/15	1
10	Data Processing: File Count and Size		4/30/15	4/30/15	1
11	Vehicle Size Metrics	Specification	9/8/14	9/8/14	1
12	Vehicle Power Metrics	Specification	9/8/14	9/8/14	1
13	Speed and Acceleration Metrics	Specification	9/8/14	9/8/14	1
14	Average On-Road Fuel Economy	Fuel Economy	4/30/15	9/8/14	2
15	Hydrogen Tank Level at Refueling	Fueling Behavior	4/30/15	4/30/15	1
16	Refueling by Time of Day	Fueling Behavior	4/30/15	4/30/15	1
17	Refueling by Day of Week	Fueling Behavior	4/30/15	4/30/15	1
18	Driving Trip Start Time	Driving Behavior	4/30/15	4/30/15	1
19	Driving by Day of Week	Driving Behavior	4/30/15	4/30/15	1
20	Daily Driving Distance	Driving Behavior	4/30/15	4/30/15	1
21	Fuel Cell Stack Operation Hours and Voltage Durability	Durability	4/30/15	4/30/15	1
22	Projected Hours to 10% Voltage Degradation Against 2,500 hour target	Durability	4/30/15	4/30/15	1
23	Fuel Cell Stack Durability as a Function of Voltage Drop Levels	Durability	4/30/15	4/30/15	1
24	Fuel Cell Stack Power Level Operation Time	FC Performance	4/30/15	4/30/15	1
25	Final Fueling Pressure - Vehicle Perspective	H2 Performance	4/30/15	4/30/15	1
26	Average Trip Speed	Driving Behavior	4/30/15	4/30/15	1
27	Trip Speed Comparison with Standard Drive Cycles	Driving Behavior	4/30/15	4/30/15	1
28	Vehicle Tank Temperatures Based on Fill Events	H2 Performance	4/30/15	4/30/15	1
29	Vehicle Tank Temperatures: Before and After a Fill	H2 Performance	4/30/15	4/30/15	1
30	Vehicle Tank Temperatures and Pressures after a Fill	H2 Performance	4/30/15	4/30/15	1
31	FC Operation Hours and Voltage Degradation Trend	Durability	4/30/15	4/30/15	1
32	On-road Fuel Economy Trend	Fuel Economy	4/30/15	4/30/15	1
33	OEM Participation Trend	Deployment	4/30/15	4/30/15	1