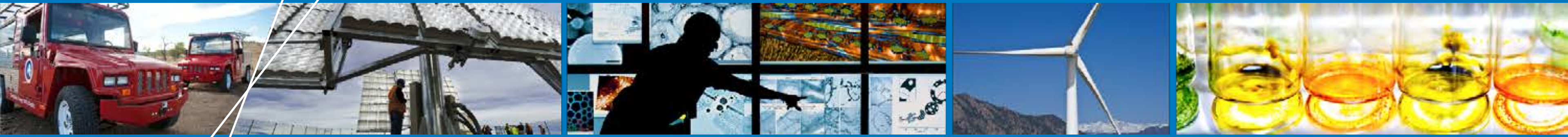
Fuel Cell Electric Vehicle Evaluation



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Washington, DC

Project ID TV001

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

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Overview

Timeline and Budget

- Project start date: 10/2012*
- Total DOE funds received to date: $1,565k
- FY15 DOE funding: $365k
- FY16 planned DOE funding: $300k

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

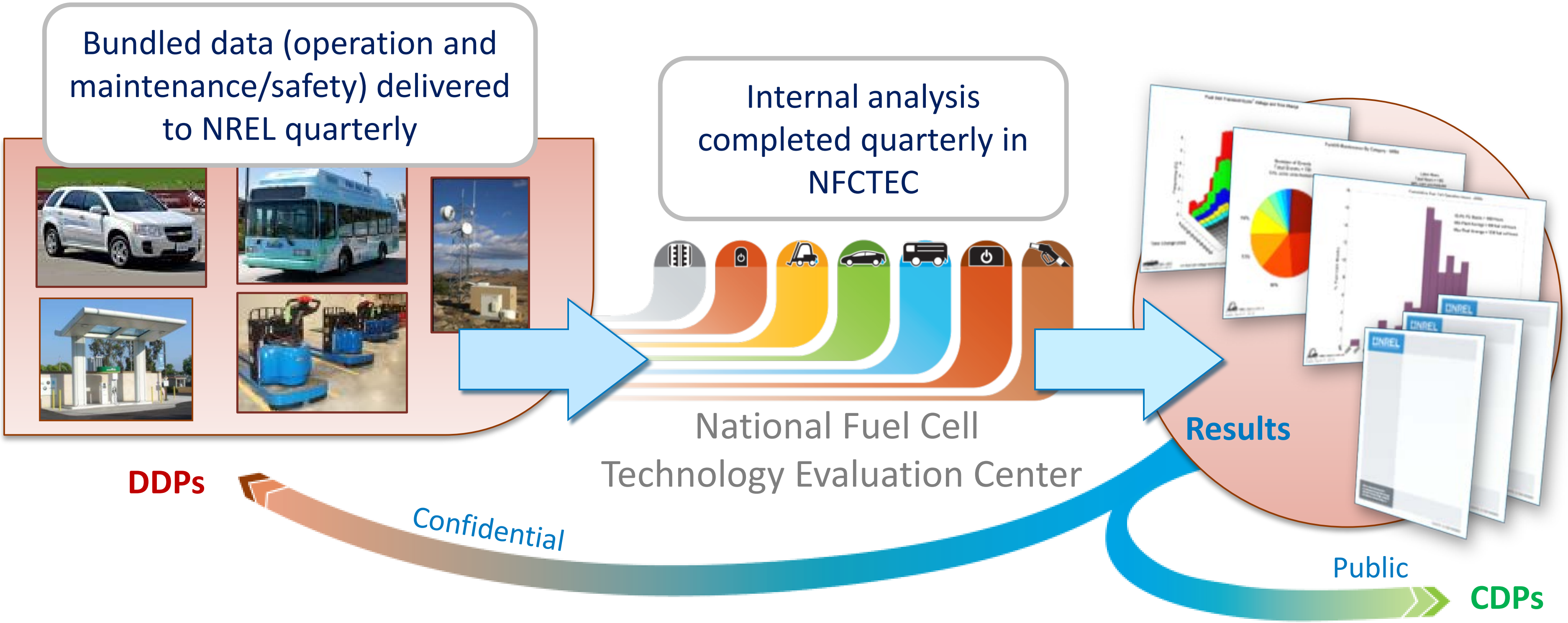
Project Objectives, Relevance, and Targets: Fuel Cell Electric Vehicle Evaluation

FY16 Objectives
Analysis and reporting on FCEV durability, fuel economy, range, fueling behavior, and reliability.

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

- **Objectives**
  - Data analysis and reporting of hydrogen fuel cell electric vehicles (FCEV) operating in real-world setting
  - Identify current status and evolution of the technology
  - Publish performance status and progress from multiple FCEV models
- **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



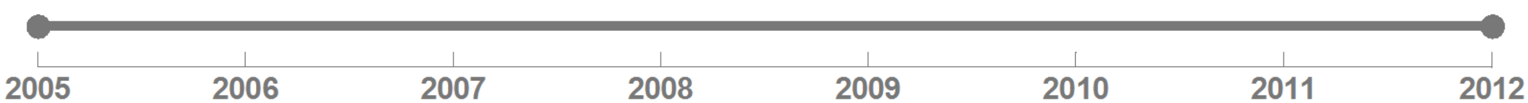
Detailed Data Products (DDPs)
- Individual data analyses
- Identify individual contribution to CDPs
- Shared every six months only with the partner who supplied the data

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: On-road FCEVs & Partners

Range of FCEV Model Years

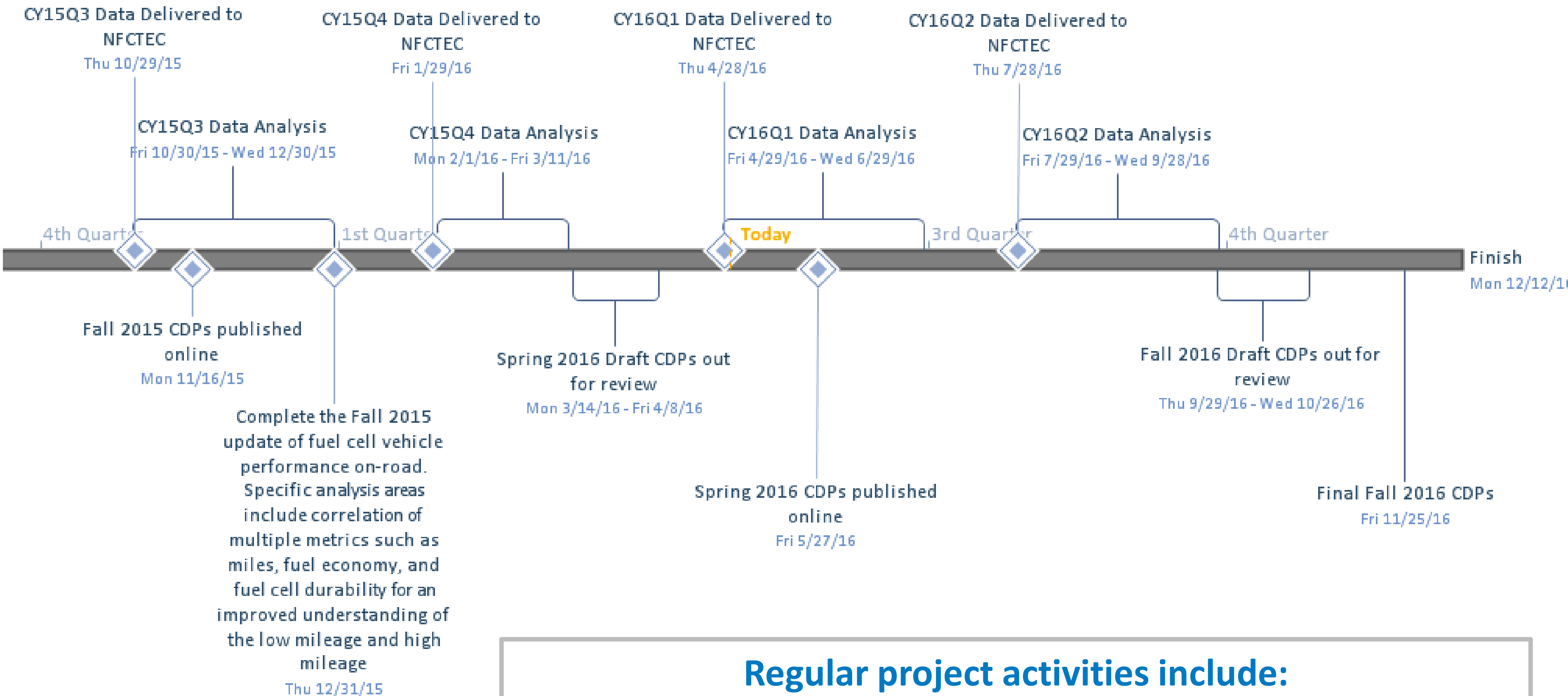


[1]DOE project overview:

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

[2]Project managed by Electricore
Award completed

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: FCEV Deployment and Operation Through 2015CYQ4

55
FCEVs total

51
Average on-road fuel economy miles/kg

4,100
Max fleet voltage durability (Hours to 10% degradation metric)

24
FCEVs retired

> 3,052,000
miles traveled

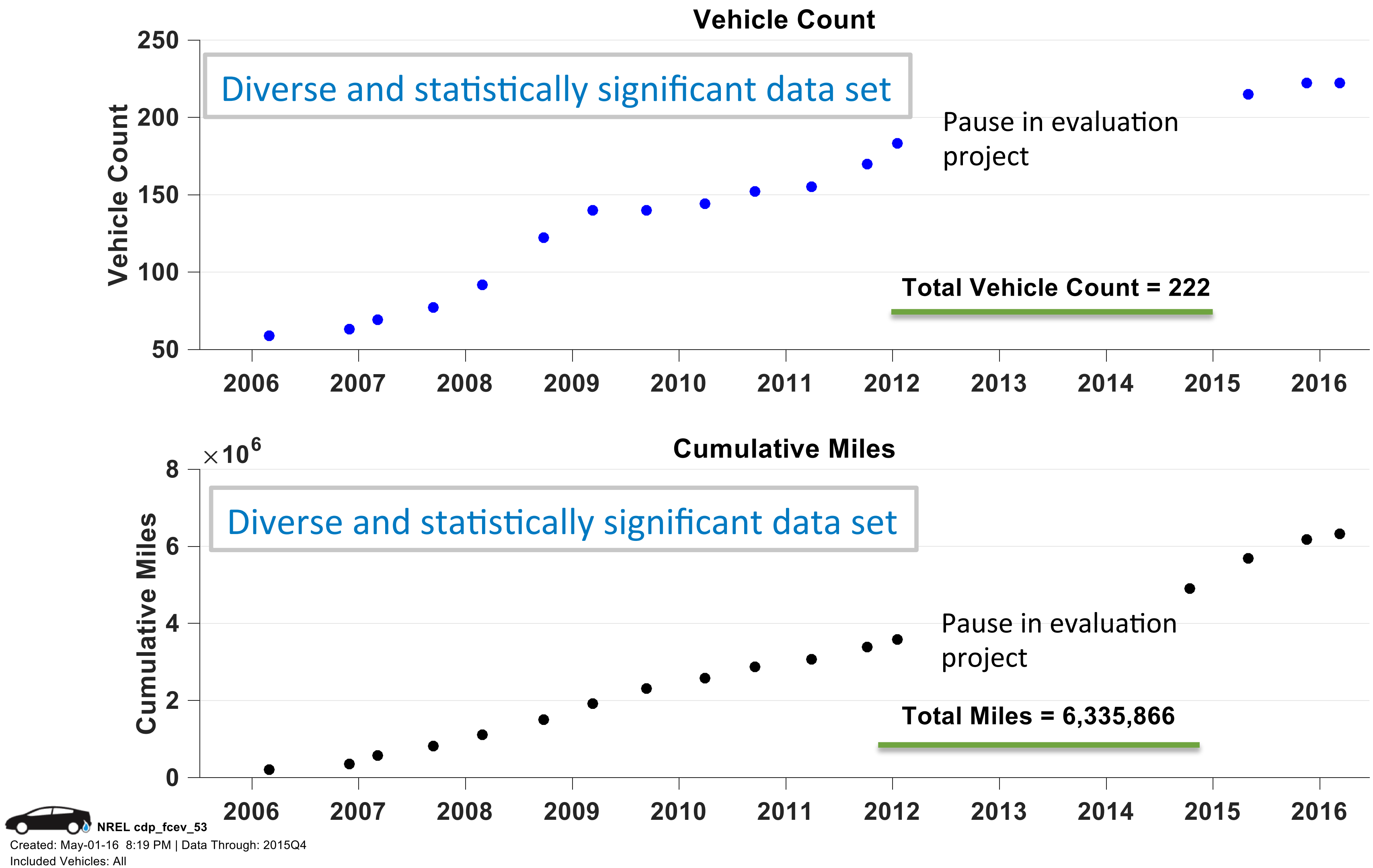
> 190,300
Max FCEV odometer miles

NREL Hydrogen Station Dedication 10/2015

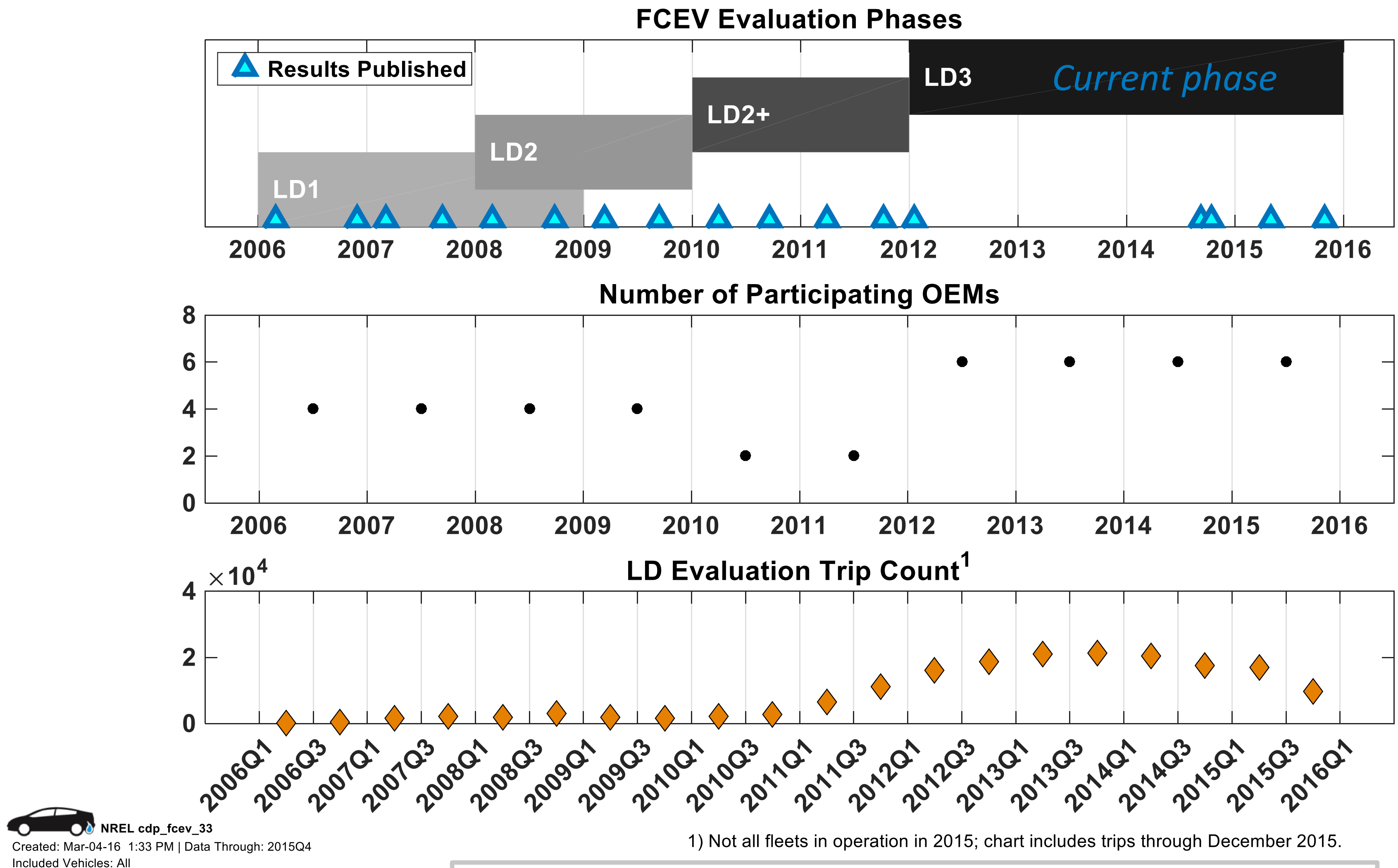
> 101,400
Fuel cell operation hours

5,600
Max fuel cell operation hours

Accomplishment: Vehicle Count & Miles Since 2006



Accomplishment: Participants and Trips Since 2006



1) Not all fleets in operation in 2015; chart includes trips through December 2015.

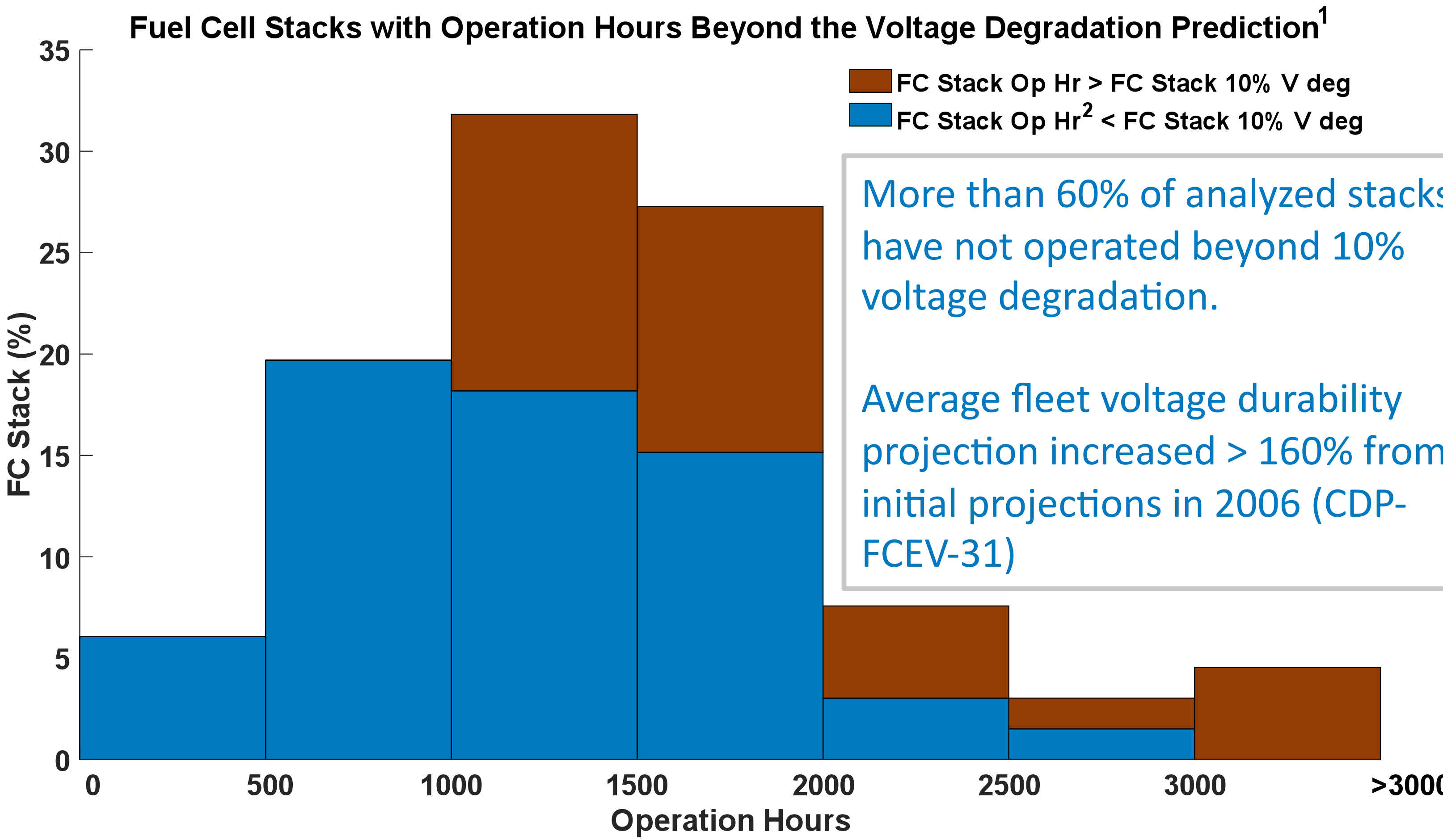
NREL analyzed trips decreasing due to planned vehicle decommissioning of older generation vehicles.

Accomplishment: Analysis Categories

- Deploy
- Driving
- FC Performance
- Reliability
- Durability
- Fuel Economy
- Range
- Fueling
- H2 Performance
- Specs
- Other

Analyzed data through 12/2015
Reliability is a new category since 6/2015
All results not included here. All results available online at www.nrel.gov/hydrogen/proj_tech_validation.html

Accomplishment: Comparison of FC Stacks Operated Beyond 10% Voltage Degradation



More than 60% of analyzed stacks have not operated beyond 10% voltage degradation.

Average fleet voltage durability projection increased > 160% from initial projections in 2006 (CDP-FCEV-31)

1. The DOE 10% voltage degradation metric is used for assessing voltage degradation; it may not be the same as end-of-life criteria and does not address catastrophic failure modes. Some data sets have operated beyond 10% voltage degradation because they are able to satisfy the operating requirements at a higher percentage of voltage degradation.
2. Fuel cell stacks in this group (63.6% of all stacks) have not operated passed 10% voltage degradation.

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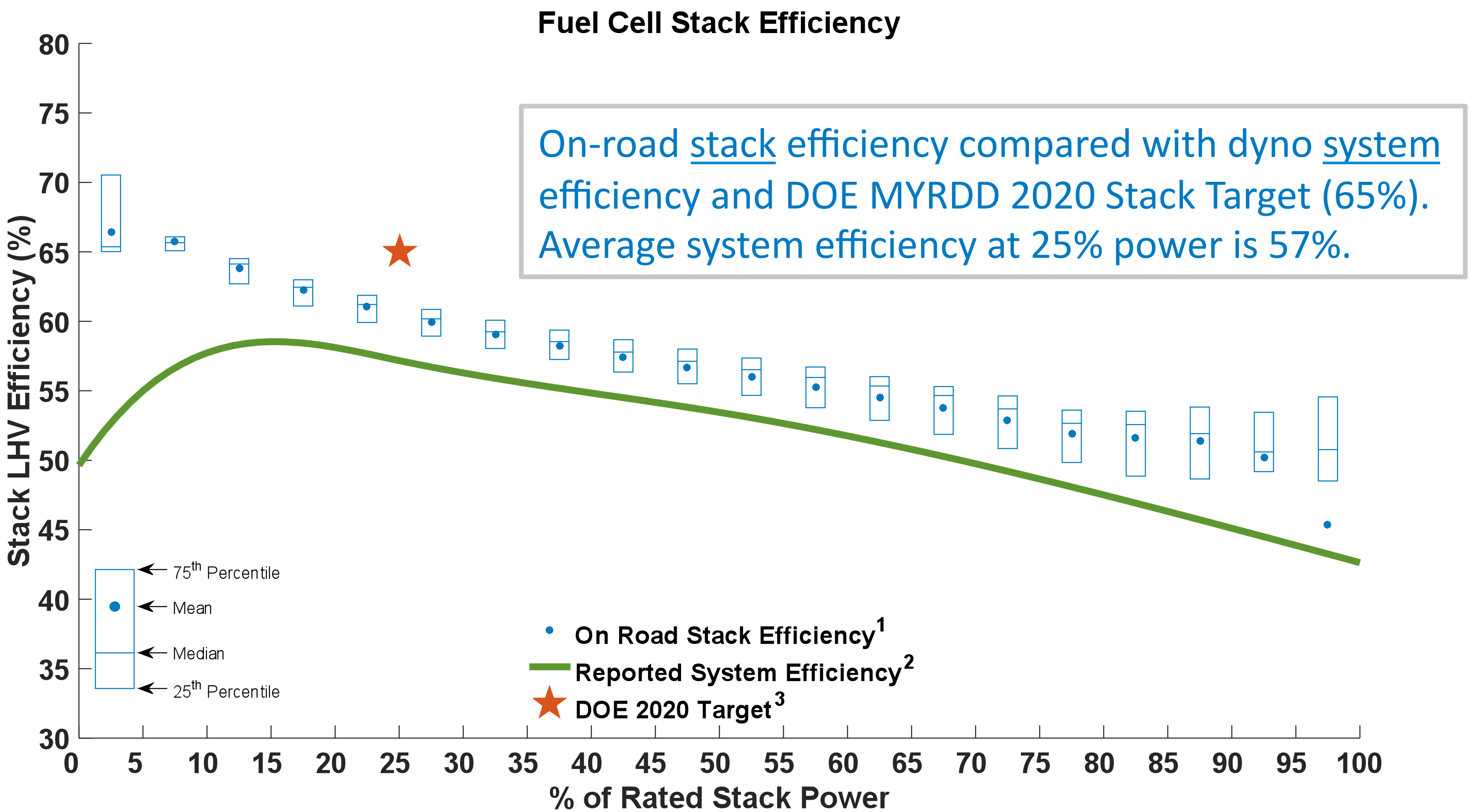
Included Vehicles: Partial

Accomplishment: On-Road Fuel Cell Stack Efficiency



1. Stack efficiency is calculated as the product of voltage and current divided by the fuel consumed. Fuel consumed is a calculation based on the number of cells, the current and the Faraday constant. Because this is gross stack power, no allowance is made for anode purge losses. The lower heating value (LHV) of hydrogen is taken as 120 MJ/kg.
2. Efficiency reported by OEMs from dynomometer testing, includes balance of plant losses.
3. DOE 2020 target is 65% efficiency at 25% of rated power

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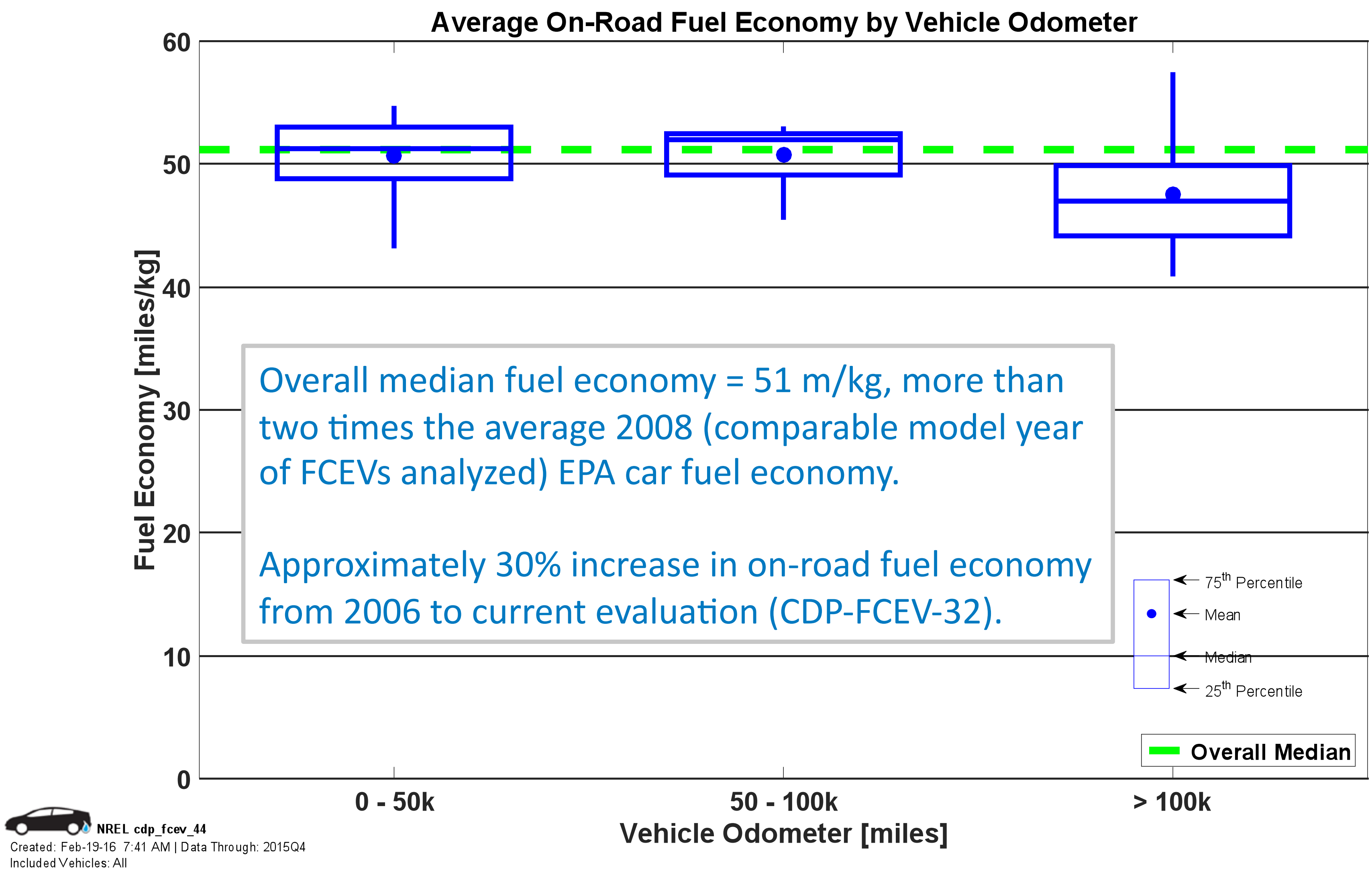
Included Vehicles: Partial

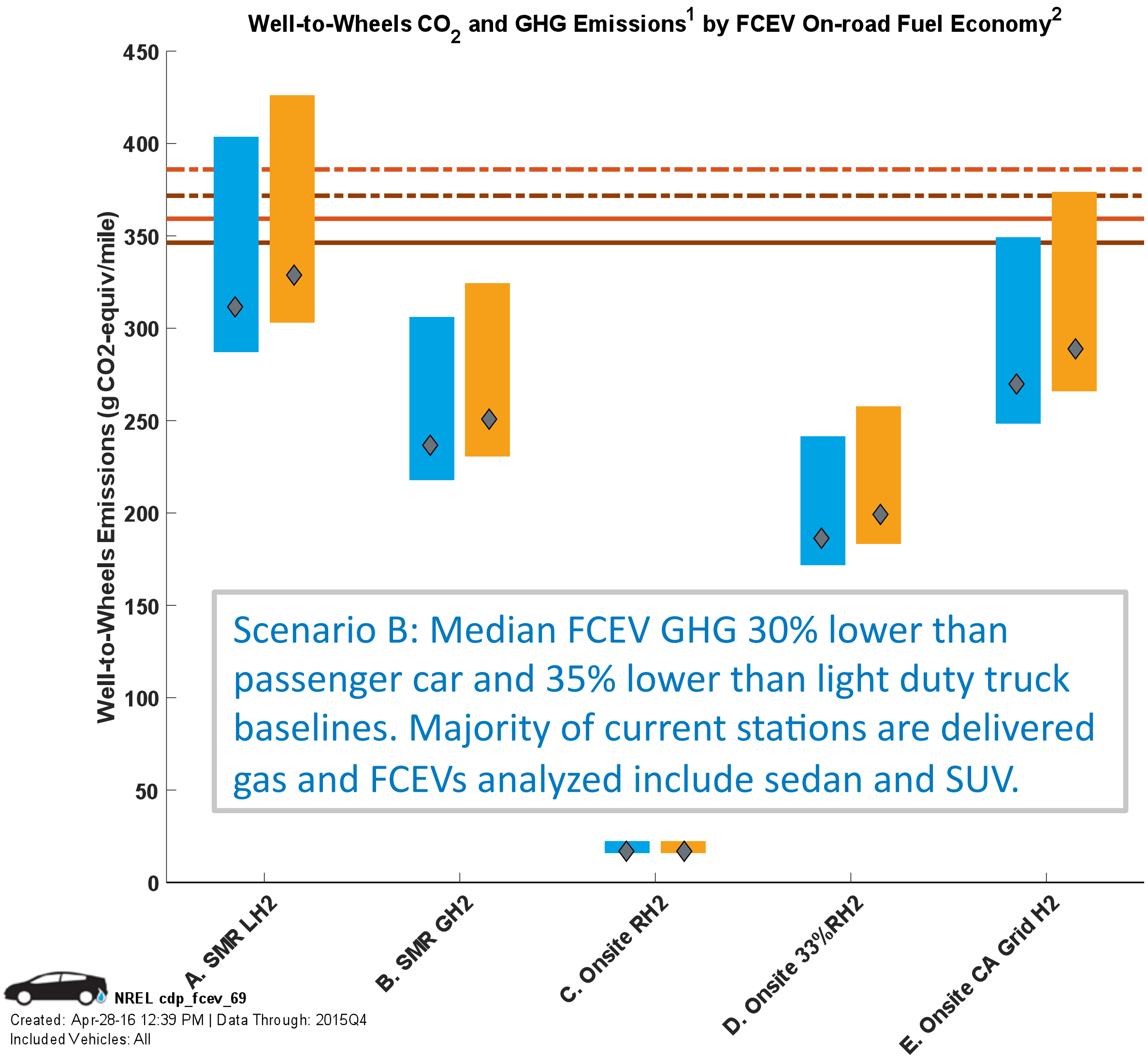
CDP-FCEV-44
Average On-Road Fuel Economy by Vehicle Odometer



Overall median fuel economy = 51 m/kg, more than two times the average 2008 (comparable model year of FCEVs analyzed) EPA car fuel economy.

Approximately 30% increase in on-road fuel economy from 2006 to current evaluation (CDP-FCEV-32).

Accomplishment: GHG Emissions Comparisons

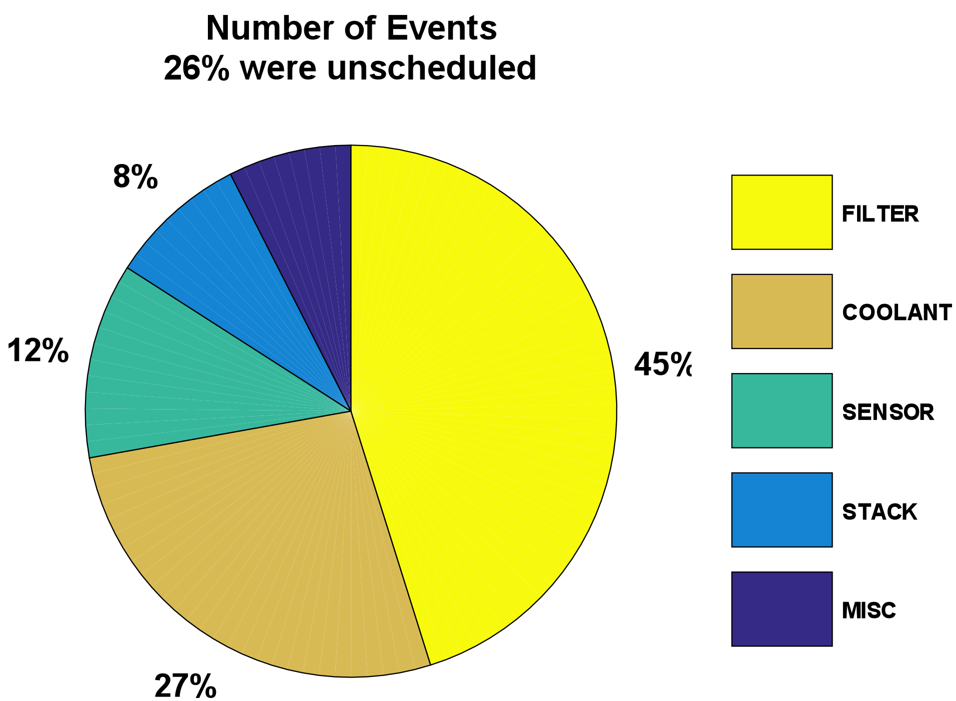


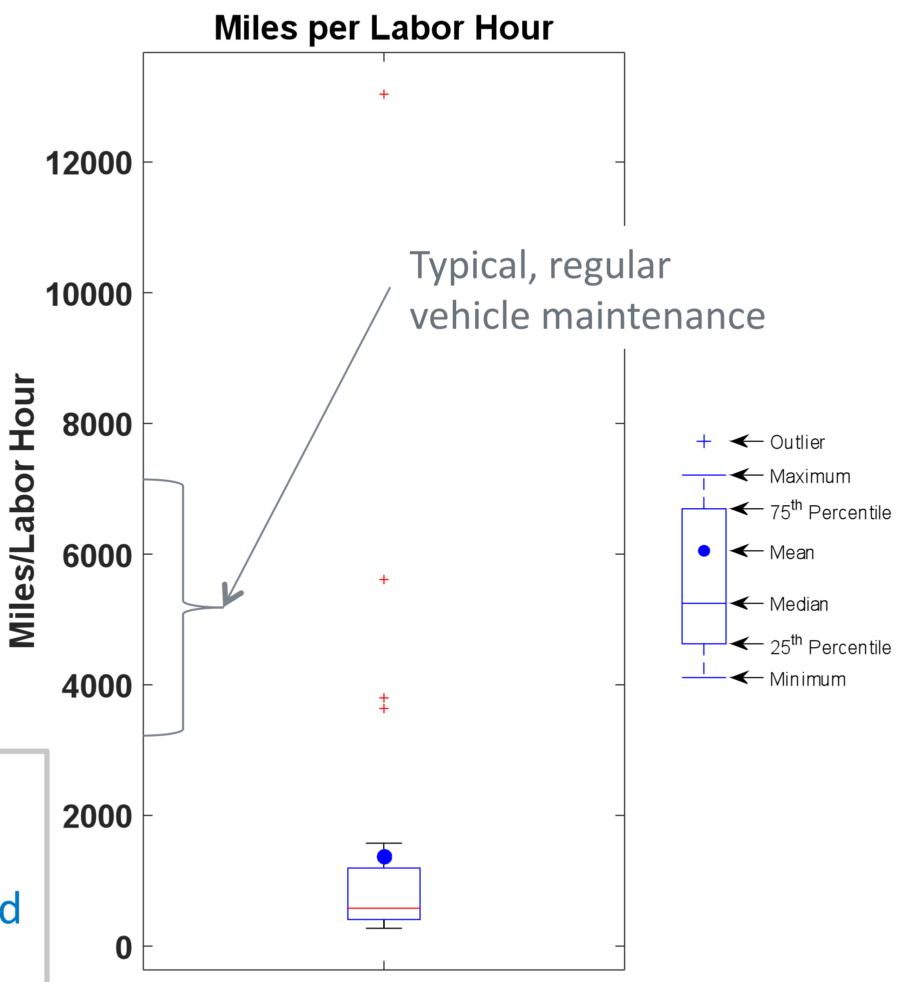
Scenario B: Median FCEV GHG 30% lower than passenger car and 35% lower than light duty truck baselines. Majority of current stations are delivered gas and FCEVs analyzed include sedan and SUV.

1. GREET Fuel Cycle
2. CDP-FCEV-14
3. On-road FCEV 40.9 – 57.5 miles/kg
4. GHG includes CO2 and CO2 equivalent global warming potential CH4, N2O, VOC, CO, NOx, Black Carbon, and Organic Carbon
5. Median FCEV EPA combined rating
6. Gasoline (model year 2015) passenger car 28.8 mpg, light duty truck 26.8 mpg

Scenario Description
A. FCEV - Central SMR Liquid H2
B. FCEV - Central SMR Gaseous H2
C. FCEV - Onsite Renewable Electrolysis H2
D. FCEV - Onsite 33% Renewable Electrolysis H2
E. FCEV - Onsite CA Grid Mix Electrolysis GH2

Accomplishment: FCEV Maintenance and Reliability



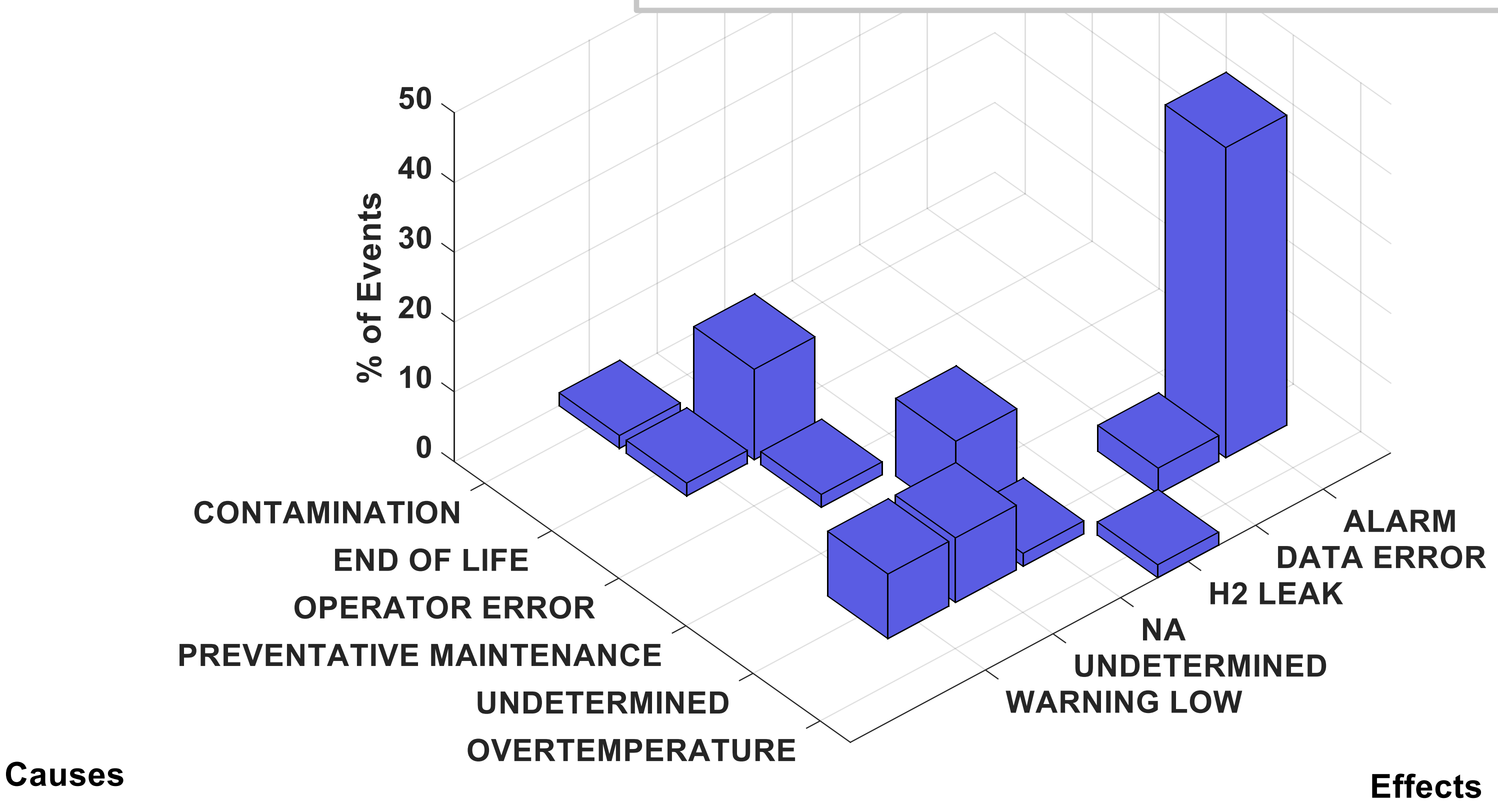


Majority of FCEVs are older generation without commercial grade maintenance expectations. Simple unscheduled maintenance (72%) filters and coolant fills. Only 3.5% of failures occurred on-road (CDP-FCEV-73). Average maintenance per vehicle decreasing since 2012 (CDP-FCEV-68).

Accomplishment: Stack Maintenance Causes and Effects

FC stack maintenance is lower frequency than filters. Contamination as cause for stack maintenance is low yet results in significant (cost and time) maintenance.

Maintenance Causes and Effects
Subsystem: STACK
Component: STACK



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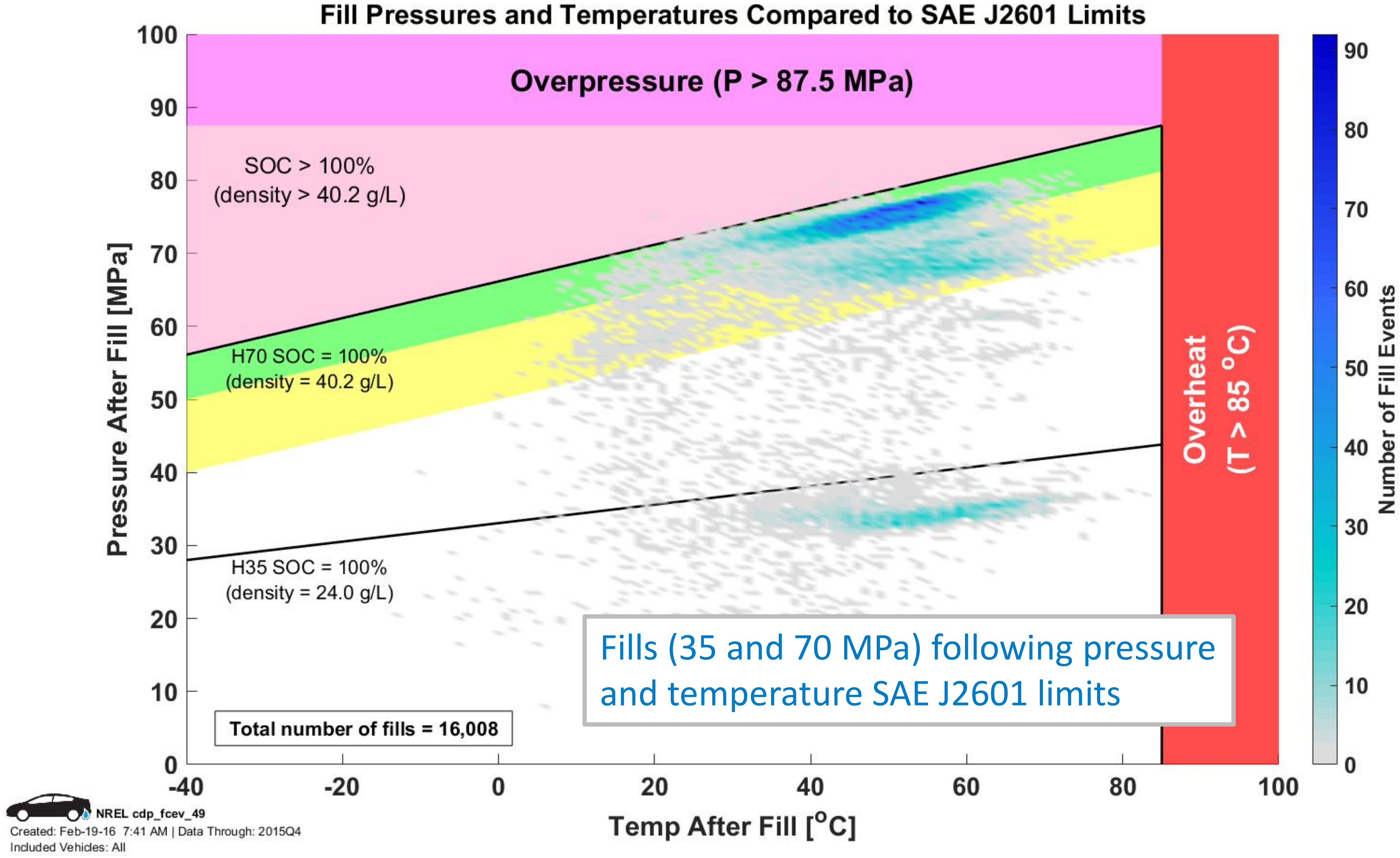
Included Vehicles: Partial

The subsystem STACK is ranked number 1 in terms of maintenance event count. The component STACK is a field replacable unit ranked number 3 in terms of maintenance event count within the STACK subsystem.

Accomplishment: Comparison of Fills to SAE J2601 Temperature and Pressure Limits



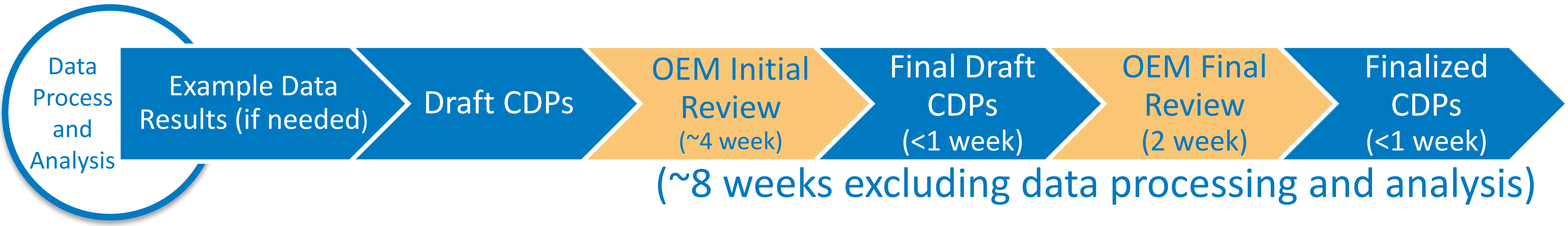
Fills (35 and 70 MPa) following pressure and temperature SAE J2601 limits

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **There is a need to aggregate data, given confidentiality issues, but it would be very useful if the aggregated data could be provided in an Excel spreadsheet and if the results were categorized by vehicle class. It would be much more useful to get the actual numbers instead of trying to guess.**
  - Aggregated data not yet presented in tabular form. Depending on the specifics, additional details could be possible to publish without a confidentiality issue. The vehicle class and model year is difficult to separate because identification by model year and vehicle class could identify an individual OEM.
- **If the number of vehicles gets to a certain minimum, then the usefulness of the data collection effort should be reconsidered.**
  - Agreed and this is a major activity for the remainder of FY16
- **New analyses: As stack production improves, consideration should be given to how to capture that repeatable process to evaluate life changes. As more cars deploy, a note on the ambient environment will become appropriate—cold-weather climate versus warm-weather climate, southern California versus the Northeast. Another metric to consider will be the impact the mechanic will have on the vehicle: his training, his tools, etc.—i.e., considering who is taking care of the car and whether the mechanic is at a factory location or a dealer. It would also be good to include collection of data for fuel efficiency at one-quarter and full power for newer-model vehicles.**
  - New analyses added for fuel cell stack and system efficiency, reliability, and GHG emissions.
- **It is not clear whether the data is being fed back to U.S. DRIVE Partnership Technical Teams to adjust model assumptions.**
  - Data was not presented specifically to U.S. DRIVE last year. A presentation is scheduled for May 2016.
- **It would be nice to substantially increase the number of vehicles in the study by establishing contracts with the automotive OEMs and the state of California for data collection and analysis services for the rollout of the commercial vehicles, especially those that will be purchased as part of the state fleet.**
  - Communicating with FCEV OEMs to identify new data sources and coordinating with CEC and CARB for data analyses and sources.
- **Some key caveats, assumptions, or key points, if any, may need to be included with composite data products (CDPs).**
  - Added analysis capability to capture key caveats, assumptions, and key points for each aggregated result, as well as avenues to record that information via reports and metadata with the online data

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.



Detailed view of a typical data cycle with OEMs

- **Industry working groups (CaFCP, H2USA, and FCHEA)**
  - Participation and briefings

Remaining Challenges and Barriers

- **Relationship between vehicle, station, and driver**
  - Interface between vehicle and station a key issue for successful market adoption, especially from the perspective of the consumer.
  - Information from customer perspective essential for complete understanding of technology gaps.
  - Station performance challenges based on increased FCEV demand.
  - Opportunities for optimization and improvement based on vehicle connectivity and adaptive learning.
- **Availability of on-road vehicle data – more significant issue than FY15 as vehicles have retired and newest FCEV not currently part of this project**
- **FCEV model year variation**
  - We are not able to publish all of the trend data if only one OEM has supplied data during a time period or if separation by model year identifies an OEM.

Proposed Future Work

- **Identification of top priority objectives and analysis topics based on stakeholder feedback (with FCEVs no longer in the development stage)**
- **Identification of commercially available FCEV data to add**
- **Interface analysis between FCEVs and hydrogen stations**
- **Estimation of FCEV demand for improved hydrogen station operation and controls to decrease operation and maintenance costs**
- **Fall 2016**
  - Complete quarterly analysis of CY16 Q1 and Q2 data
  - Publish analysis results dependent on number of on-road vehicles (10/2016)
- **Spring 2017**
  - Complete quarterly analysis of CY16 Q3 and Q4 data
  - Publish analysis results dependent on number of on-road vehicles (4/2016)

Summary of Key Metrics

	Vehicle Performance Metrics	DOE Target (Year 2020)[a]	LD3[b]	LD2+[c]	LD2[c]	LD1[c]
Durability	Max Fuel Cell Durability Projection (hours)	5,000	4,130	--	2,521	1,807
	Average Fuel Cell Durability Projection (hours)		2,149	1,748	1,062	821
	Max Fuel Cell Operation (hours)		5,605	1,582	1,261	2,375
Efficiency	Adjusted Dyno (Window Sticker) Range		200 - 320 miles	--	196-254 miles	103-190 miles
	Median On-Road Distance Between Fuelings		123	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%	57% (average)	--	53% – 59%	51% – 58%
	Fuel Cell Efficiency at Full Power		43% (average)	--	42% – 53%	30% – 54%
Specs	Specific Power (W/kg)	650	240 - 563		306-406	183-323
	Power Density (W/L)	850	278 - 619		300-400	300-400
Storage	System Gravimetric Capacity (kg H2/kg system)	5.5%	2.5% - 3.7%			
	System Volumetric Capacity (kg H2/L system)	0.04	0.018 - 0.054			

a) 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)

b) Current results are available at http://www.nrel.gov/hydrogen/proj_fc_vehicle_evaluation.html (Updated 11/2015)

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

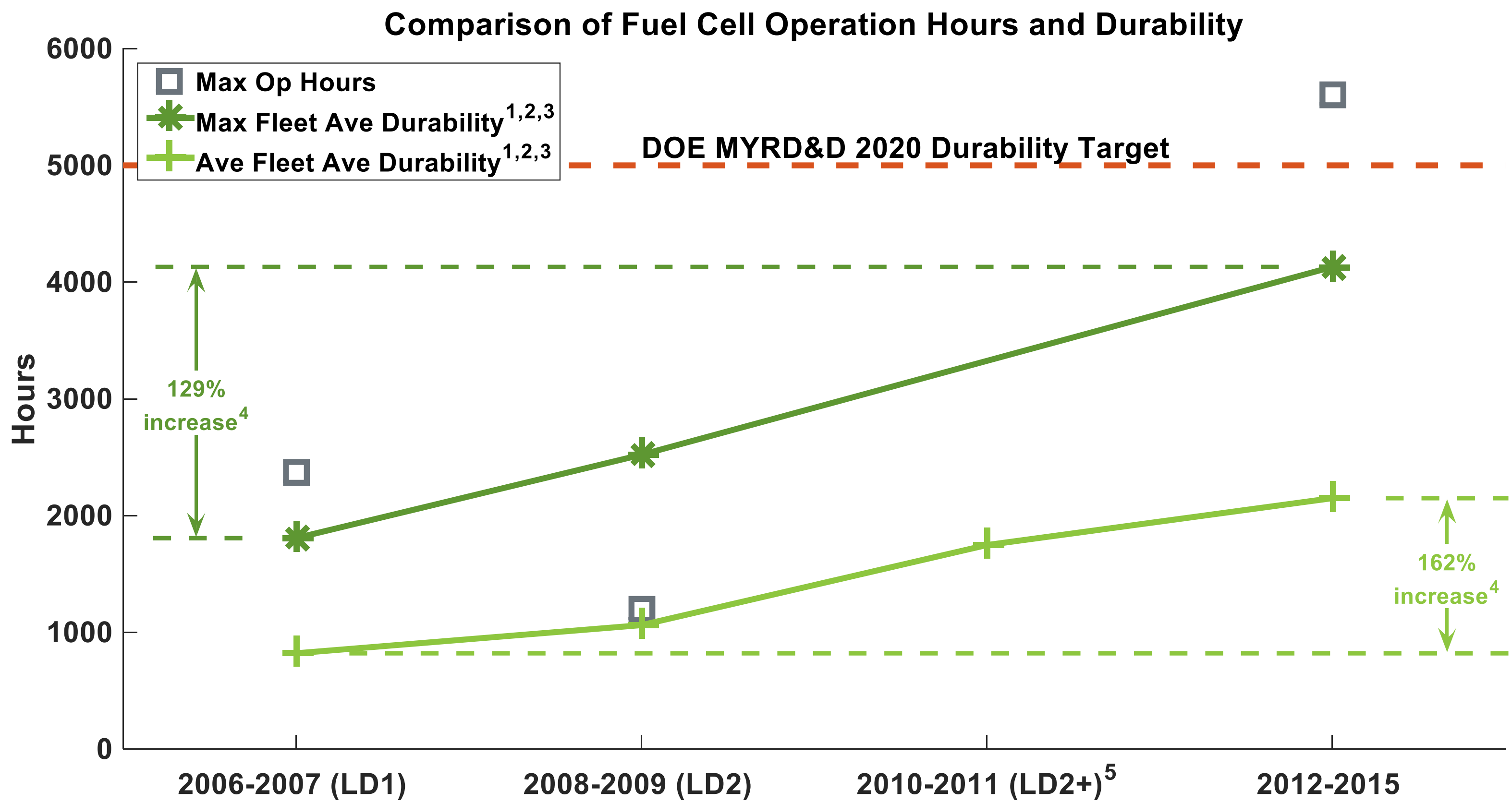
Updated values since 6/2015 report and continued progress demonstrated over the four evaluation periods with FCEV technology improvements especially in key technical areas like fuel cell durability, range, and fuel economy.

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 73 CDPs that cover topics such as deployment, fuel cell performance, durability, fuel economy, range, driving, fueling, specifications, and reliability.
- **Collaborations**
  - Working closely with industry partners to validate methodology and with other key stakeholders to ensure relevance and accuracy of results
- **Future Work**
  - New objectives and priorities with commercial FCEVs instead of development FCEVs
  - New data from commercially available FCEVs
  - Analyze on-road FCEVs and publish updated results in Fall 2016

Technical Back-Up Slides

Accomplishment: Comparison of voltage degradation



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 Learning Demonstration 1 (LD1) (2006-2007).
5. Maximum operational hours not reported in Learning Demonstration 2 continuation (LD2+) (2010-2011).

NREL cdp_fcev_31
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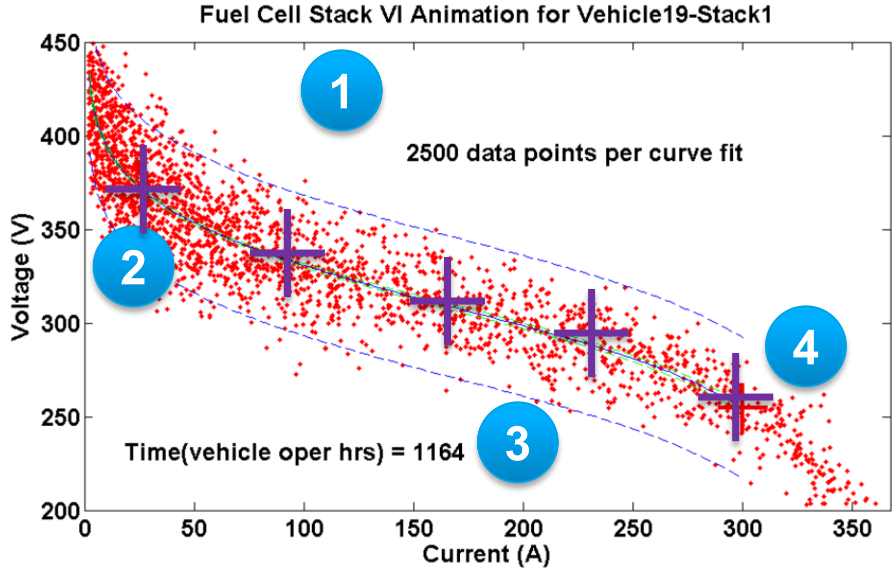
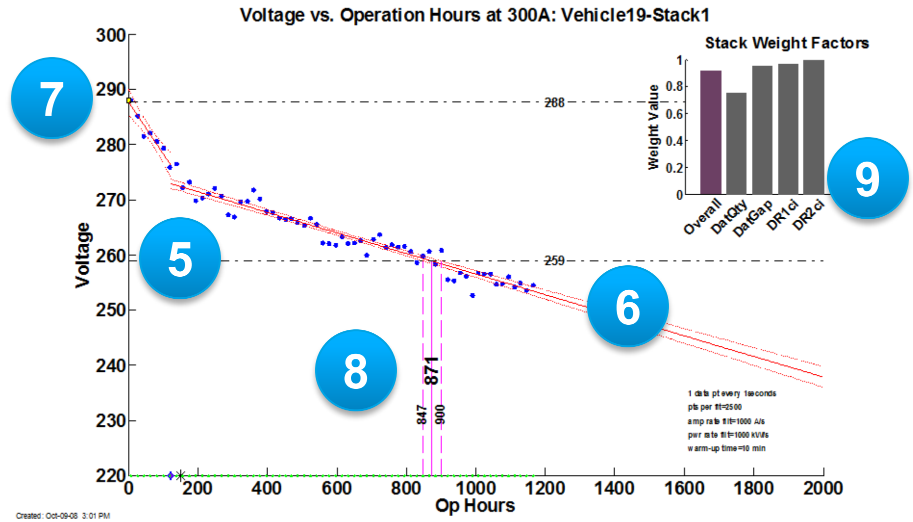
Included Vehicles: Partial

Approach – Voltage Degradation Analysis

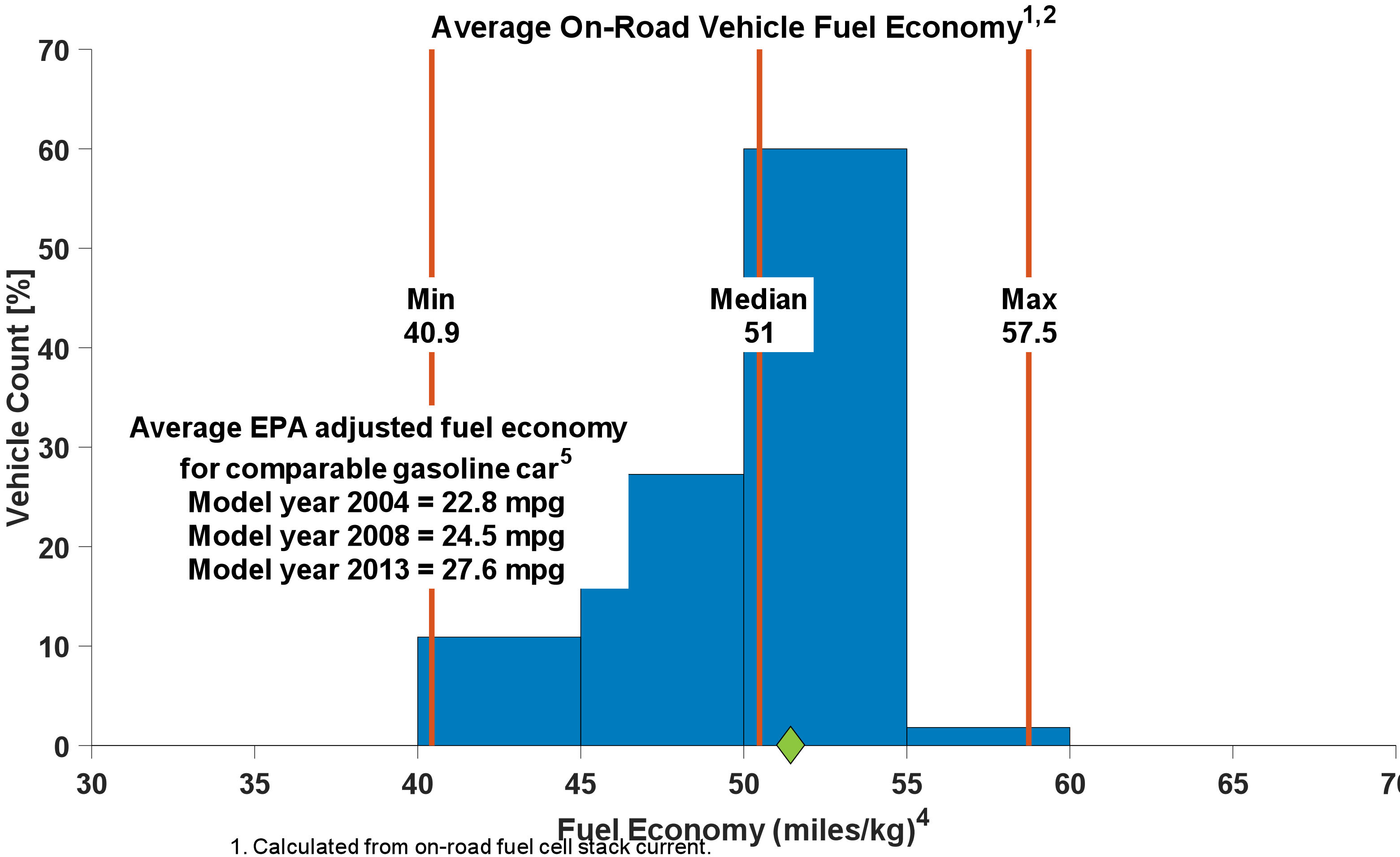
Analysis – EXAMPLE DATA

1. Voltage and current data
2. Apply polarization fit
3. Corresponding operation hour
4. Voltages from polarization fit at set currents
5. Fit voltage and operation data
6. Degradation linear fit
7. Y-intercept beginning of life voltage
8. Record operation hour when fit crosses 10% nominal voltage drop
9. Investigate fit quality





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 Economy Trends: 1975 - 2014.

NREL cdp_fcev_14
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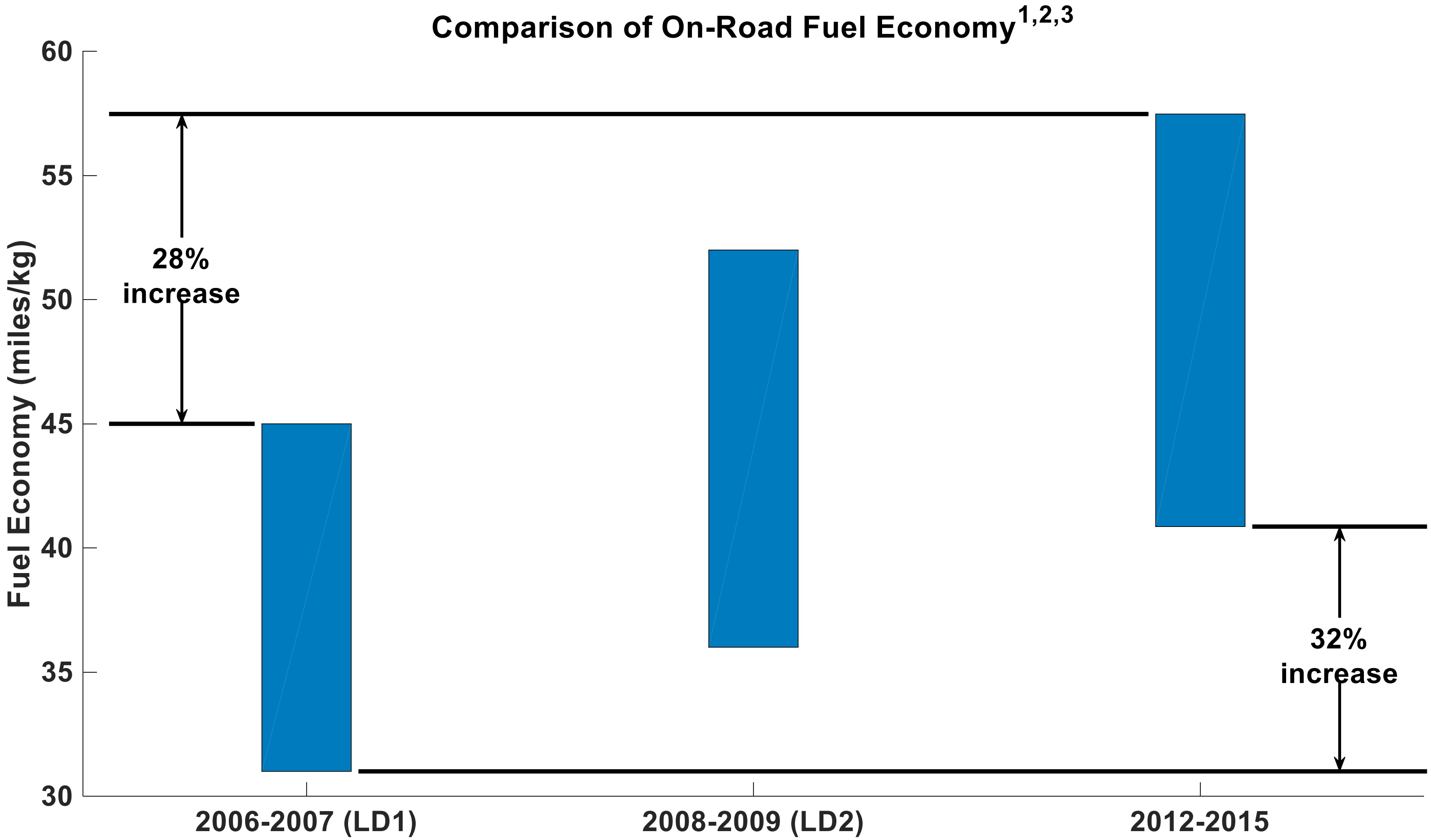
Included Vehicles: All

Accomplishment: Comparison of On-Road Fuel Economy



1. Range bars in the learning demo (LD) represented one data point for OEM's fleet mean. 2012-2015 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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Included Vehicles: All