Fuel Cell Electric Vehicle Driving and Fueling Behavior

Jennifer Kurtz, Sam Sprik, Genevieve Saur, and Shaun Onorato

National Renewable Energy Laboratory

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Technical Report
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Acknowledgments

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List of Acronyms

CDP	composite data product
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FCEV	fuel cell electric vehicle
FCTO	Fuel Cell Technologies Office
NHTS	National Household Travel Survey
LD	Learning Demonstration
NFCTEC	National Fuel Cell Technology Evaluation Center
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer

Summary

The objectives of this project are to validate hydrogen fuel cell electric vehicles in real-world settings and to identify the current status and evolution of the technology. The analysis objectively assesses progress toward targets and market needs defined by the U.S. Department of Energy and stakeholders, provides feedback for early-stage hydrogen research and development, and publishes results for key stakeholder use and investment decisions. Fiscal year 2018 objectives focused on analysis and reporting of fuel cell electric vehicle driving range, fuel economy, drive and fill behaviors, durability, fill performance, and fuel cell performance. This report specifically addresses the topics of driving range, fuel economy, drive and fill behaviors, and fill performance.

Keywords: fuel cell, hydrogen, FCEV, driving range, fuel economy, fill performance, drive and fill behaviors, NFCTEC, National Fuel Cell Technology Evaluation Center, National Renewable Energy Laboratory, NREL

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Introduction and Background

The National Renewable Energy Laboratory's (NREL's) objective in this project is to support the U.S. Department of Energy (DOE) in the technical evaluation of hydrogen fuel cell electric vehicles (FCEVs) under real-world conditions. This is accomplished through evaluating and analyzing data from the FCEVs to identify the current status of the technology, compare it to DOE program targets, and assist in evaluating progress between multiple generations of FCEV technology. DOE funds projects for the collection and delivery of data to the National Fuel Cell Technology Evaluation Center (NFCTEC) at NREL for analysis, aggregation, and reporting. The effort has been ongoing since the U.S. Department of Energy Fuel Cell Technologies Office Learning Demonstration project began in 2005.

The project partners included six original equipment manufacturers (OEMs): General Motors, Honda, Hyundai, Mercedes-Benz, Nissan, and Toyota. Three OEMs (Nissan, Toyota, and Honda) submitted data under one DOE project awarded to Electricore Inc. Each project partner had more than one vehicle included in this evaluation project, referred to as a FCEV fleet, for a total of six fleets. These vehicles are a mixture of pre-commercial and commercial vehicles, operated within fleets and by individual drivers, with model years from 2005 to 2012. The Toyota Mirai and Hyundai Nexo were not included in the analysis due to lack of data contribution and/or model year not being available during the evaluation timeline. The OEMs supplied on-road vehicle data to NREL for evaluation in the following categories: fuel cell stack 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), benchmarking against technical targets and typical gasoline vehicle operation, maintenance, on-board storage, and safety. The on-road vehicle data were supplied to NFCTEC at least every 3 months. More project details and background information can be found in the overview report (Kurtz et al. 2018).

Evaluation metrics are derived from the DOE Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (FCTO 2015), specifically in the categories of fuel cell durability, efficiency, specifications, and hydrogen storage. These metrics are also used to derive some of the composite data products (CDPs) contained in this report. The analysis also utilizes National Household Travel Survey (NHTS) data collected by the Federal Highway Administration under the U.S. Department of Transportation. In addition, typical gasoline station fueling data and trends from a major gasoline supplier was used to compare against FCEV fueling data.

This report specifically addresses the topics of driving range, fuel economy, drive and fill behaviors, and fill performance. Data from the current technology validation project were incorporated into the results of previous vehicle technology validation projects (Wipke et al. 2012), as the project has been ongoing since 2005 in various iterations (FCEV Learning Demonstration, also referred to as the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project). The current FCEV technology advancements and technology generations are varied between the OEMs due to their individual development and production schedules.

Deployment

As of spring 2018, more than 230 vehicles from a variety of manufacturers generated more than 7 million miles of data that contributed to this analysis effort. Figure 1 depicts the progression of vehicle count and cumulative miles generated since 2006. The gap in data indicates the dates where the program transitioned from the Learning Demonstration to the current evaluation project and data were not being reported.

The majority of vehicles included in this study were early-generation demonstration and pre-production models dating back to 2006. Data from the latest generation of commercially available FCEVs were not included in the analysis due to restrictions in contract or a lack of a contributing data partner.

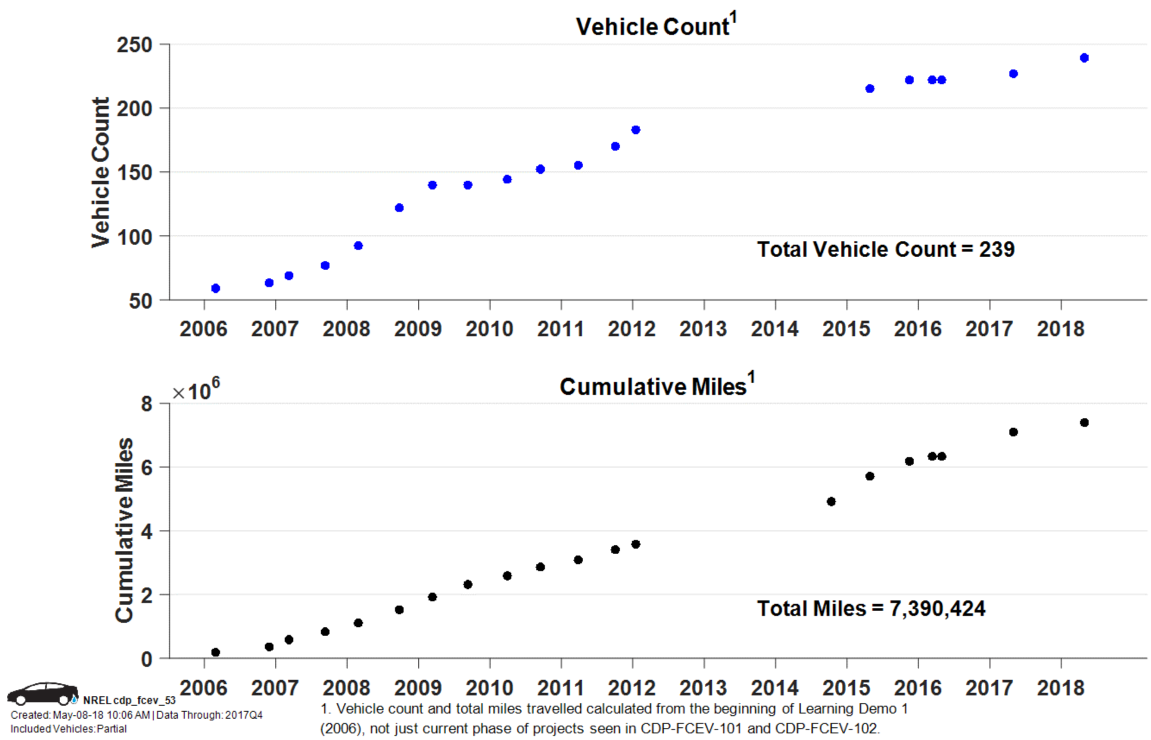

Figure 1. Total vehicle count and cumulative miles driven, including legacy data (CDP-FCEV-53)

Vehicle Range

FCEVs have both range and fueling time advantages over other alternative zero-emission vehicles. Range and fueling rates of newer-generation FCEVs are comparable to that of conventional gasoline-powered vehicles, making this an important evaluation topic. There are three considerations studied for an evaluation of FCEV range: the U.S. Environmental Protection Agency (EPA) determined fuel economy (Fueleconomy.gov 2018), actual on-road fuel economy, and driving behaviors between fueling. The data collected for the analysis incorporate a variety of driving styles, driving distances, routes, and routines provided and determined by the vehicle manufacturers. Fueling station availability and location also contribute heavily to fueling behaviors.

Table 1 lists the EPA-rated fuel efficiencies (miles per gallon of gasoline equivalent [MPGe]) and vehicle driving ranges for some of the FCEVs included in the six vehicle OEM fleets. It is also assumed that one gallon of gasoline (3.2 kg) has the same energy content as 1 kg of hydrogen for fuel efficiency conversions. Vehicle driving range and fuel efficiency can vary greatly with driving style and usage. FCEV manufacturers determined the nature, manner, or appropriate drive cycle to operate their vehicles.

Table 1. Published Vehicle Range and Miles per Gallon of Gasoline Equivalents

Vehicle Manufacturer	Model	Range (mi)	Fuel Economy (MPGe combined)
General Motors[a]	Equinox Fuel Cell	190	39
Honda[b]	2008 FCX Clarity	240	59
Hyundai[c]	Tucson FCEV/ix	265	50
Mercedes-Benz[d]	F-Cell	190	54
Nissan[e]	X-Trail (2005) FCEV	311	Not listed
Toyota[f]	Highlander FCHV-adv	491	68
Production and Pre-Production Models Not Included in Study			
Honda[g]	Clarity Fuel Cell	366	68
Hyundai[h]	2019 Nexo/Nexo Blue	354/380	57/61
Mercedes-Benz[i]	2019 GLC F-Cell	271 est.	Not listed
Toyota[j]	Mirai	312	67

[a] Hydrogen Motors 2006

[b] Honda Worldwide 2012

[c] Hyundai 2011

[d] Mercedes-Benz 2012

[e] Nissan Motor Corporation 2005

[f] Wipke, Anton, and Sprik 2009

[g] American Honda Motor Co. 2018

[h] Hyundai 2018

[i] Mercedes-Benz 2017

[j] Toyota 2018

In this evaluation, vehicle range was calculated from on-road fuel economy data and individual vehicle hydrogen storage tank capacity. The on-road fuel economy data include vehicle fill date, time, amount, and miles driven. As shown in Figure 2, the on-road vehicle range of the fleet demonstrates that some of the vehicles are being operated to their maximum driving range. The window sticker driving range varies from 200 to 320 miles and includes multiple types of FCEVs (small sedans to sport utility vehicles) and vehicle generation models that go back to

2006. Maximum driving range is limited by individual driving conditions, driving behaviors, and range anxiety/availability of hydrogen fueling infrastructure. The large percentage of vehicles in the 175–200 mile range are a result of older vehicles in the fleet. As the technology matures, newer vehicles will achieve higher ranges above 250 miles. The window sticker range for all currently available commercial FCEVs exceeds 250 miles with some exceeding 300 miles.

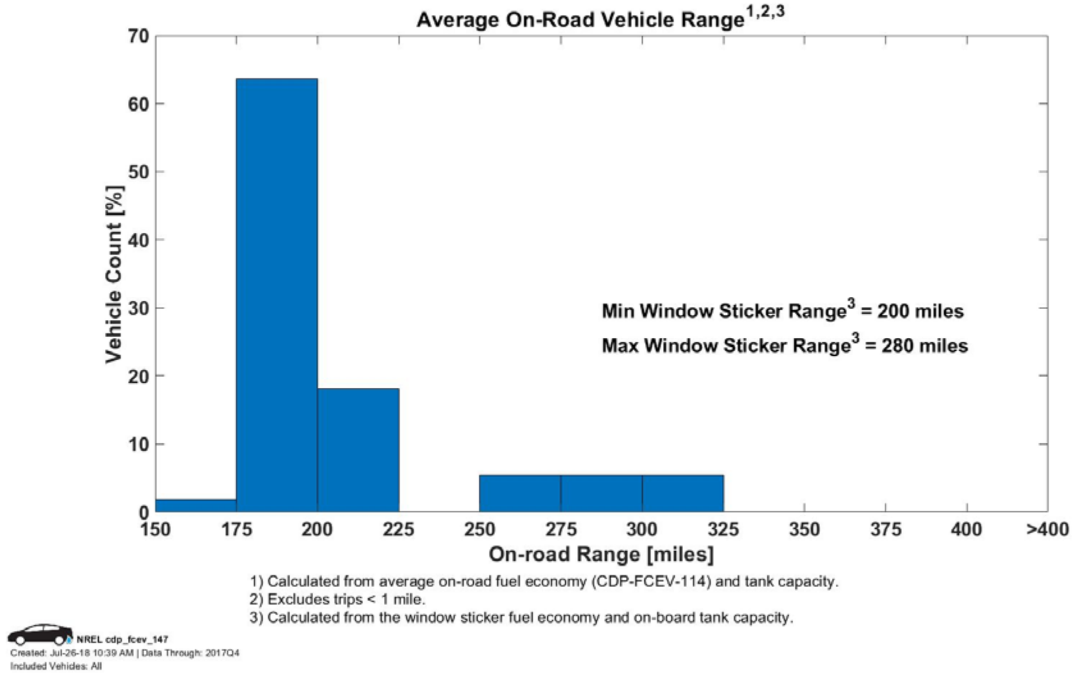

Figure 2. Average on-road vehicle range (CDP-FCEV-147)

The actual range between fills for fuel cell vehicles is currently influenced by the availability of fueling infrastructure and driving behaviors. Two major factors considered for station access are station location (convenience) and confidence in station availability (i.e., whether the station can complete a fill when the driver needs it). Drivers may choose to fill sooner than needed to ensure they have adequate driving range; therefore, the number of days between fueling becomes an important analysis topic for planning hydrogen infrastructure demands. Figure 3 organizes the distribution of actual driving distance between fills to days between fueling. Some vehicles in the test fleet are conducting accelerated mileage testing and fuel daily, and trips less than one mile were excluded from the study. The analysis reveals that FCEVs in the fleet are fueling after 1–4 days at 200 miles or less. Only 3.6% of the fleet fueled after 14 days or more. The days between fueling are expected to increase as more commercially available vehicles enter the market, the technology advances, and more hydrogen stations become available.

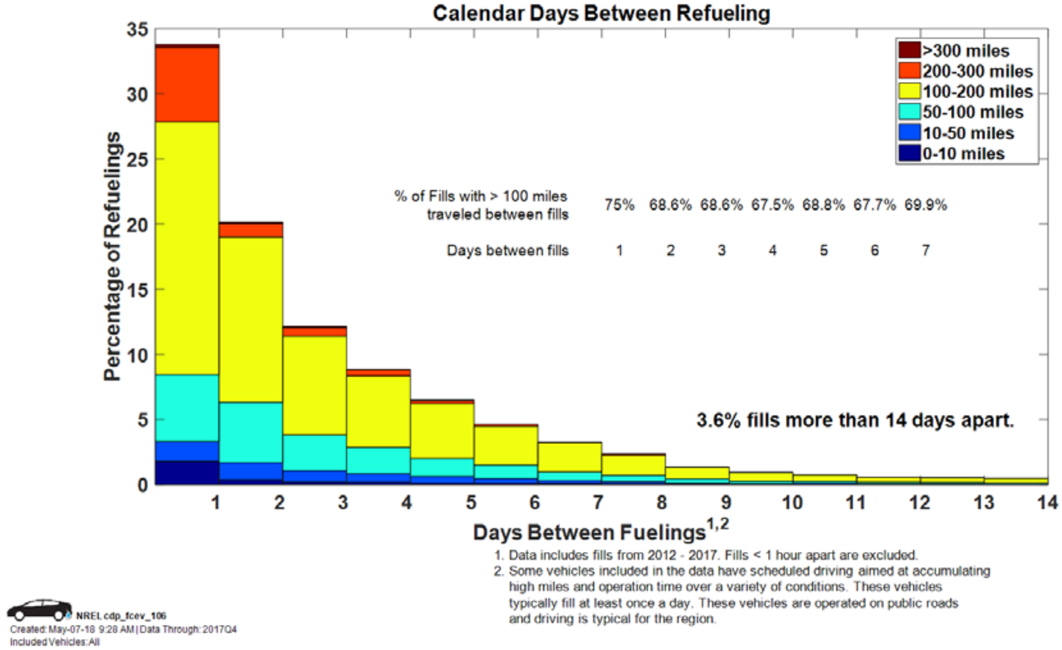

Figure 3. Actual distance driven between fueling, including legacy data (CDP-FCEV-106)

Fuel Economy

Fuel economy was measured from a combination of on-road fuel cell stack current and EPA fuel economy ratings. The results shown in Figure 4 aggregate the average on-road fuel economy to the percentage of vehicles being tested. The analysis excludes trips less than one mile and provides an EPA combined city/highway rating. The average median fuel efficiency for the FCEV fleet was 51 mi/kg (51.6 mpge) with an average range of 34–57.5 mi/kg (34.4–58.1 mpge). The on-road fuel economy for the Learning Demonstration fleet ranged from 31–45 mi/kg hydrogen for Gen 1 and 36–52 miles/kg hydrogen for Gen 2 (Reference Figure 5). In comparison, the average gasoline-powered car from 2013 returned 27.6 mpg in EPA tests, demonstrating that FCEVs almost double the average on-road fuel efficiency (and this includes multiple vehicle platforms from sedan to sport utility vehicle). The average actual on-road fuel economy of the FCEV fleet was slightly lower than the EPA-determined “window sticker” values, as is true with most conventionally powered vehicles on sale today.

The overall on-road fuel economy of the entire fleet as a function of average trip speed and trip length also was examined. As shown in Figure 6, the average trip speed directly influences on-road fuel economy. The data indicate that fuel economy peaks around 25 mph with an average fuel efficiency of 51 mi/kg (doubling from ~5 mph) and begins to drop after speeds greater than 45 mph.

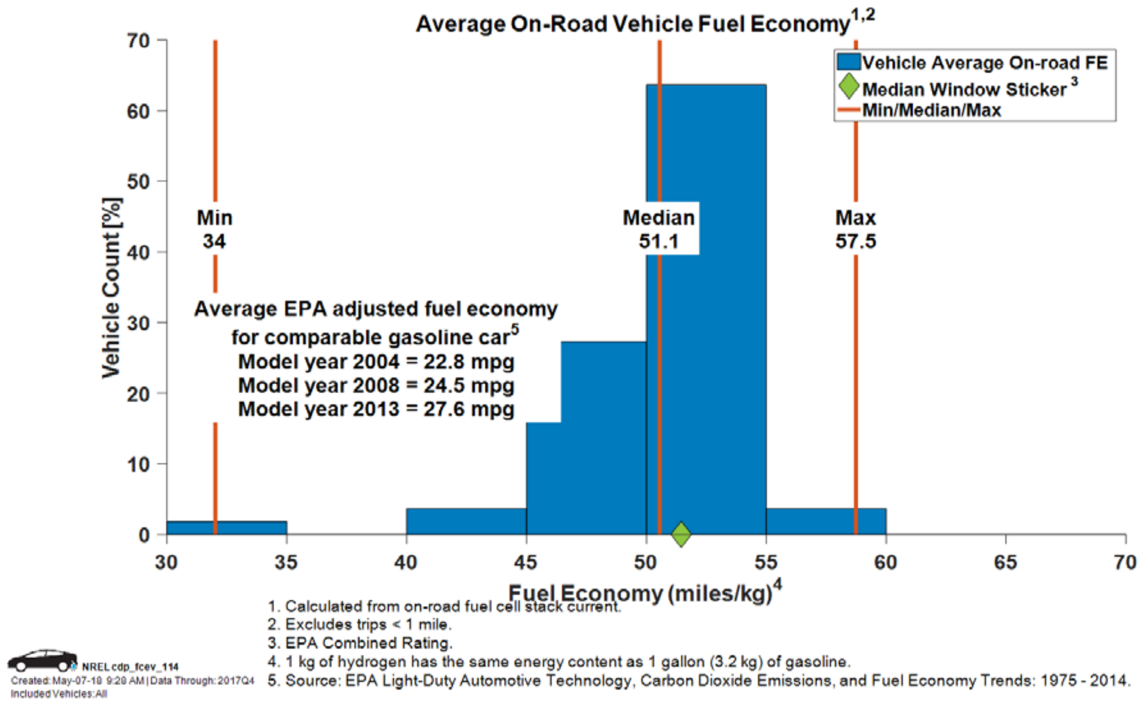

Figure 4. Average on-road vehicle fuel economy (CDP-FCEV-114)

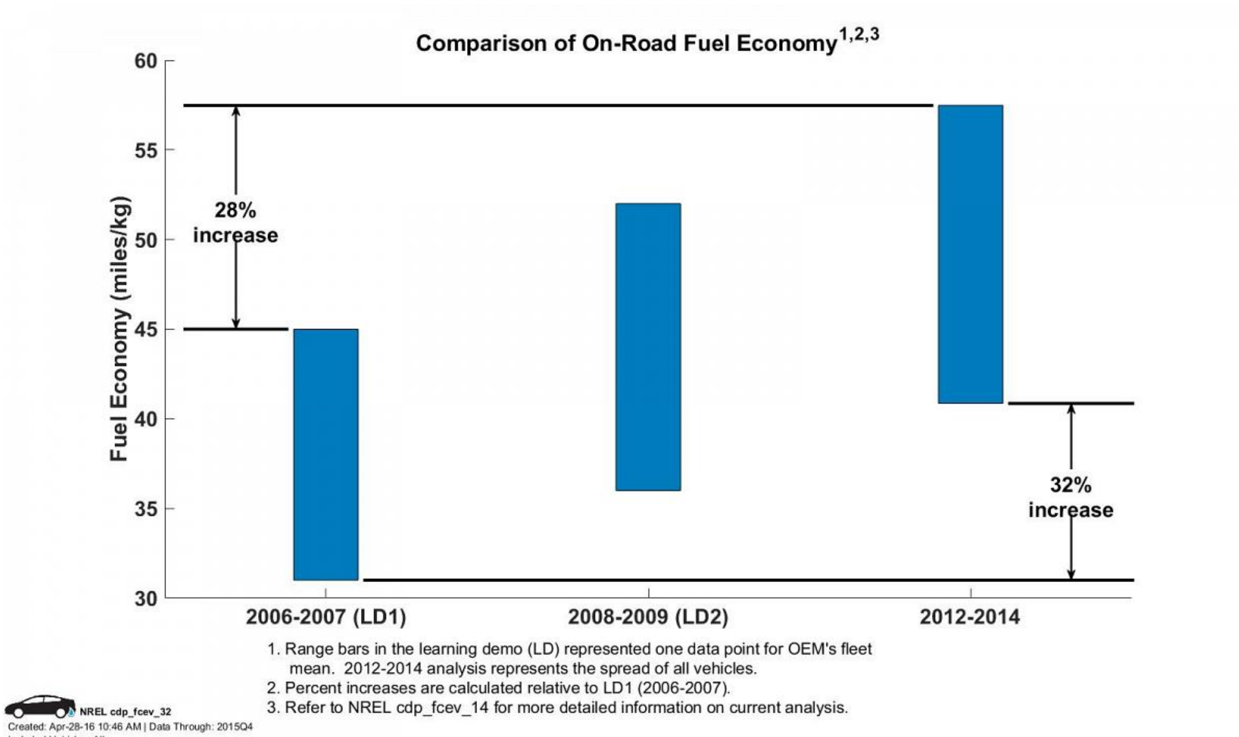

Figure 5. On-Road Fuel Economy Trends (CDP-FCEV-32)

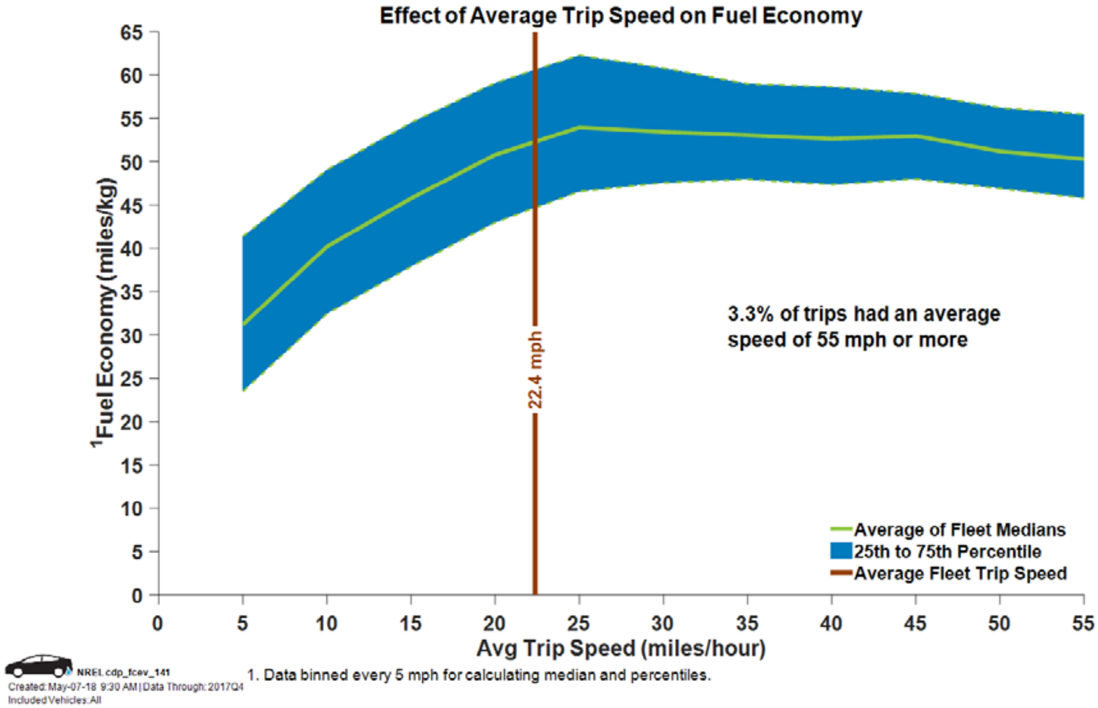

Figure 6. Effect of average trip speed on fuel economy (CDP-FCEV-141)

Fueling Behavior

FCEVs offer a driving and fueling experience similar to that of conventional gasoline-powered vehicles. Manufacturers and stakeholders seek to understand if the vehicles are being utilized in the same manner as conventional cars or if their usage is being too "controlled" to match typical driving behaviors. Usage data for FCEV driving and fueling events for both time of day and day of the week were compared to typical NHTS gasoline-powered-car usage data[1] (NHTS 2009) and to a typical gasoline station profile derived from Chevron usage data[2] (Chen 2008).

Figure 7 and Figure 8 show drive events by time of day and by day of the week for the FCEV fleet. A total of 177,428 driving events were recorded and 75% of those trips occurred between 6 a.m. and 7 p.m. The data indicate that the FCEVs operating in the fleets are being driven in the same manner as conventional gasoline-powered cars. FCEV usage was slightly less during both morning and evening commute hours and there was less overall usage on Fridays and Saturdays. This could be a result of the on-road testing protocols and driving schedules created by each fleet operator and a large percentage of hired drivers during weekdays.

Similar trends are observed for fueling events by time of day and by day of the week. The FCEV fleet generated 18,568 fueling events and 75% of the fills occurred between 6 a.m. and 6 p.m. Figure 9 and Figure 10 show fueling trends by time of day and by day of the week. The data indicate that the FCEV fueling profiles are similar to that of conventional gasoline-powered cars, with some variation that is likely due to on-road testing protocols and driving schedules created

[1] The NHTS data include car, truck, van, and sport utility vehicle day trips for the U.S. market in the year 2009.
[2] Friday Chevron profile.

by each fleet operator. The fleets generally fueled more during the weekdays while on-road testing occurred and less during the weekends when vehicles were not being operated as frequently. Fueling events by time of day show that FCEVs generally followed the gasoline station profile, but the vehicles fueled more at the start of the workday and less during the working hours. The typical rush hour fueling peak occurred at the end of the workday for the FCEV fleet followed by an unusual peak at 8 p.m. that may be due to testing protocols.

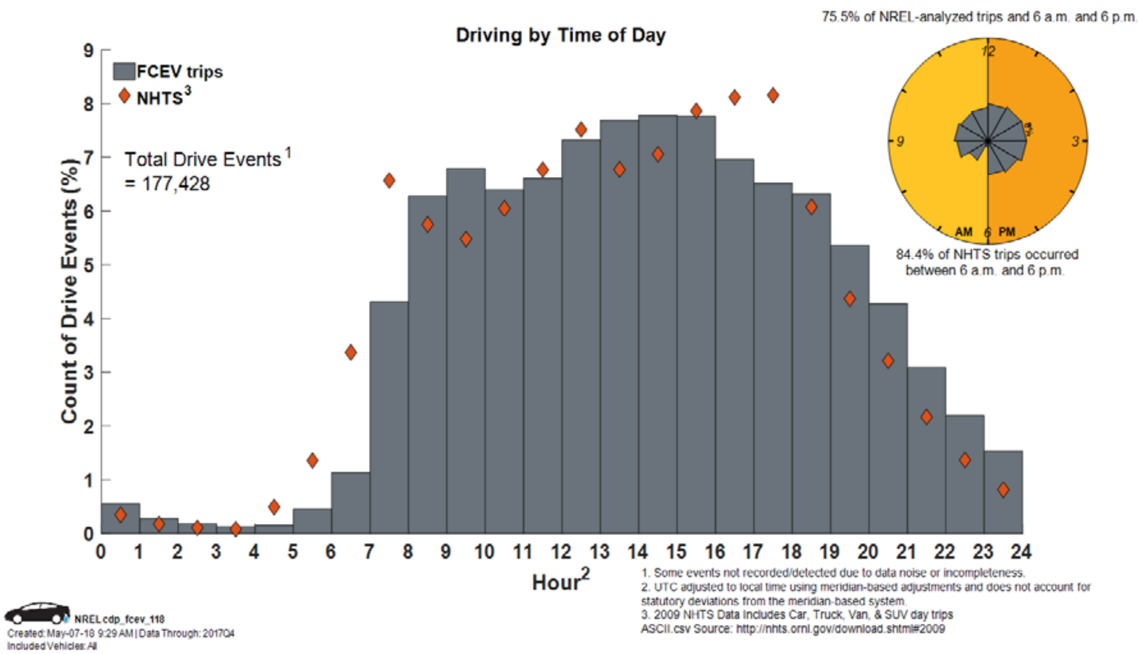

Figure 7. FCEV driving by time of day (CDP-FCEV 118)

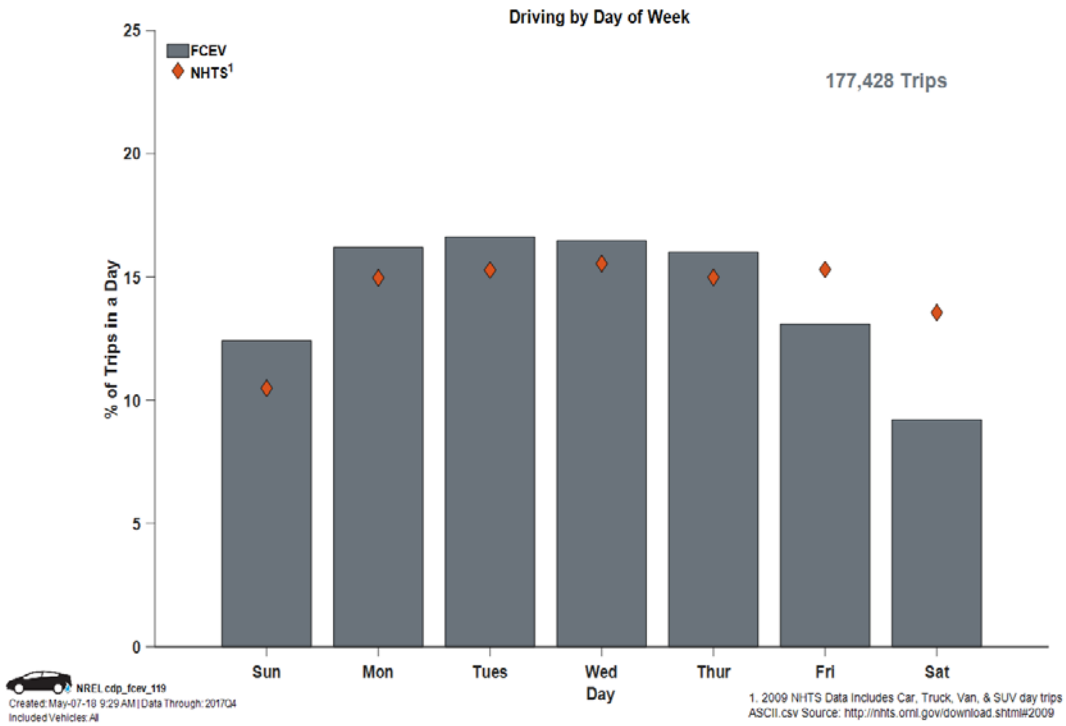

Figure 8. FCEV driving by day of the week (CDP-FCEV 119)

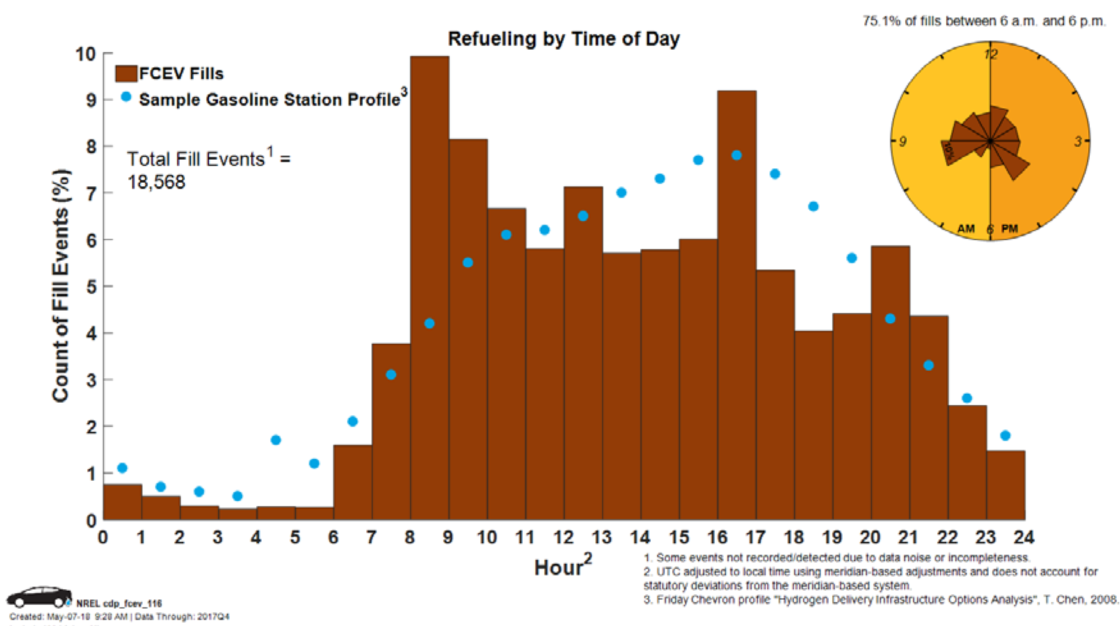

Figure 9. Fueling by time of day (CDP-FCEV 116)

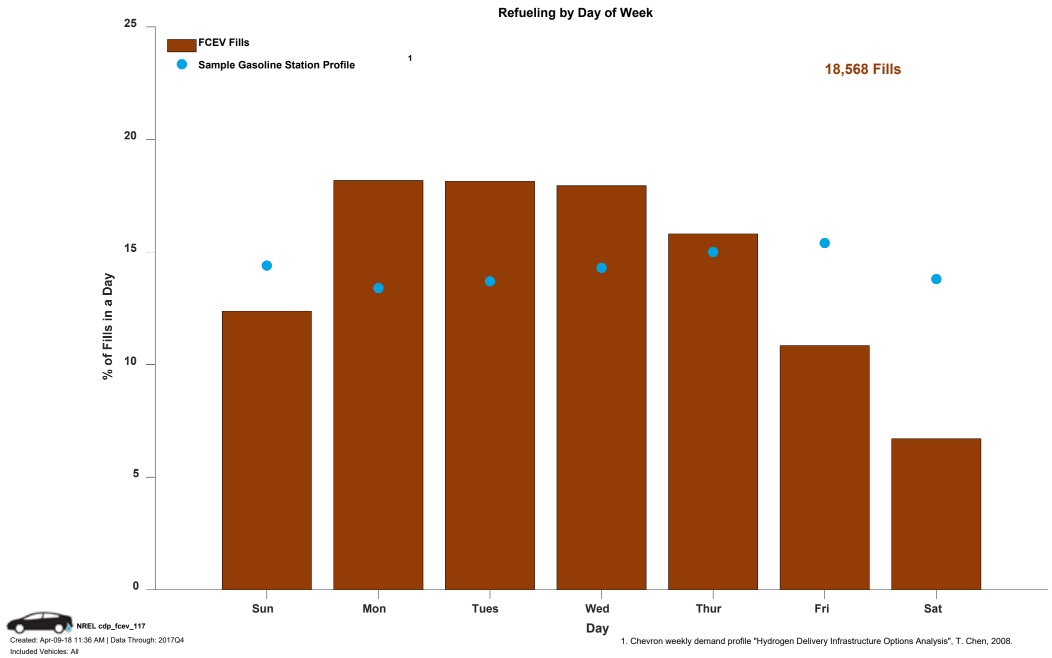

Figure 10. Fueling by day of the week (CDP-FCEV 117)

Fill Performance

Vehicle OEMs collect data on hydrogen fill performance to determine the quality of hydrogen fills from the vehicle as well as the hydrogen station side. The data are also used to determine whether the fills are in compliance with SAE standards (SAE J2601 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles). Fill performance data are of interest to a wide spectrum of stakeholders outside OEMs—station operators, federal, state, and local government, and safety officials utilize these data to help steer codes and standards development. Variations in the trend data also point out potential areas for investigation as to why the quality of certain fueling events was poor.

Figure 11 shows fill pressures and temperatures in comparison to SAEJ2601 standards for 18,568 fueling events. Fill events are denoted by grey markings that darken to blue with increased density of fills. Information was collected on both 70 MPa fills and 35 MPa fills. More data points exist for 70 MPa as OEMs have moved to this pressure as the standard over 35 MPa. The results show that a large density of fills are being completed in the optimal temperature and pressure range within the zone of 100% state of charge (SOC). As seen in the chart there were no extraordinary fueling events within the overpressure zone or the overheating zone, indicating strong compliance with SAE standards and safety. However, the data show a large degree of variation of underperformed fill events. These events could either be related to issues associated with the vehicle or the hydrogen station. The trends indicate that more work is required to ensure vehicles are receiving fills closer to the full state of charge level.

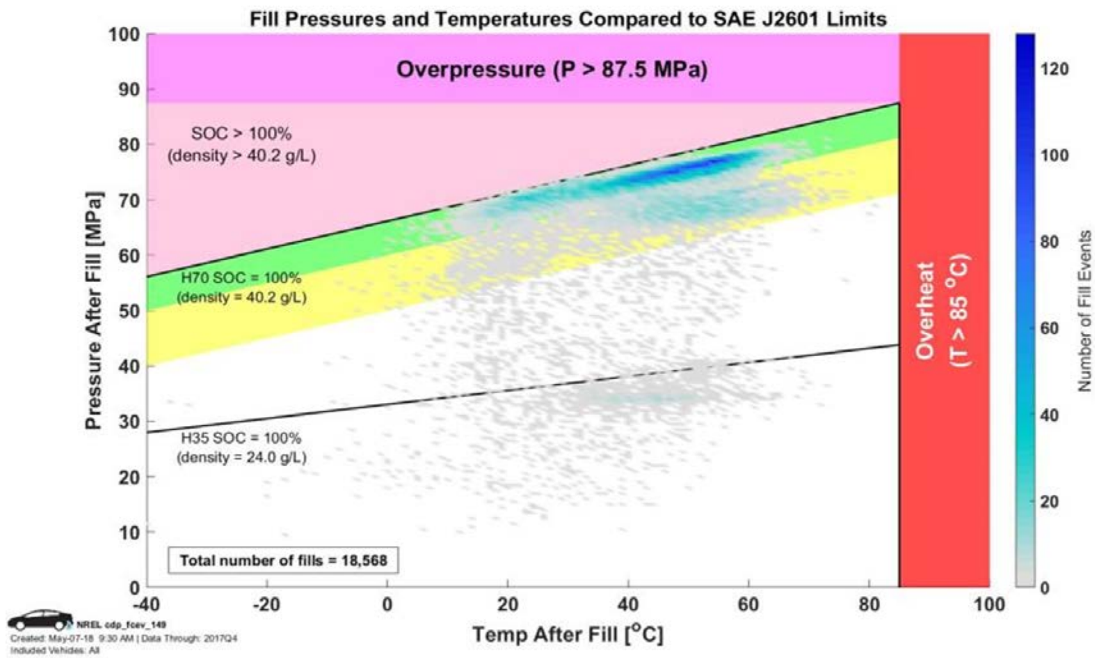

Figure 11. Fill pressures and temperatures compared to SAEJ2601 (CDP-FCEV 149)

Figure 12 and Figure 13 specifically look at vehicle tank temperatures and pressures after fill events. The data show that both pressure and temperature of the hydrogen storage tanks are below the maximum limits set by SAEJ2601. This demonstrates that all vehicles within the tested fleet are operating within the appropriate safety standards and that no notable events occurred.

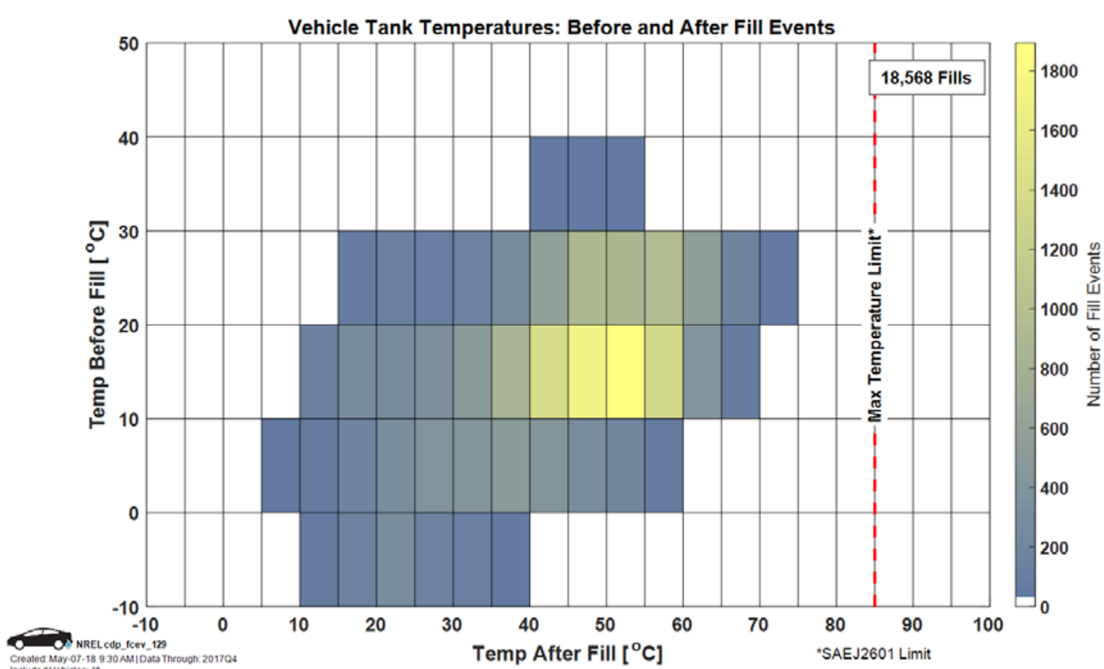

Figure 12. Vehicle tank temperature: before and after fill events (CDP-FCEV 129)

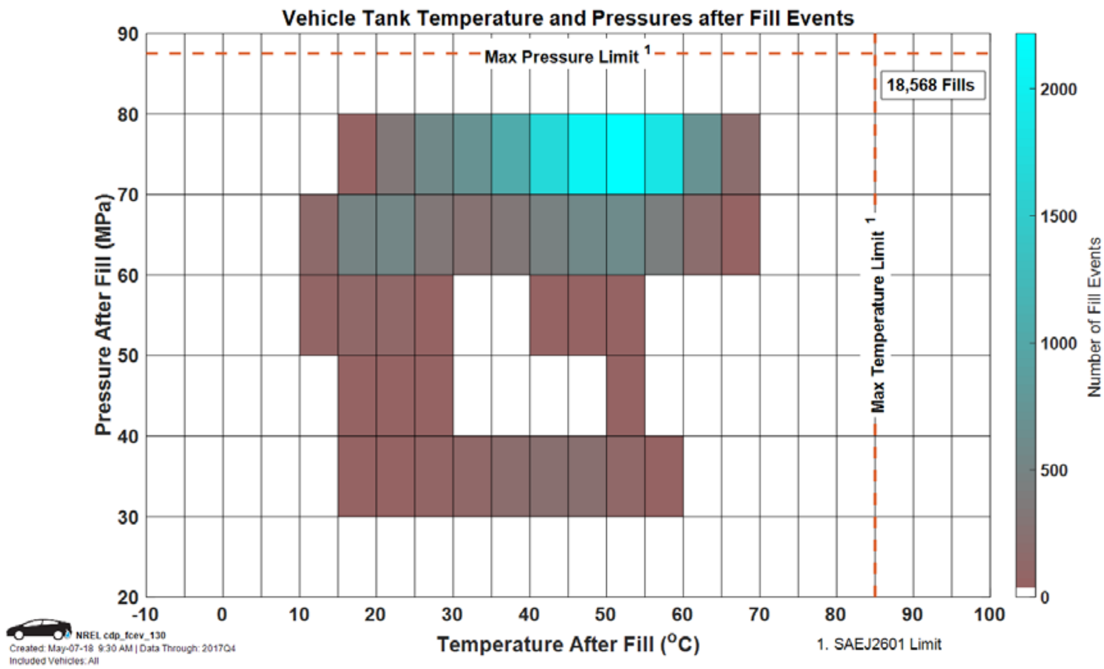

Figure 13. Vehicle tank temperature and pressure after fill events (CDP-FCEV 130)

Conclusion

Through 12 years of real-world validation NREL has evaluated 230 deployed vehicles traveling 7.4 million miles of second-by-second data delivered and published more than 100 CDPs to communicate the technical results to a broad audience of stakeholders. This project addressed the critical need for data analytics to inform both early-stage R&D and commercial readiness of vehicle and station technologies. Detailed data products were sent to each contributing data partner and informed vehicle manufacturers how they compared to the overall industry performance, which supported internal R&D decisions related to increased range, fuel economy, performance, and usability. Results have also been used to inform Technical Teams[3] on progress against key technologies and identify gaps.

From the data, NREL observed that FCEVs are on average achieving double the fuel economy of conventional gasoline-powered cars. In addition, driving range has improved and been demonstrated over 250 miles for pre-production FCEV models. The currently available commercial FCEVs exceed 300 miles. FCEVs have also demonstrated safe operation within industry adopted standards. FCEVs are also being used and fueled in the same manner as conventional gasoline powered cars are, which provides detailed data for hydrogen infrastructure utilization and demand planning. NREL is utilizing the fueling data to develop a model for predictive fueling demand that can be integrated with hydrogen stations for operation and control improvements as well as optimization. The similarity in driving times and trends help support the predictive hydrogen refueling demand. The on-board tank fueling data support understanding of station fueling performance from the perspective of the vehicle and are used to understand the actual range of tank temperatures during the expected extreme temperature conditions at a fill.

FCEVs have advanced rapidly in recent years, and as the automotive OEMs have released commercially available FCEV models. Performance and durability data generated during the technology validation project were crucial in validating DOE targets but also helped to update long-term targets and drive future research and development needs leading to more robust FCEVs.

NREL's website[4] will continue to be the primary repository for NFCTEC's hydrogen fuel cell vehicle and infrastructure analysis results, as well as results from evaluation of other hydrogen components and systems.

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[3] United States Council for Automotive Research LLC, https://uscar.org

[4] https://www.nrel.gov/hydrogen/technology-validation.html

References and Publications

For the full list of published CDPs, please see NREL's website at https://www.nrel.gov/hydrogen/fuel-cell-electric-vehicle-cdps.html.

American Honda Motor Co., Inc. 2018. "Clarity Fuel Cell." https://automobiles.honda.com/clarity-fuel-cell.

Chen, Tan-Ping. 2008. "Hydrogen Delivery Infrastructure Options Analysis." Friday Chevron Profile. Nexant, Inc.

FCTO (Fuel Cell Technologies Office). 2015. *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan*. Washington, DC: U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22.

Fueleconomy.gov. 2018. "Compare Fuel Cell Vehicles." U.S. Department of Energy and U.S. Environmental Protection Agency. https://www.fueleconomy.gov/feg/fcv_sbs.shtml.

Honda Worldwide. 2012. "FCX Clarity: Specifications." http://world.honda.com/FCXClarity/specifications/index.html.

Hydrogen Motors. 2006. "Chevrolet Equinox Fuel Cell (2006)." www.hydrogen-motors.com/chevrolet-equinox-fuel-cell.html.

Hyundai. 2018. "Hyundai Nexo: The Next-Generation Fuel Cell Vehicle." https://www.hyundaiusa.com/nexo/index.aspx.

Hyundai. 2011. "Hyundai Unveils Tucson ix Hydrogen Fuel Cell Electric Vehicle at Fuel Cell Hydrogen Energy 2011." Press release. https://www.hyundai.com/worldwide/en/about-hyundai/news-room/news/hyundai-unveils-tucson-ix-hydrogen-fuel-cell-electric-vehicle-at-fuel-cell-hydrogen-energy-2011-0000001187.

Kurtz, Jennifer, Sam Sprik, Genevieve Saur, and Shaun Onorato. 2019. *On-Road Fuel Cell Electric Vehicles Evaluation: Overview*. Golden, CO: National Renewable Energy Laboratory.

Mercedes-Benz. 2017. "The New GLC F-CELL." https://www.mercedes-benz.com/en/mercedes-benz/vehicles/passenger-cars/glc/the-new-glc-f-cell/.

Mercedes-Benz. 2012. "2012 Mercedes-Benz F-CELL Technical Data." https://media.mbusa.com/releases/2012-mercedes-benz-f-cell-technical-data.

NHTS (National Household Travel Survey). 2009. "2009 NHTS Survey Data." ASCII.csv. http://nhts.ornl.gov/download.shtml#2009.

Nissan Motor Corporation. 2005. "New X-TRAIL Fuel Cell Vehicle (FCV)." https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/fcv.html.

Toyota. 2018. "2018 Toyota Mirai Fuel Cell Vehicle." https://ssl.toyota.com/mirai/fcv.html.

Wipke, Keith, Donald Anton, and Sam Sprik. 2009. *Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions*. Savannah River National Laboratory. SRNS-STI-2009-00446. https://www.energy.gov/sites/prod/files/2014/03/f9/toyota_fchv-adv_range_verification.pdf.

Wipke, Keith, Sam Sprik, Jennifer Kurtz, Todd Ramsden, Chris Ainscough, and Genevieve Saur. 2012. *National Fuel Cell Vehicle Learning Demonstration Final Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5600-54860. https://www.nrel.gov/docs/fy12osti/54860.pdf.