VII.A.1 Fuel Cell Electric Vehicle Evaluation

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Project Start Date: October 1, 2012
Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Validate hydrogen fuel cell electric vehicles (FCEVs) in a real-world setting.
- Identify current status and evolution of the technology.

Fiscal Year (FY) 2016 Objectives

- Provide a status of FCEV durability compared with the DOE 2020 durability target.
- Analyze real-world fuel economy and range.
- Make results available through online publications, highlights, and presentations.
- Complete two publication cycles (Fall 2015 and Spring 2016).

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(A) Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data

Contribution to Achievement of DOE Technology Validation Milestones

This project contributes to the achievement of the following DOE milestone from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- Milestone 2.3: Validate fuel cell electric vehicles achieving 5,000-hour durability (service life of vehicle) and a driving range of 300 miles between fuelings. (4Q, 2019)

FY 2016 Accomplishments

- Completed two publication cycles of real-world FCEV operation data. The data analyzed have come from 55 vehicles, with model years spanning 2006 to 2012.
- Published new analyses for driving behavior, fueling behavior, fuel economy, emissions, range, and reliability.
- While the 55 vehicles analyzed do not represent all FCEVs on the road today, it is a statistically significant set of data for evaluation with 3,052,000 total miles traveled and 101,400 total fuel cell operation hours. The maximum vehicle odometer is 190,300 miles (approximately 10% of vehicles have passed 100,000 miles), and the maximum hours of fuel cell operation is 5,605.
- Compared current FCEV performance with past data from the Learning Demonstration (LD) phases. The comparisons to the LD project have provided insight into the steady progress made over the last eight years, specifically in fuel cell voltage durability, fuel economy, range, and driving trends. The current values are summarized in Table 1.

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INTRODUCTION

Under FOA-625, the U.S. DOE has funded projects for the collection and delivery of FCEV data to NREL for analysis, aggregation, and reporting. Multiple real-world sites and customers are included in this FCEV demonstration project. This activity addresses the lack of on-road FCEV data and seeks to validate improved performance and longer durability from comprehensive sets of early FCEVs, including first-production vehicles. NREL's objective in this project is to support DOE in the technical validation of hydrogen FCEVs under real-world conditions. This is accomplished through evaluating and analyzing data from the FCEVs to identify the current status of the technology, comparing that status to DOE program targets, and assisting in evaluating progress between multiple generations of technology, some of which will include commercial FCEVs for the first time.

TABLE 1. Current Status against DOE 2020 Targets

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 range (miles) (window sticker)		200–320	—	196–254	103–190
Median on-road distance between fuelings (miles)		123 miles	98	81	56
Fuel economy (mi/kg) (window sticker)		51 (median)	—	43–58	42–57
Fuel cell efficiency at ¼ power	60%	57% (average)	—	53%–59% (max)	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 H_2/kg system)	5.5%	2.5%–3.7%	—	—	2.5%–4.4%
System volumetric capacity (kg H_2/L system)	0.04	0.018–0.054	—	—	0.017–0.025

[a] Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan [1]
[b] Current results are available online [3] (updated May 2016)
[c] National Fuel Cell Vehicle Learning Demonstration Final Report [2]

The project includes six original equipment manufacturers (OEMs): General Motors, Mercedes-Benz, Hyundai, Nissan, Toyota, and Honda. The latter three OEMs were part of one DOE project with Electricore. Up to 90 vehicles are expected to supply data over potentially two phases, with particular attention on fuel cell stack durability and efficiency, vehicle range and fuel economy, driving behavior, maintenance, on-board storage, refueling, and safety. Previous technology validation work on FCEVs and hydrogen infrastructure was performed through the FCEV LD [2], also known as the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project. Some of the current partners were also part of the LD. Those vehicles and technologies are not necessarily the same as the vehicles currently under evaluation even though some of the platforms are the same. Except where referenced or labeled, all of the data reported here are for the current project.

APPROACH

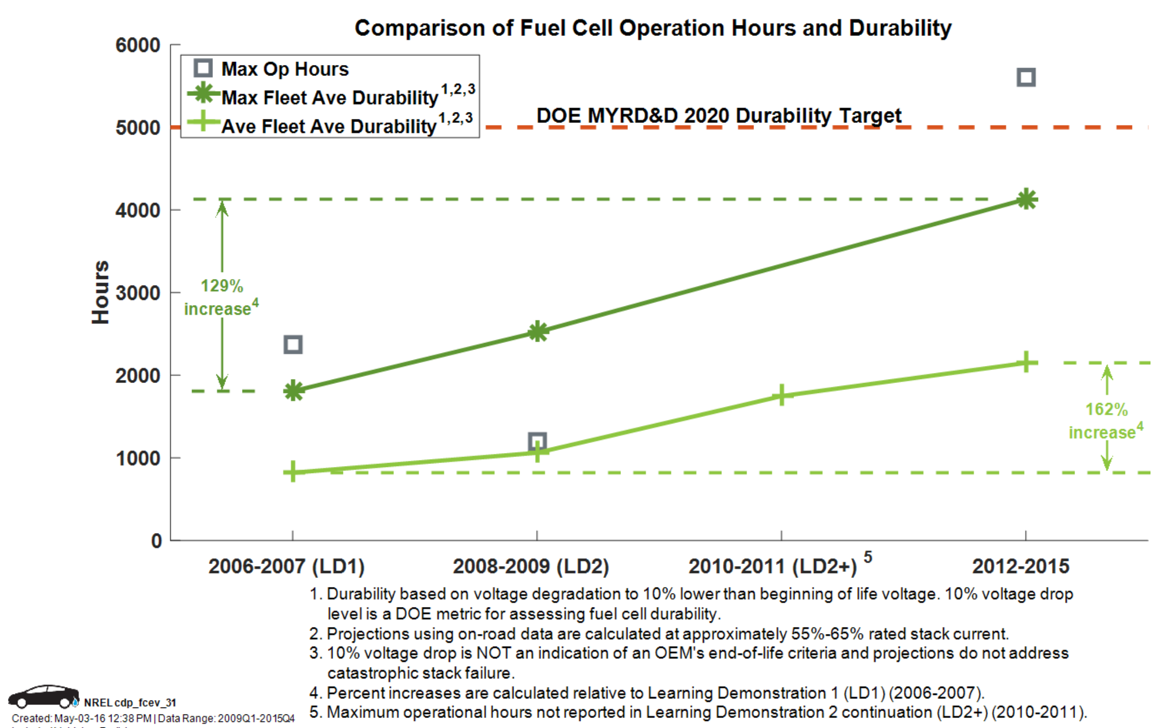
The project's data collection plan builds on other technology validation activities. Operation, maintenance, and safety data for fuel cell system(s) and accompanying infrastructure are collected on site by project partners. NREL receives the data quarterly and stores, processes, and analyzes the data in NREL's National Fuel Cell Technology Evaluation Center (NFCTEC). The NFCTEC is an off-network room with access provided to a small set of approved users. An internal analysis of all available data is completed quarterly and a set of technical composite data products (CDPs) is published every six months. Publications are uploaded to NREL's technology validation website [3] and presented at industry-relevant conferences. The CDPs present aggregated data across multiple systems, sites, and teams in order to protect proprietary data and summarize the performance of hundreds of fuel cell systems and thousands of data records. A review cycle is completed before the CDPs are published. This review cycle includes providing detailed data products of individual system- and site-performance results to the specific data provider. Detailed data products also identify the individual contribution to the CDPs. The NREL Fleet Analysis Toolkit is an internally developed tool for data processing and analysis structured for flexibility, growth, and simple addition of new applications. Analyses are created for general performance studies as well as application- or technology-specific studies.

RESULTS

The current FCEV evaluation analyses include the following categories: durability, deployment (e.g., number of vehicles included), system specifications, range, fuel economy, efficiency, fill performance, reliability, drive and fill behaviors, power and energy management, fuel cell transients (e.g., frequency of rapid increases or decreases in fuel cell power), emissions, and benchmarking against technical targets and typical gasoline vehicle operation. All of the public results are available on NREL's technology validation website [3].

The current evaluation includes 55 vehicles with more than three million miles traveled and more than 101,000 fuel cell operation hours. As of December 2015, 24 vehicles were retired. Many of the OEMs are retiring legacy vehicles because commercial product vehicles are on the road or are soon to be on the road. The durability target for fuel cell systems is 5,000 hours (equivalent to 150,000 miles), which is on par with light-duty vehicle customer expectations and conventional technologies. Two parameters used in this evaluation project to track and validate system durability are projected operation time to 10% voltage degradation and actual operation hours. Fuel cell durability results were initially published in 2006 (the first generation of the LD project). The voltage durability trend from four unique reporting periods is shown in Figure 1. FCEVs in a fleet and a reporting period are of the same generation and design. The operation time to 10% voltage degradation for each stack in a fleet is averaged to determine the fleet voltage degradation value. The average of the fleets' average operation time to 10% voltage degradation in a reporting period is shown in light green and has increased 162% since the first LD period. The maximum of the fleets' average operation time to 10% voltage degradation, 4,130 hours, has increased 129% since the first reporting period in 2006–2007. More than 60% of analyzed stacks have not yet operated beyond the 10% voltage degradation metric.

In a newly released CDP, NFCTEC has evaluated the carbon dioxide (CO_2) and greenhouse gas (GHG [includes CO_2 and the CO_2-equivalent global warming potential of methane, nitrous oxide, volatile organic carbon VOC, carbon monoxide, nitrogen oxides, black carbon, and organic carbon]) emissions of FCEVs versus two baseline vehicles (passenger car and light-duty truck) using the GREET Fuel Cycle Model [4]. Five hydrogen production pathways are evaluated using validated FCEV fuel economy ratings to illustrate the well-to-wheels emissions effects of different pathways and how they compare to baseline gasoline vehicles. The scenarios for hydrogen refueling stations are as follows: (A) central steam methane reforming (SMR) of natural gas for liquid hydrogen delivery, (B) central SMR for gaseous hydrogen delivery, (C) onsite renewable electrolysis, (D) onsite electrolysis with 33% renewable electricity, and (E) onsite electrolysis using California grid mix electricity. These scenarios are evaluated with the min, max, and median FCEV fuel economies reported [5] in the project—40.9 mi/kg, 57.5 mi/kg, and 52.9 mi/kg, respectively—to show a range of emissions for each scenario (note: 1 kg of hydrogen has the same energy content as 1 gallon [3.2 kg] of gasoline). The FCEV scenarios are compared to the emissions of a passenger vehicle and light duty truck using California mix gasoline and the GREET baseline fuel economy values for model year 2015, which



Op – Operation

FIGURE 1. FCEV durability trend and comparison

are 28.8 mpg for a gasoline passenger car and 26.8 mpg for a gasoline light-duty truck (gross weight <6,000 lb). Two baseline gasoline vehicles were chosen to represent the range of body types in the evaluated FCEVs.

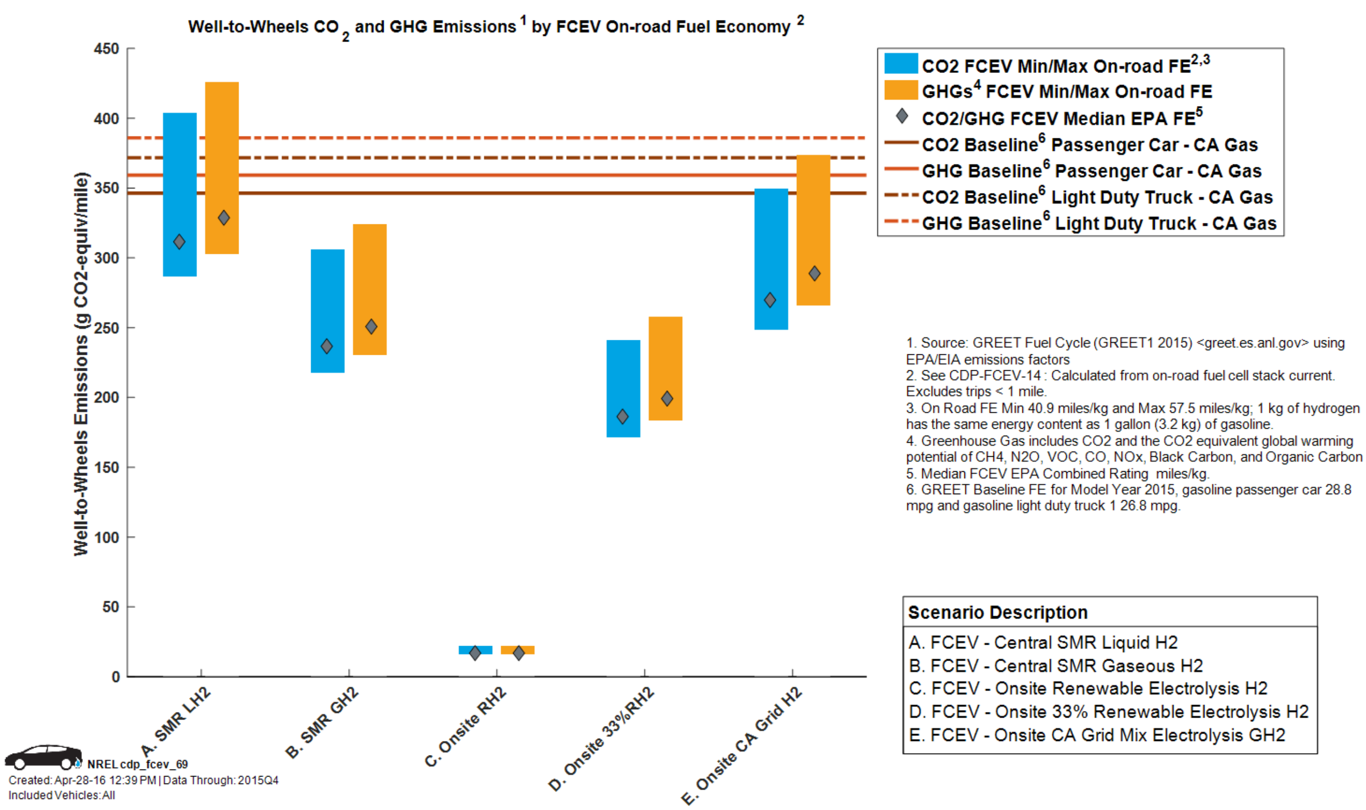
CDP FCEV 69 (Figure 2) shows that, on average, FCEV GHG emissions are 23% lower than that of a baseline gasoline passenger vehicle for the most common hydrogen production and delivery pathway, Scenario B—gaseous hydrogen produced from natural gas at a central SMR plant—and 95% lower for the 100% renewable hydrogen production pathway, Scenario C—onsite electrolysis using 100% renewable electricity. Even partially renewable onsite electrolysis can provide emissions benefits as seen in Scenario D using California's requirements [6] for hydrogen produced from 33% renewables. In this scenario, FCEV GHG emissions are 21% lower than that of FCEVs using hydrogen from average central SMR (Scenario B) and 39% lower than that of the baseline gasoline passenger vehicle.

Figure 3 is a graphic depiction of a study looking at the temperature and pressure limits of 35 MPa and 70 MPa hydrogen fills. More than 16,000 fills were analyzed. The highest concentration of fills were in the preferred (that is, fastest fills within acceptable safety limits) region (shown in green), and the pressure and temperature limits were not exceeded. The temperature and pressure measurements were all taken from the vehicles' on-board storage systems.

Maintenance analysis (Figure 4) shows that three subsystems account for approximately 75% of all maintenance events analyzed; nearly 75% of all maintenance events are filter replacements and coolant top offs. The maintenance events analyzed include maintenance to early model versions that were not specifically designed for commercial-grade maintenance expectations. However, the majority of these maintenance events were relatively simple and only 3.5% of failures occurred on the road. The average maintenance event count and labor time per vehicle both have been decreasing over the last couple of years.

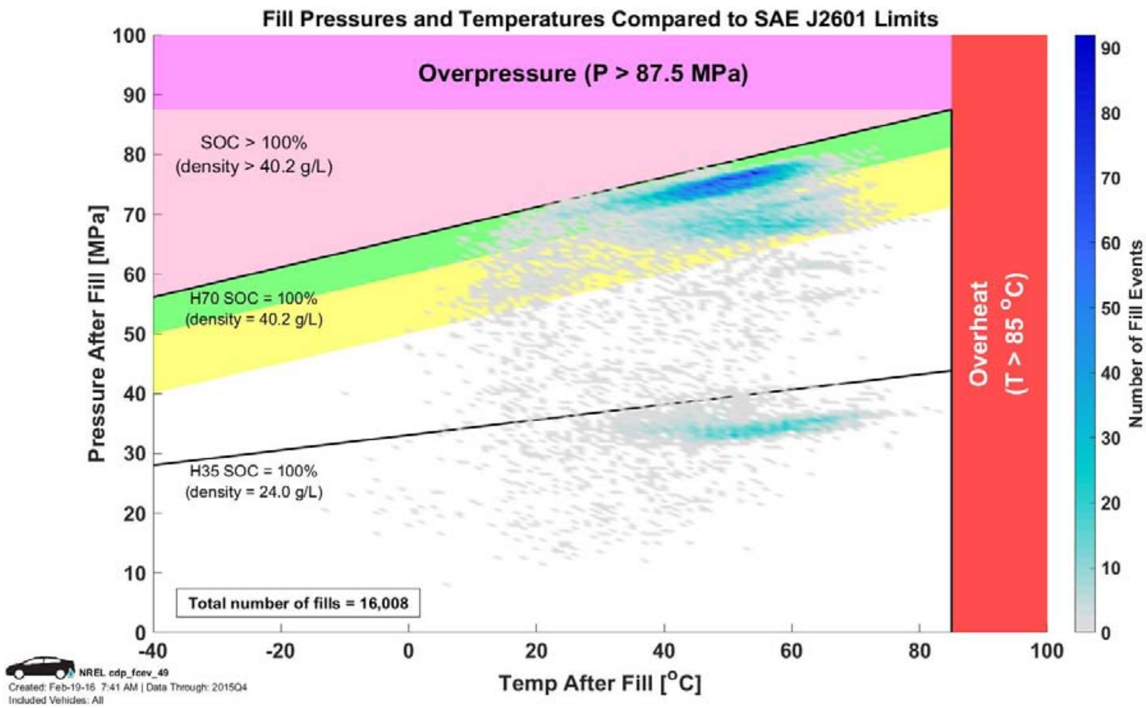
CONCLUSIONS AND FUTURE DIRECTIONS

Over the last 10 years, NFCTEC has completed analysis of 222 on-road vehicles that have accumulated more than 6.3 million miles. The current data analyzed come from 55 vehicles and six OEMs, with model years spanning 2006 to 2012. Fuel cell durability has steadily and significantly improved over the last decade, and on-road fuel economy and actual driving range between fills have also increased over the last 10 years.



EPA – Environmental Protection Agency; FE – Fuel economy; CA – California; VOC – Volatile organic compound

FIGURE 2. GHG emissions comparisons



SOC – State of charge

FIGURE 3. FCEV fill comparison to SAE J2601 temperature and pressure limits

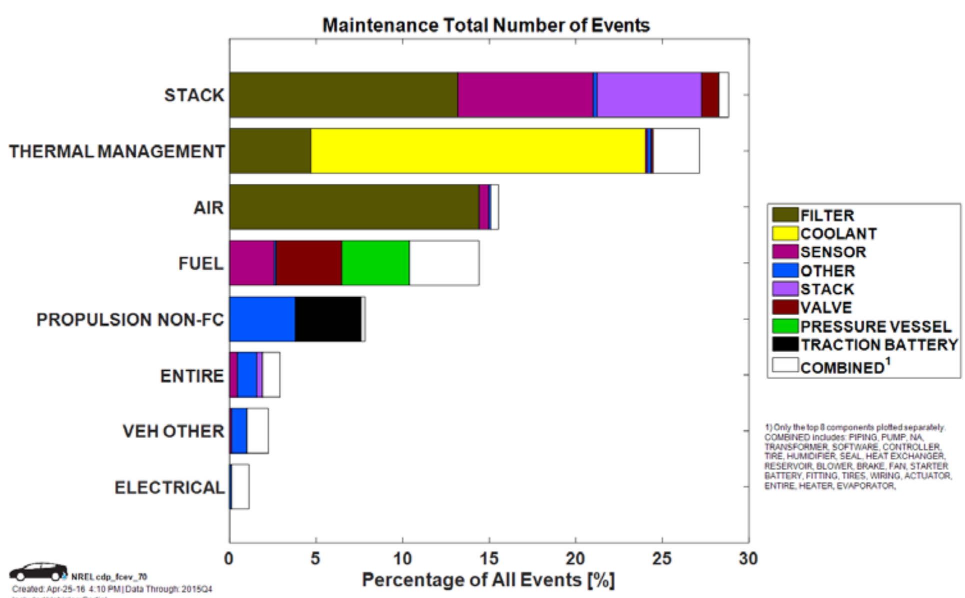


FIGURE 4. FCEV maintenance by system and category

While the 55 vehicles in the current analysis do not represent all FCEVs on the road today, it is a statistically significant set of data for evaluation with more than three million miles traveled, 101,000 total fuel cell operation hours, and 15% of vehicles passing 100,000 miles. The future work includes the following:

- Study the interdependence between FCEV and hydrogen station performance.
- Quantify FCEV benefits based on real-world data.
- Complete a drive cycle analysis to categorize the different FCEV drive cycles for comparison with

standard drive cycles and supply data to the research and development community for fuel cell testing.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. J. Kurtz, S. Sprik, C. Ainscough, G. Saur, and M. Jeffers, "Fuel Cell Electric Vehicle Evaluation," presented at the Advanced Automotive Battery Conference, Detroit, Michigan, June 2016.

2. J. Kurtz, S. Sprik, C. Ainscough, G. Saur, and M. Jeffers, "Fuel Cell Electric Vehicle Evaluation: 2016 Annual Merit Review," presented at the 2016 DOE Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., June 2016.

3. "Transportation Big Data: Unbiased Analysis and Tools to Inform Sustainable Transportation Decisions," NREL/BR-5400-66285, Golden, CO: National Renewable Energy Laboratory, June 2016.

4. J. Kurtz, S. Sprik, C. Ainscough, G. Saur, and M. Jeffers, "Spring 2016 FCEV Evaluation Results," Golden, CO: National Renewable Energy Laboratory, May 2016.

5. J. Kurtz, S. Sprik, C. Ainscough, G. Saur, and M. Jeffers, "Fuel Cell Electric Vehicle Evaluation," presented via webinar at the Interagency Working Group Meeting, Washington, D.C., December 2015.

6. J. Kurtz, S. Sprik, C. Ainscough, and G. Saur, "Fuel Cell Electric Vehicle Evaluation," excerpt from the 2015 DOE Hydrogen and Fuel Cells Program Annual Progress Report, December 2015.

7. S. Sprik and J. Kurtz, "Technology Validation of Fuel Cell Vehicles and Infrastructure," presented at the Fuel Cell Seminar 2015, Los Angeles, California, November 2015.

8. J. Kurtz and S. Sprik, "Fall 2015 FCEV Evaluation Results," Golden, CO: National Renewable Energy Laboratory, November 2015.

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1. *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan*, Fuel Cells chapter, Table 3.4.3 Technical targets for automotive application, Washington, D.C.: U.S. Department of Energy, 2012, accessed October 13, 2014, http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22.

2. K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL/TP-5600-54860. Golden, CO: National Renewable Energy Laboratory, July 2012, http://www.nrel.gov/hydrogen/pdfs/54860.pdf.

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4. "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model," GREET Fuel Cycle (GREET 1) 2015 using EPA/EIA emissions factors, Argonne National Laboratory, https://greet.es.anl.gov.

5. "Fuel Cell Electric Vehicle Evaluations: Composite Data Products," CDP FCEV 14: Average Vehicle Fuel Economy, National Renewable Energy Laboratory, http://www.nrel.gov/hydrogen/proj_fc_vehicle_evaluation.html.

6. California Senate Bill 1505, September 2006, http://www.leginfo.ca.gov/pub/05-06/bill/sen/sb_1501-1550/sb_1505_bill_20060930_chaptered.pdf.