Toyota Mirai Testing

Henning Lohse-Busch (Primary Contact),
Kevin Stutenberg
Argonne National Laboratory
9700 South Cass Ave.
Lemont, IL 60439
Phone: (630) 252-1978
Email: hlb@anl.gov

DOE Manager: Jason Marcinkoski
Phone: (202) 586-7466
Email: Jason.Marcinkoski@ee.doe.gov

Project Start Date: October 1, 2017
Project End Date: September 30, 2018

Overall Objectives

This is the technology assessment of a 2017 Toyota Mirai fuel cell (FC) vehicle using a chassis dynamometer in a controlled laboratory environment and in-depth instrumentation. The objectives are to:

- Establish vehicle level energy consumption, efficiency, and performance data on varying drive cycles at ambient temperatures ranging from 20°F (-7°C) to 95°F (35°C) with a stretch goal of testing a cold start at 0°F (-18°C).
- Generate an efficiency map of the FC system.
- Establish the performance envelope and synergies between the FC system and the hybrid system (including FC system idle).
- Publish an independent data set of a production automotive FC system as a public reference for researchers at DOE, national laboratories, original equipment manufacturers (OEMs), suppliers, standards committees, and academia.

Fiscal Year (FY) 2018 Objectives

This is a one-year project.

Technical Barriers

This project addresses the following technical barrier from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan[1]:

(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 will contribute to 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 2018 Accomplishments

The chassis dynamometer testing of a fully instrumented vehicle yielded the following accomplishments.

- Determined the performance envelope and synergies between the FC system and the hybrid system.
- Generated an efficiency map of the FC system.
- Measured the hydrogen consumption of the 2017 Toyota Mirai on the standard North American certification drive cycles (EPA Urban Dynamometer Driving Schedule [UDDS], Highway, and US06) at three conditions: 20°F (-7°C); 72°F (25°C), and 95°F (35°C) with 850 W/m^2 of solar load.
- Determined the FC system idle fuel flow rate.
- Characterized the FC system start-up behavior on a UDDS drive cycle after weekend cold soak at 0°F (-18°C).
- Posted the test data and comprehensive analysis report at www.anl.gov/d3.

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

INTRODUCTION

The research community is lacking public and independent laboratory-grade data of production automotive FC vehicles. The FC stack and system performance and efficiency data generated in this work serve to refine and validate modeling and simulation work, inform the research target-setting process, and highlight potential challenges that necessitate further research. The testing of the vehicle generated 10-Hz-resolved FC stack, FC system, and hybrid system data to determine component performance envelopes, component efficiencies, and overall control strategies for a range of thermal conditions.

APPROACH

Argonne has been providing technology assessment of advanced technology powertrain vehicles to the DOE Vehicle Technologies Office since the early 2000s. To evaluate a vehicle in a variety of real-world conditions, the team used a chassis dynamometer in a thermal chamber. The test conditions were based on the EPA 5-cycle fuel economy procedures, which included ambient temperatures of 20°F (-7°C), 72°F (25°C), and 95°F (35°C) with 850 W/m^2 of radiant sun energy. Testing also occurred at 0°F (-17°C). The test cell is set up with passive and active hydrogen safety systems and it is fully equipped to test hydrogen-powered vehicles. The instrumentation focus was on measuring the power flows between the major powertrain components as shown in Figure 1. A Hioki high-precision power analyzer was used to measure the electrical power flows. The hydrogen mass flow was measured with two Micro Motion Coriolis mass flow meters integrated into the test cell. More than 400 significant signals were recorded at 10 Hz for the more than 100 tests. For more detail on the chassis dynamometer testing and the instrumentation approach review Argonne's "Chassis Dynamometer Testing Reference Document" [1].

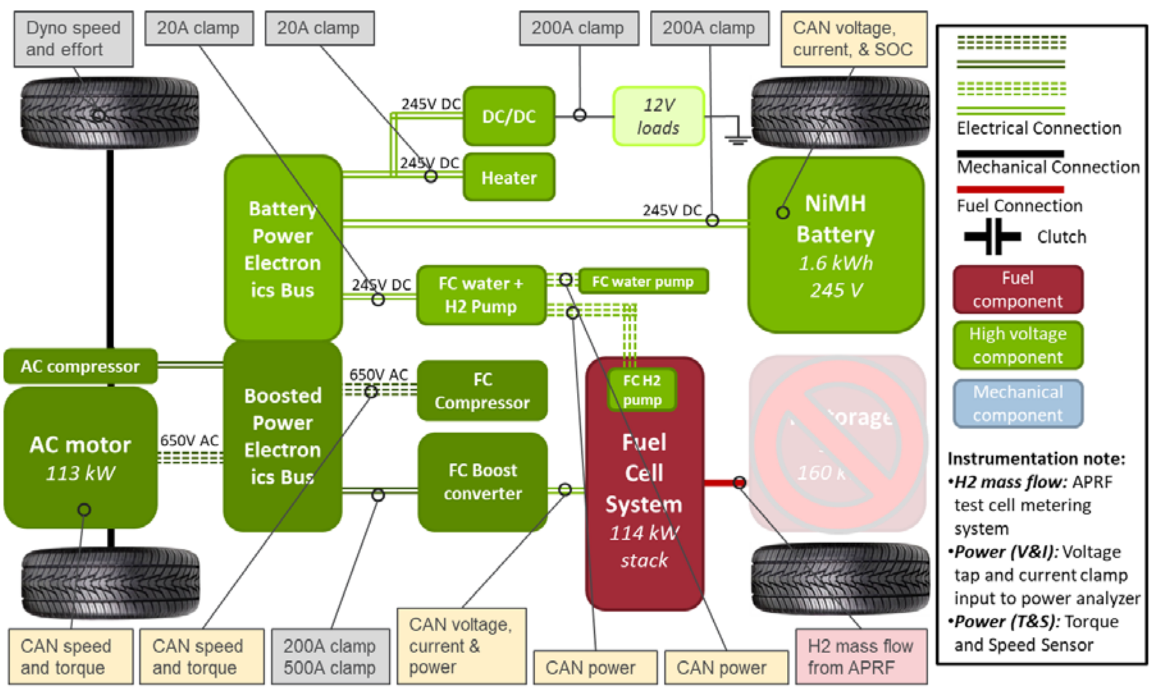

Figure 1. Power flow instrumentation summary

This technology assessment was a collaboration with Transport Canada, which provided a 2017 Toyota Mirai. Table 1 provides some relevant vehicle details.

Table 1. Data Parameters and Powertrain Specifications of the 2017 Toyota Mirai

Vehicle Architecture	FC series hybrid vehicle
Test Weight[a]	4,250 lb (1,928 kg)
Road Load[a]	A = 32.325 lbf B = 0.20003 lbf/mph C = 0.018292 lbf/mph^2
FC System[b]	Solid polymer electrolyte fuel cell 370 cells in stack 114 kW, 3.1 kW/L, 2.0 kW/kg
Battery[b]	Nickel-metal hydride, 1.6 kWh, 245 V DC

[a] EPA data
[b] Manufacturer data

RESULTS

Fuel Cell System and Hybrid System Operation

This powertrain is a FC-dominant hybrid. Similar to the internal combustion engine in a mild hybrid electric vehicle, the FC stack provides the majority of the traction power, the FC stack typically does not operate while the vehicle is stopped, and the FC stack has the ability to turn "off" or idle to enable the car to operate as an electric vehicle momentarily. The open circuit voltage slowly decreases as the FC system idles. Figure 2 illustrates these different powertrain operating modes on the New European Driving Cycle. This drive cycle requires relatively low power (20 kW or less) from the vehicle and at these low power levels the air compressor power consumption is only a few hundred watts, which results in high average FC system efficiency.

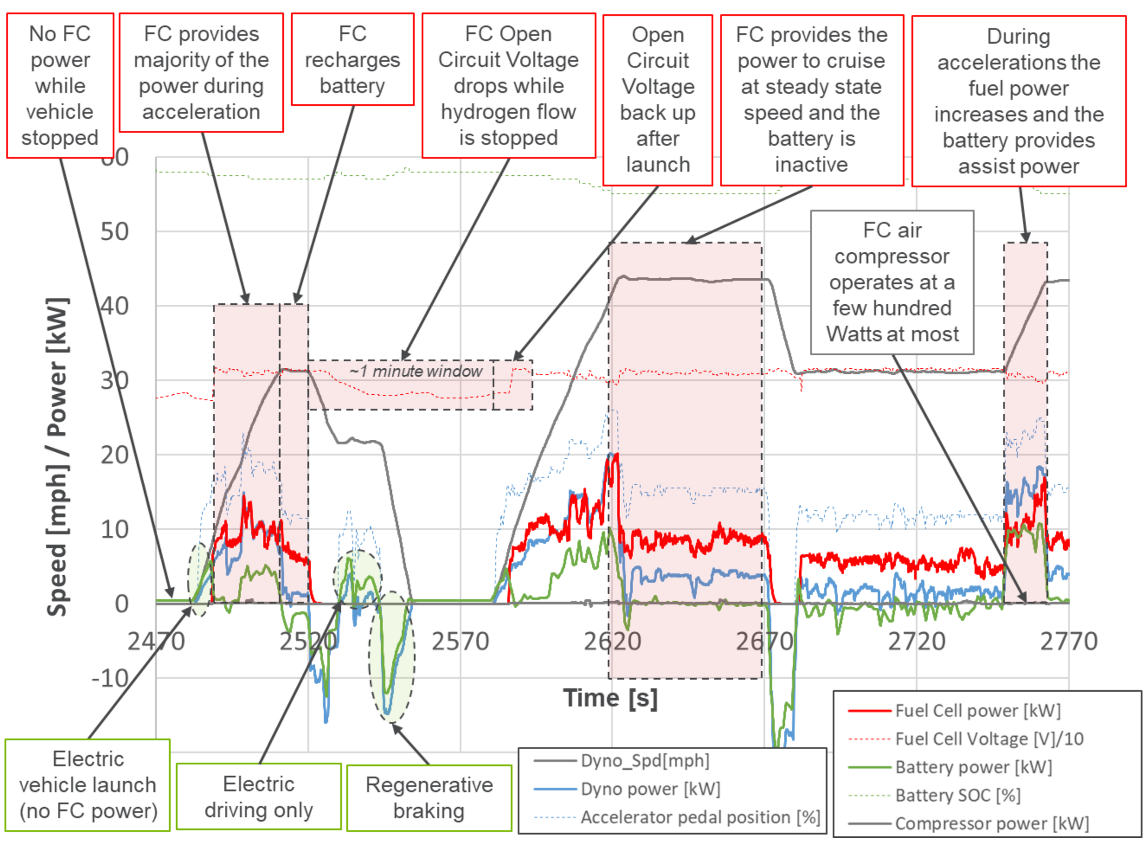

Figure 2. Powertrain and FC system operation in different drive modes on the linear segment drive cycle

On a high-power-demand drive cycle—such as the US06—the FC system demonstrates a great dynamic response that meets the high and fast power swings imposed on the powertrain. The power consumption of the air compressor at high FC stack loads can be up to 15 kW, which negatively impacts the FC system efficiency.

Fuel Cell Stack and System Efficiency Map

The vehicle also was tested at different steady-state speeds and steady-state load points to establish an FC stack and system efficiency map. The FC stack, FC system, and boost converter efficiencies, shown in Figure 3, were derived from the 10 Hz data. Figure 1 defines the system boundaries used to define the FC stack and the FC system.

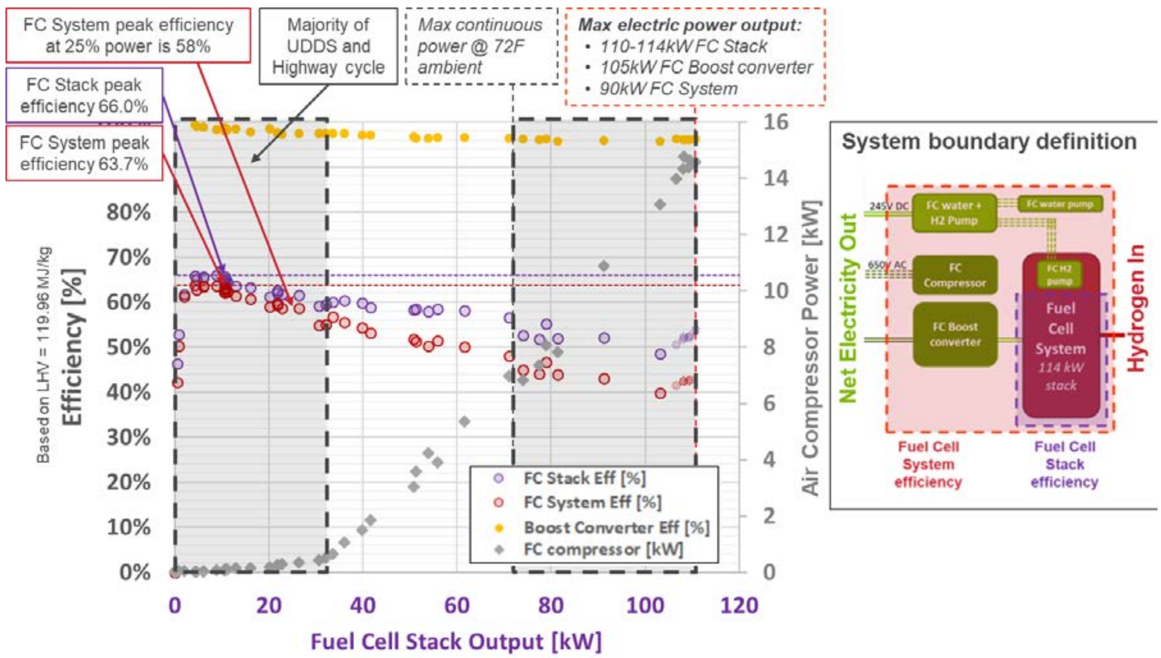

Figure 3. FC stack and FC system efficiency as a function of electric power output of the stack

The measured FC stack peak efficiency is 66.0%. The measured FC system peak efficiency is 63.7%. The FC system efficiency at 25% of maximum power is 58%. The low air-compressor power consumption of a few hundred watts at low stack power (<30 kW) results in high system efficiencies. The majority of the certification drive cycles, as well as typical driving conditions, are characterized by such low power demands, therefore the FC system typically operates in its most efficient range. Toyota redesigned the air-management system and anode flow channels to minimize the auxiliary power losses to the air compressor in this generation FC system [2].

The maximum power output of the fuel cell stack was measured around 110 kW to 114.6 kW depending on the thermal conditions. At these high power levels, the air-compressor consumption is up to 15 kW, which penalizes the FC system efficiency at those conditions. The peak power and the duration of continuous power are highly dependent on the cooling conditions such as ambient temperature and relative wind speed. All the testing was performed with a variable-speed fan that matched the vehicle speed. At 72°F (25°C) on a simulated 25% grade, the fuel cell stack produced 112 kW for 30 seconds and the continuous FC stack power settled at 73 kW with a vehicle speed of 27 mph.

Hydrogen Energy Consumption on Standard Drive Cycles Across Different Temperatures

The hydrogen energy consumption is shown in Figure 4. The energy consumption at 72°F (25°C) for the UDDS and Highway drive cycles are similar. On these low-load drive cycles, the losses attributed to the air compressor and boost converter are almost insignificant. On the higher-power US06 cycle, the boost converter and air compressor losses become significant. The overall average FC system efficiency on the UDDS is 61.8% as compared to 48.1% on the US06. The drop in efficiency is driven by low stack efficiency and higher air-compressor power at the higher loads.

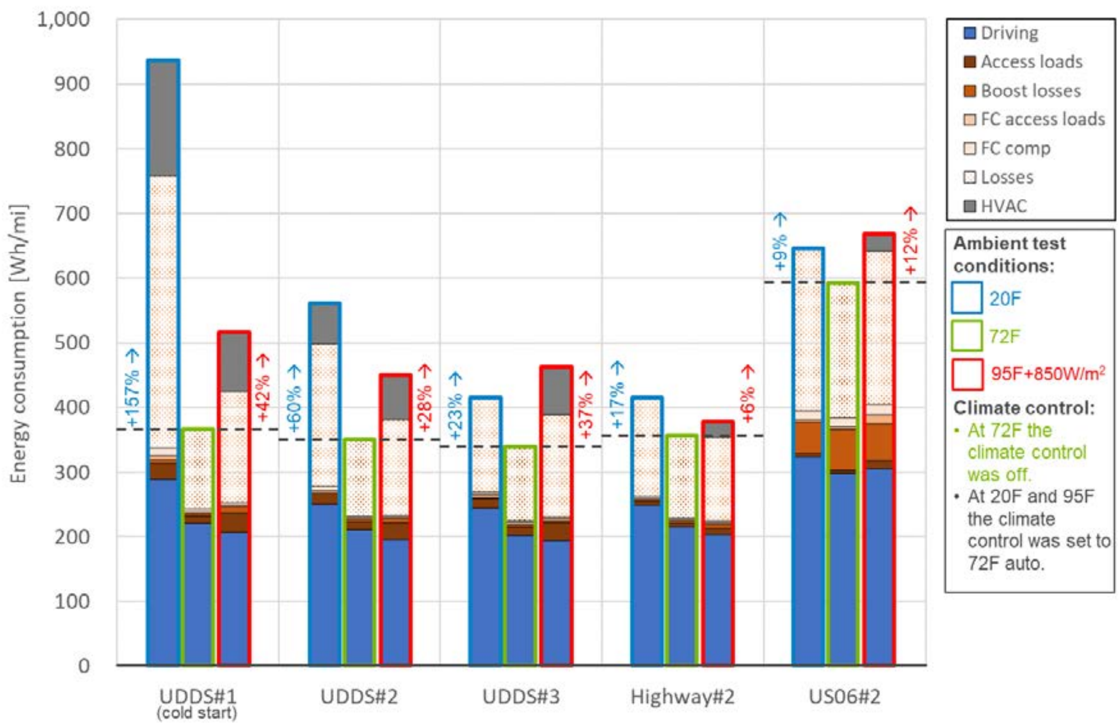

Figure 4. Hydrogen energy consumption and energy breakdown for different drive cycles across different temperatures

Results for the different ambient conditions also are presented in Figure 4. A cold-start test means that the vehicle, and therefore the powertrain, was soaked at the target ambient temperature for more than 12 hours before the start of the test. The Toyota Mirai purges the water from the FC stack when the vehicle is turned off and again when the temperature drops to freezing conditions. The cold-start UDDS cycle energy consumption at 20°F (-7°C) is 1.5 times greater than at 72°F (25°C) due to the electric heating of the FC system and the cabin, as well as the hydrogen used to recondition the dried-out proton exchange membranes. It is noteworthy that the FC system generates enough heat to maintain the cabin temperature at 72°F (25°C) on the third UDDS cycle. The increase in energy consumption at 95°F (35°C) ambient temperature with the 850 W/m^2 solar energy is driven by the power demand of the high-voltage refrigerant compressor for the climate control system.

Cold Start After a Weekend-Long Thermal Soak at 0°F (-18°C) Ambient Temperatures

The vehicle was temperature soaked over a full weekend at 0°F (-18°C). On the cold-start UDDS cycle, the driving starts 20 seconds after the vehicle is turned on. The electric heater warms up the FC system and extra hydrogen is used to recondition the dry proton exchange membranes. The standard open circuit voltage is achieved after 150 seconds of operation. The FC stack power is limited during these first 150 seconds of the drive cycle and the battery pack provides extra power to meet the acceleration demands. The fuel economy on the 0°F (-18°C) cold-start UDDS cycle is 30 mi/kg/mi of hydrogen, which is 60% less than at 72°F (25°C), as shown in Table 2.

Table 2. Fuel Economy Results in Kilogram of Hydrogen per Mile [mi/kg]

Ambient Conditions	0°F (-18°C)	20°F (-7°C)	72°F (25°C)	95°F (35°C)
UDDS#1 (cold start)	30.0	35.6	91.5	64.5
UDDS#1	39.8	59.5	95.3	74.2
UDDS#3	40.4	80.0	98.7	71.8
Highway	N/A	80.1	94.1	88.6
US06	N/A	51.6	56.1	50.0

Fuel Cell System Idle Fuel Flow Rate

As noted, the FC system turns "off" when FC power is not needed. This FC idle condition produces zero electric power output. To investigate this idle operation, a special 1-hour test was performed. After 505 seconds of driving, the vehicle was put in park and left "on." The FC system produced no electric power for 1,400 seconds. The data shows that the FC stack is starved for hydrogen to maintain an open circuit stack voltage around 74 V (typical open circuit voltage is 315 V). Periodically, a small amount of hydrogen is released in the system and some air is pushed into the stack. Over the 1,400 seconds of idle, 1.71 grams of hydrogen were consumed, which results in an idle fuel flow rate of 4.39 g/h. The low idle fuel flow rate enables the FC system to have enough reactants in the channels to provide immediate power when needed. After the 1,400 seconds of idling, the state of charge of the high-voltage battery pack had dropped low enough that the FC system produced power to recharge the battery pack.

More Detailed Analysis and Public Data Access

A comprehensive analysis is available in the full report titled *Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai* [3]. The report along with data files are posted at www.anl.gov/d3. The analysis report provides in-depth details on the following topics:

- Vehicle overview and instrumentation details
- Fuel cell hybrid powertrain operation overview
- Fuel cell stack and system efficiency (steady load mapping)
- Energy and efficiency analysis of certification drive cycle testing and results at 72°F
- Fuel cell system operation (including system operation, idle mode, maximum power analysis)
- Impact of temperatures: 0°F, 20°F, 72°F, and 95°F + 850 W/m^2 (includes energy analysis, FC system shut down and start up at cold start, power delivery, and hill-climb test).

CONCLUSIONS AND UPCOMING ACTIVITIES

This work was an in-depth technology assessment of a 2017 Toyota Mirai FC vehicle using a chassis dynamometer in a controlled laboratory environment and in-depth instrumentation. The FC stack had a high dynamic response, which enabled this powertrain to be an FC-dominant hybrid electric vehicle. The measured peak efficiency was 66.0% and 63.7% for the stack and FC system, respectively. The maximum stack power output was measured as approximately 110 kW to 114 kW. The overall average FC system efficiency on the UDDS drive cycle (mild city driving) was 61.8% as compared to 48.1% on the US06 drive cycle (aggressive high-speed driving). The FC system efficiency at high load suffered from the air compressor load, which could be as much as 15 kW. The cold-start UDDS cycle energy consumption at 20°F (-7°C) was 1.5 times greater than at 72°F (25°C) due to the electric heating of the FC system and the cabin, as well as the hydrogen used to recondition the dried-out proton exchange membranes. At 0°F (-18°C), the FC stack power was limited during these first 150 seconds of the drive cycle and the battery pack provided extra power to meet the acceleration demands. The FC system had an idle fuel flow rate of 4.39 g/h while producing zero power output. The low idle fuel flow rate enabled the FC system to have enough reactants in the channels to provide immediate power when needed.

All the raw 10 Hz data along with an in-depth analysis report is available to the public for download at www.anl.gov/d3. This provides much-needed public reference data on an automotive FC system for the research community.

This project is completed. Argonne stands ready to perform a technology assessment on other fuel cell vehicles or advanced technology vehicles for DOE.

ACKNOWLEDGEMENTS

This project is complete. Argonne thanks Transport Canada for its collaboration.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. H. Lohse-Busch, "Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai," 2018 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Project TV149 (June 13, 2018).
2. H. Lohse-Busch, K. Stutenberg, M. Duoba, S. Iliev, M. Kern, B. Richards, and M. Christenson, *Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai*, ANL Report ANL/ESD-18/12 (Argonne National Laboratory, June 2018).

REFERENCES

1. H. Lohse-Busch et al., "Chassis Dynamometer Testing Reference Document" (July 2013), https://anl.app.box.com/s/5tlld40tjhhhtoj2tg0n4y3fkwdbs4m3.
2. T. Hasegawa, H. Imanishi, M. Nada, and Y. Ikogi, "Development of the Fuel Cell System in the Mirai FCV," SAE Technical Paper 2016-01-1185 (2016). doi:10.4271/2016-01-1185.
3. H. Lohse-Busch, K. Stutenberg, M. Duoba, S. Iliev, M. Kern, B. Richards, and M. Christenson, *Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai*, ANL Report ANL/ESD-18/12 (Argonne National Laboratory, June 2018).