Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai

Energy Systems Division
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Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai

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June 2018
TECHNOLOGY ASSESSMENT OF A FUEL CELL VEHICLE: 2017 TOYOTA MIRAI

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GOALS OF THE TESTING

Testing of a fuel cell production vehicle in a controlled laboratory environment

The technical objectives* of the technology assessment of this advanced production vehicle are to:

- Establish vehicle level energy consumption, efficiency, and performance data on varying drive cycles at ambient temperatures ranging from 20F to 95F with a stretch goal of testing a cold start at 0F.
- Measure the performance envelops and synergies between the fuel cell system and the hybrid system (incl. fuel cell system idle).
- Generate an efficiency map of the fuel cell systems.

* SOW_v5 submitted to FCTO in September 2017
# OVERVIEW

**Testing of a fuel cell production vehicle in a controlled laboratory environment in order to generate public powertrain data**

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<td>Impact of temperatures: 0F, 20F, 72F and 95F+850W/m²</td>
<td></td>
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<td>• Fuel economy results and energy analysis ults for UDDS, Highway and US06 across temperatures</td>
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<td>• Fuel cell system cold start from 72F to 0F</td>
<td></td>
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<td></td>
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<td></td>
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<tr>
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<td></td>
</tr>
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**Collaboration with Transport Canada**

Transport Canada provided the vehicle and engaged in technical exchange of ideas. Argonne is very grateful for the successful collaboration.

**Abbreviations used in the presentation:**

- FC → Fuel Cell
- HEV → Hybrid Electric Vehicle
- BEV → Battery Electric Vehicle
- Mpge → Miles per gallon gasoline equivalent
- Le/100km → Liter gasoline equivalent per 100 kilometers
ARGONNE VEHICLE TECHNOLOGY ASSESSMENT AND ANALYSIS REPORTING

“We assess state-of-the-art transportation technology for the Department of Energy and Argonne research interests”

Research Oriented Test Facilities

Vehicle Technology Assessment

Downloadable Dynamometer Database www.anl.gov/d3

Vehicle level

- Energy consumption (fuel + electricity)
- Emissions
- Performance
- Vehicle operation and strategy

‘In-situ’ component & system testing

- Component performance, efficiency, and operation over drive cycles
- Component mapping

Downloadable Dynamometer Database www.anl.gov/d3

Test summary results
- 10Hz data of major signals
- Analysis Presentations
VEHICLE OVERVIEW AND INSTRUMENTATION
# 2017 TOYOTA MIRAI FUEL CELL VEHICLE

## 2017 Toyota Mirai Fuel Cell Vehicle

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vehicle architecture</strong></td>
<td>Fuel Cell Series Hybrid Vehicle</td>
</tr>
<tr>
<td><strong>Test weight</strong></td>
<td>4250 lbs</td>
</tr>
<tr>
<td><strong>Power plant</strong></td>
<td><strong>Fuel Cell</strong></td>
</tr>
<tr>
<td></td>
<td><em>Solid Polymer Electrolyte Fuel Cell</em></td>
</tr>
<tr>
<td></td>
<td>370 cells in stack</td>
</tr>
<tr>
<td></td>
<td>114kW*, 3.1 kW/L, 2.0 kW/kg</td>
</tr>
<tr>
<td></td>
<td>Flow channel: 3D fine-mesh flow field (cathode)</td>
</tr>
<tr>
<td></td>
<td>Humidification: Internal circulation system (humidifier-less)</td>
</tr>
<tr>
<td><strong>Hydrogen storage</strong></td>
<td>10,000 psi, 5 kg of H2</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td>Nickel-metal Hydride, 1.6 kWh, 245V *</td>
</tr>
<tr>
<td><strong>Climate control</strong></td>
<td>Electrical AC compressor</td>
</tr>
<tr>
<td></td>
<td>Electric heater</td>
</tr>
<tr>
<td><strong>EPA Label Fuel Economy (mpge)</strong></td>
<td>66 City /66 Hwy /66 Combined*</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td>Reported 0-60 Time: 9.0s*</td>
</tr>
</tbody>
</table>

*Manufacturer data  
*www.fueleconomy.gov  
^www.zeroto60times.com
The high voltage power distribution system is under the hood along with the inverters for the motors.

The air cooled NiMH battery pack is packaged in the trunk similar to most Toyota Hybrid vehicles.

The electric drive motor and the air compressor are packaged in-line between the front wheels.

The fuel cell stack along with the boost converter is under the center of the vehicle.

The two hydrogen tanks are under the trunk and the rear passenger seats. These tanks are disabled for the testing.

https://youtu.be/qofykBQre5o
HYDROGEN MEASUREMENT FOR THE MIRAI

Different metering technics:
- Integrated mass flow meter → Yes
- Ideal gas law → Possible but more complicated and not the intension of this work
- Gravimetric → No too expensive for the budget of this work

Outside H2 Storage
Laboratory grade hydrogen (99.999% pure) in 12 packs with is equivalent to 6 gallons of gasoline. Hydrogen is piped into the building at 245 psi.

Safety and Metering Panel
The hydrogen is metered by two Micro Motion® ELITE® Coriolis mass flow meters. The panel has over pressure safeties, automatic shut-off valves, hydrogen sensors and a venting system. Any hydrogen sensor can trigger the active test cell safeties and alert the fire department.

Test cell Connection
The vehicle hydrogen tanks are disabled and completely by-passed. The hydrogen is stepped down at the exit of the panel to 220 psi and fed into the pressure regulator in the middle of the vehicle.

Vehicle Connection
Note: The 30 ft delivery hose and the vehicle piping between the mass flow meters and the fuel cell stack creates a filtering effect and time delay on the fuel flow measurement.
POWER MEASUREMENTS EQUIPMENT

Hydrogen Flow:
**Micro Motion® ELITE® Coriolis meters**
- Argonne’s uses the CMF010M and CMF025M.
- ±0.25% gas flow accuracy; 0.0002 g/cc density accuracy
- The output of the meters is 4-20mA. The output on both meters is scaled from 4-20mA to 0-3gr/sec in the data acquisition system

Electric Power Flow:
**Hioki® High Precision Power Analyzer**
- Hioki® Power Analyzers PW3390-10
- Hioki current clamps: CT6841, CT6843
- ±0.1% power accuracy
- Outputs (V, I, P, IH, WH) transferred to DAQ via ethernet. V, I transfer via analog signal in addition to ethernet.
<table>
<thead>
<tr>
<th>Possible Vehicle Communication Signal</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC Voltage before Boosting</td>
<td>239.1 V</td>
<td></td>
</tr>
<tr>
<td>FC Voltage after Boosting</td>
<td>345.5 V</td>
<td></td>
</tr>
<tr>
<td>FC Current</td>
<td>2.9 A</td>
<td></td>
</tr>
<tr>
<td>Target FC Output Power</td>
<td>4.7 kW</td>
<td></td>
</tr>
<tr>
<td>FC output Power</td>
<td>0.94 KW</td>
<td></td>
</tr>
<tr>
<td>FC Stack Coolant Temperature (FC Stack Inlet)</td>
<td>29 C</td>
<td></td>
</tr>
<tr>
<td>FC Stack Air Pressure (FC Stack Inlet)</td>
<td>-0.91 kPa(gauge)</td>
<td></td>
</tr>
<tr>
<td>Intake Air Temperature</td>
<td>26 C</td>
<td></td>
</tr>
<tr>
<td>Mass Air Flow Value</td>
<td>300.9 NL/min</td>
<td></td>
</tr>
<tr>
<td>Air Compressor Revolution</td>
<td>639.5 rpm</td>
<td></td>
</tr>
<tr>
<td>Air Compressor Consumption Power</td>
<td>0 W</td>
<td></td>
</tr>
<tr>
<td>FC Stack Coolant Temperature (Radiator Outlet)</td>
<td>29 C</td>
<td></td>
</tr>
<tr>
<td>FC Stack Coolant Temperature (FC Stack Outlet)</td>
<td>45 C</td>
<td></td>
</tr>
<tr>
<td>FC Water Pump Revolution</td>
<td>735.25 rpm</td>
<td></td>
</tr>
<tr>
<td>FC Water Pump Consumption Power</td>
<td>19 V</td>
<td></td>
</tr>
<tr>
<td>Radiator Fan 1 Driving Request</td>
<td>0 %</td>
<td></td>
</tr>
<tr>
<td>Radiator Fan 2 Driving Request</td>
<td>0 %</td>
<td></td>
</tr>
<tr>
<td>Estimated Radiator Rotary Valve Position</td>
<td>0 %</td>
<td></td>
</tr>
<tr>
<td>FC Stack Air Temperature (FC Stack Outlet)</td>
<td>38 C</td>
<td></td>
</tr>
<tr>
<td>FC Stack Air Pressure (FC Stack Inlet)</td>
<td>-1.35 kPa(gauge)</td>
<td></td>
</tr>
<tr>
<td>Mass Air Flow Value</td>
<td>299.7 NL/min</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Pump Revolution</td>
<td>607.35 rpm</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Pump Consumption Power</td>
<td>19 W</td>
<td></td>
</tr>
<tr>
<td>Smoothed Value of Low-range Hydrogen Pressure</td>
<td>54.5 kPa(gauge)</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Injector Injection Number</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>FC Voltage before Boosting</td>
<td>293.9</td>
<td></td>
</tr>
<tr>
<td>FC Current</td>
<td>3.35</td>
<td></td>
</tr>
<tr>
<td>FC Mode</td>
<td>FC Working</td>
<td></td>
</tr>
<tr>
<td>Low Temperature Mode</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>FC Stack Power Generation Mode</td>
<td>Intermittent</td>
<td></td>
</tr>
<tr>
<td>FC Stack Cell Average Minimum Voltage</td>
<td>0.02 V</td>
<td></td>
</tr>
<tr>
<td>FC Stack Cell Minimum Voltage</td>
<td>0 V</td>
<td></td>
</tr>
<tr>
<td>FC Stack Cell Minimum Average Voltage Cell Channel No</td>
<td>31 ch</td>
<td></td>
</tr>
<tr>
<td>FC Stack Cell Minimum Voltage Cell Channel No</td>
<td>1 ch</td>
<td></td>
</tr>
<tr>
<td>FC Total Voltage</td>
<td>293.9</td>
<td></td>
</tr>
<tr>
<td>FC Stack Internal Resistance</td>
<td>0.11 ohm</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Pump Motor Temperature</td>
<td>38 ch</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Injector 1 Injection Request</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Injector 2 Injection Request</td>
<td>Off</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Injector 3 Injection Request</td>
<td>Off</td>
<td></td>
</tr>
</tbody>
</table>

### Exhaust Drainage Valve Driving Request
- Off

### Low-range Hydrogen Pressure
- 29.07 kPa(gauge)

### Internal Resistance ROB
- 0.019 ohm

### Internal Resistance RI17
- 0.019 ohm

### Battery Pack Current Value (1B Correction)
- -1.97 A

### Delta SOC
- 0%

### SOC IG-ON
- 64%

### Status of Charge Min
- 45.5%

### Cooling Fan Mode 1
- 0

### Drive Motor Revolution
- 0 rpm

### Drive Motor Execution Torque
- -0.5 N.m

### Inverter Water Pump Revolution
- 3500 rpm

### DC/DC Converter target Pulse Duty
- 79.3%

### Inverter Water Pump Run Control Duty
- 10%

### Boost Ratio
- 31.5%

### Boosting Converter Carrier Frequency
- 9.55 kHz

### A/C Consumption Power
- 0 W

### H20 Switch
- OFF

### Battery Charging Request
- Off

### FC Startup Request
- Off

### FC Stop Request
- Off

### FC Converter Available Output Current
- 100 A

### Heater Temperature
- 21.87 C

### Water Heater Drive Status
- Off

### FC Converter Input Voltage
- 297.2 V

### FC Converter Output Voltage
- 346.6 V

### FC Current
- 3 A

### FC Converter Shutdown Request
- Off

### FC Converter Request Power
- 26.04 kW

### FC Air Compressor Motor Temperature
- 29 C

### FC Air Compressor Motor Temperature after IG-ON
- 21 C

### Max FC Air Compressor Motor Temperature
- 29 C

### FC Air Compressor Revolution
- 638 rpm

### Target FC Air Compressor Motor Torque
- 0.7 N.m

### FC Air Compressor Motor Torque
- 0.6 N.m

### Accel Pedal Position No. 1
- 15.68 %

### Auxiliary Battery Voltage
- 14.12 V

### Motor Cooler Oil Pump Status
- 0

### Target Motor Cooler Oil Pump Duty
- 10%

### H20 Indicator
- Off

### Water Heater Duty
- 0 %
The CAN reported air compressor power message ('air_compressor_consumption_power_FC_W') clips at the value of ~3.97 kW.

The air compressor power can be calculated using the compressor motor speed and the compressor torque reported on CAN. A linear efficiency of 85% is applied to achieve a correlation to the reported air compressor power below 4 kW.

Air compressor power in the remainder of the analysis is the calculated power.

**Note:**
The 10 Hz data to generate these graphs is from UDDSx3, Highwayx2, US06x2, maximum acceleration x3, and steady state speed tests.
POWERTRAIN ARCHITECTURE AND MEASUREMENTS

Instrumentation note:
• **H2 mass flow**: APRF test cell metering system
• **Power (V&I)**: Voltage tap and current clamp input to power analyzer
• **Power (T&S)**: Torque and Speed Sensor
FUEL CELL HYBRID POWERTRAIN OPERATION OVERVIEW
**BASIC FUEL CELL HYBRID SYSTEM OPERATION**

- **FC provides majority of the power during acceleration**
- **FC recharges battery**
- **FC open circuit voltage drops while hydrogen flow is stopped**
- **FC back up to OCV at startup**
- **FC provide the power to cruise at steady state speed and the battery is inactive**
- **During accelerations the fuel power increases and the battery provides assist power**

No FC power while vehicle stopped

**Note:** NEDC drive cycle has low power demands

**Electric vehicle launch (no FC power)**

**EV only driving**

**Regenerative braking**

**FC air compressor operates at a few hundred Watts at most**
Highly dynamic speed changes while cruising and the FC power follows the dynamic load changes.

Large peak power demand during acceleration at high speed.

Fuel deceleration cut like feature.

Sequence of heavy accelerations with power from FC with battery assist.

Large peak power demand of 100kW met by FC with battery assist.

The Mirai is a fuel cell dominant hybrid electric vehicle with a strong load following control strategy.
Compared to gasoline HEVs the battery polarization curves is more extensive on the charging side for the fuel cell hybrid.

Three acceleration operations emerge: 1) High load fuel cell power with little battery assist; 2) Medium load fuel cell power with battery assist; 3) Low load battery charging.

*Note:* The 10 Hz data to generate these graphs is from NEDC×2, UDDS×3, Highway×2, US06×2, maximum acceleration ×3, and steady state speed tests.
**FUEL CELL AND BATTERY USAGE ENVELOPES**

**FC vs Battery power**

1) High load fuel cell power with little battery assist;

2) Medium load fuel cell power with battery assist;

3) Low load battery charging.

Regenerative braking.

The modeling and simulation team will use the data to validate their current models and control strategies.

**Note:**
The 10 Hz data to generate these graphs is from NEDCx2, UDDSx3, Highwayx2, US06x2, maximum acceleration x3, and steady state speed tests.
FUEL CELL STACK AND SYSTEM EFFICIENCY (STEADY LOAD MAPPING)
DEFINING THE SYSTEM BOUNDARIES FOR EFFICIENCY CALCULATIONS

Instrumentation note:
- **H2 mass flow**: APRF test cell metering system
- **Power (V&I)**: Voltage tap and current clamp input to power analyzer
- **Power (T&S)**: Torque and Speed Sensor
The dynamometer is locked at 30 mph for the test and serves as an power absorption device.

The driver in the vehicle tips into the accelerator pedal to reach specific power level based on the instrumentation.

The driver maintain that power level until power level, fuel flow levels, temperatures stabilize and ‘enough’ data is recorded to calculate the efficiency with certainty.

Moving to the next power level.

**Note:** The low and high power level are alternated to attempt to maintain ‘normal’ operating temperatures and avoid abnormally high powertrain temperatures. In this test 10-20-30-20-40-30-50-10 kW FC stack output were targeted.

A window for steady operation (cst flow, cst power output, cst temperatures,...) is used to compute the average values which are used for the efficiency analysis.
FUEL CELL STACK AND SYSTEM EFFICIENCY

Net Electric Fuel Cell System Output [kW]

Based on LHV = 119.96 MJ/kg


Max electric power output:
- 110kW FC Stack
- 105kW FC Boost converter
- 90kW FC System

Note:
- Analysis based on steady state speed tests with 0%, 3% and 6% grade + WOT at 72F ambient temperatures
- Hood closed, test cell fan in vehicle speed match mode. Climate control off.
FUEL CELL EFFICIENCY IN OPERATING ZONE

Key finding of efficiency based on laboratory data

Tested the power level multiple times.

The ‘spread’ in the data is caused by thermal conditions, stack conditions from previous test sequence, accessory loads, data processing decisions.

FC Stack peak efficiency 66.0%

FC System peak efficiency 63.7%

Net Electric Fuel Cell System Output [kW]

Based on LHV = 119.96 MJ/kg

At higher loads the air compressor other system accessories affect the system efficiency

Net Electricity Out
Hydrogen In

Tested multiple times.

Net Electric Fuel Cell System Output [kW]

Based on LHV = 119.96 MJ/kg

Note:
• Analysis based on steady state speed tests with 0%, 3% and 6% grade + WOT at 72F ambient temperatures
• Hood closed, test cell fan in vehicle speed match mode. Climate control off.

2017 Toyota Mirai test data
DOE TECHNICAL TARGETS FOR FUEL CELL SYSTEMS AND STACKS FOR TRANSPORTATION APPLICATIONS

Technical Targets: 80-kW_e (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen^a

<table>
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<th>Characteristic</th>
<th>Units</th>
<th>2015 Status</th>
<th>2020 Targets</th>
<th>Ultimate Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak energy efficiency^b</td>
<td>%</td>
<td>60^c</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>Power density</td>
<td>W/L</td>
<td>640^d</td>
<td>650</td>
<td>850</td>
</tr>
<tr>
<td>Specific power</td>
<td>W/kg</td>
<td>659^e</td>
<td>650</td>
<td>650</td>
</tr>
<tr>
<td>Cost^f</td>
<td>$/kW_{net}</td>
<td>53^g</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Cold start-up time to 50% of rated power</td>
<td>seconds</td>
<td>20^h</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>@–20°C ambient temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@+20°C ambient temperature</td>
<td>seconds</td>
<td>&lt;10^h</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Start-up and shutdown energy^i</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>from -20°C ambient temperature</td>
<td>MJ</td>
<td>7.5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>from +20°C ambient temperature</td>
<td>MJ</td>
<td>–</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

^b Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at less than 25% rated power.

“As a result of the implemented fuel efficiency strategies, the tested Borrego FCEV has attained a fuel cell efficiency of 65% and thereby fuel cell system efficiency of 62%, in the mean time, the tested Tucson FCEV has achieved a fuel economy of over 72 mpg city. The fuel efficiency was estimated while running at about 60 mph on average whereas the hydrogen consumption was in-house measured based on the FTP-72 test cycle and is represented in miles per gasoline equivalent gallons for comparison purposes.”, W. Sung,
COMPARISON OF SERIES HYBRID “GENERATORS”

**Fuel Cell Hybrid Electric Vehicle:**
- Charge sustain
- Fuel Cell dominant
- Generator max output 114 kW

**Battery Electric Vehicle with range extender:**
- Primarily BEV
- Small 649cc 2cyl engine
- Generator max output 25 kW
CERTIFICATION DRIVE CYCLE TESTING AND RESULTS AT 72F AMBIENT TEMPERATURE
### Powertrain thermal conditions

- **‘Cold Start’** test means that the vehicle, and therefore the powertrain, was soaked at the target ambient temperature for over 12 hours before the start of the test. 16 hours is the typical soak time in the test cell on the dynamometer for this testing.

- **‘Hot Start’** test means that the vehicle just completed a test and that the powertrain is already warm. Argonne tries to keep 10 minutes between the end of a test and the start of the hot start test.

### Cooling setup:
The test cell fan was run dynamically to match the air flow speed to the vehicle speed and the hood was closed for all testing regardless of ambient temperature.

---

**STANDARD TEST SEQUENCE FOR CERTIFICATION TESTS**

**Prep UDDS cycle completed followed by vehicle temperature soak over night in the test cell**

- **Cold Start** UDDS#1
  - Key off
  - 10 minute break
- **Hot Start** UDDS#2
  - Key off
- **UDDS#3**
  - Key off
- **Highway**
  - Key off
- **US06**
  - Key off

**Report fuel economy from these cycles**

**FC ‘Reactor’ temperature**
- 20F
- 72F
- 95F
- Speed

**Vehicle Speed [mph]**

**Temperature [°C]**

**Time [s]**

0 1000 2000 3000 4000 5000 6000 7000 8000
CERTIFICATION CYCLES TEST RESULT AT 72F AMBIENT TEMPERATURE

**Fuel Economy**

![Bar chart showing fuel economy for different driving cycles.]

- UDDS#1 (cold start): 91.5 mi/kg
- UDDS#2: 95.3 mi/kg
- UDDS#3: 98.7 mi/kg
- Highway#2: 94.1 mi/kg
- US06#2: 56.1 mi/kg

**Vehicle Efficiency**

- UDDS#1 (cold start): 62.8%
- UDDS#2: 65.7%
- UDDS#3: 67.7%
- Highway#2: 57.6%
- US06#2: 57.1%

**Notes:**
- SAE J2951™ defines "Cycle Energy" as the integration of positive power at the wheel over the cycle.
- Regenerative braking = "free" energy.
- Thus enabling 100% efficiencies for EVs.

**High fuel economy.**

*Caution: MPG illusion area.*

**Overall high powertrain efficiencies.**

Efficiency drops for higher driving intensity contrary to conventional vehicles.
FUEL ECONOMY COMPARISON TO EPA RESULTS

Argonne test results appear to match the EPA published test results

<table>
<thead>
<tr>
<th>Test</th>
<th>EPA(1)</th>
<th>ANL</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTP 75 (43% cold start and 57% hot start)</td>
<td>94.1 mpge (2)</td>
<td>91.9 mpge</td>
</tr>
<tr>
<td>Highway</td>
<td>94.1 mpge (2)</td>
<td>92.4 mpge</td>
</tr>
<tr>
<td>Testing</td>
<td>Manufacturer submitted to EPA</td>
<td>ANL internal</td>
</tr>
</tbody>
</table>

(1) The data comes from the EPA testing database published on their website: https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy
(2) The EPA file indicate the “FE_UNIT” to be “MPG”. It has been suggest that the units are “mi/kg” in which case using a Petroleum Equivalent Factor (PEF) of 1.02 (H₂ kg/gallon) the EPA fuel economy is 96.0 mpge for FTP75 and Highway. Argonne was not able to confirm if this is a mistake in the EPA file.

Test EPA(1) ANL
FTP 75 (43% cold start and 57% hot start) 94.1 mpge (2) 91.9 mpge
Highway 94.1 mpge (2) 92.4 mpge
Testing Manufacturer submitted to EPA ANL internal

Note: Individual drive cycle fuel economy test results are different from label fuel economy. The drive cycles fuel economy results are used to calculate the label fuel economy which intends to represent real world fuel economy.
WHERE DID THE ENERGY GO?

FC auxiliary loads on low load cycles are very low

On high load drive cycles the energy for the air compressor becomes significant

On high load drive cycles the boost converter losses are noticeable

Fuel cell system losses are very low for low load drive cycles

Ambient test conditions:
- 72F

Climate control:
- At 72F the climate control was off.

Average 12V accessory loads

UDDS#1 (cold start) 239W
UDDS#2 243W
UDDS#3 249W
Highway#2 235W
US06#2 321W
FUEL CELL VEHICLE EFFICIENCY CONTEXT

The fuel cell vehicle efficiency is higher compared to vehicles that use an internal combustion engine.
FUEL CELL SYSTEM PEAK EFFICIENCY CORRELATES WITH VEHICLE DEMANDS

UDDS - 90% of all power demand is below 12kW
Highway - 90% of all power demand is below 20kW
US06 - 90% of all power demand is below 40kW

The higher load demands of the aggressive US06 cycle decrease the fuel cell system efficiency (lower stack eff and high compressor power).

The fuel cell system is more efficient at low load demands. Most driving scenarios are relatively low power demand.

<table>
<thead>
<tr>
<th>Average Efficiency</th>
<th>UDDS #1</th>
<th>UDDS #2</th>
<th>UDDS #3</th>
<th>Highway #2</th>
<th>US06 #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC Stack</td>
<td>64.8%</td>
<td>64.8%</td>
<td>64.7%</td>
<td>63.4%</td>
<td>61.8%</td>
</tr>
<tr>
<td>FC System</td>
<td>62.0%</td>
<td>62.2%</td>
<td>61.8%</td>
<td>61.1%</td>
<td>48.1%</td>
</tr>
</tbody>
</table>

The fuel cell system is more efficient at low load demands. Most driving scenarios are relatively low power demand.
**FURTHER DRIVE CYCLE RESULTS AT 72F AMBIENT TEMPERATURE**

<table>
<thead>
<tr>
<th></th>
<th>UDDS#2</th>
<th>Highway#2</th>
<th>US06#2</th>
<th>JC08#2</th>
<th>NEDC#2</th>
<th>WLTP#2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel economy [mpge]</td>
<td>93.5</td>
<td>92.4</td>
<td>55.0</td>
<td>94.8</td>
<td>85.9</td>
<td>90.8</td>
</tr>
<tr>
<td>Hydrogen consumed [kWh]</td>
<td>2.60</td>
<td>3.63</td>
<td>4.76</td>
<td>1.76</td>
<td>2.61</td>
<td>6.34</td>
</tr>
<tr>
<td>Fuel consumption [kWh/mi]</td>
<td>349.7</td>
<td>354.0</td>
<td>594.2</td>
<td>344.8</td>
<td>380.5</td>
<td>441.6</td>
</tr>
<tr>
<td>Average FC Stack efficiency [%]</td>
<td>64.8%</td>
<td>63.4%</td>
<td>61.8%</td>
<td>64.2%</td>
<td>62.4%</td>
<td>61.8%</td>
</tr>
<tr>
<td>Average FC System efficiency [%]</td>
<td>62.2%</td>
<td>61.1%</td>
<td>48.1%</td>
<td>57.7%</td>
<td>59.3%</td>
<td>56.9%</td>
</tr>
<tr>
<td>Vehicle efficiency [%]</td>
<td>65.7%</td>
<td>57.6%</td>
<td>57.1%</td>
<td>65.0%</td>
<td>58.2%</td>
<td>59.0%</td>
</tr>
<tr>
<td>FC power covering 90% demand [kW]</td>
<td>12</td>
<td>20</td>
<td>40</td>
<td>12</td>
<td>14</td>
<td>22</td>
</tr>
</tbody>
</table>

**Note:** Each drive cycle was tested in pairs back to back. The results presented in the table are from the second cycle. The second cycles were always charge sustain by net energy change (less than 1% of fuel energy) and SOC (delta = 0%)
FUEL CONSUMPTION WITH BATTERY STATE OF CHARGE CORRECTION

**Note:** The battery SOC was adjusted to high and low before the beginning of specific UDDS tests to obtain the results below.

Same approach as for other Hybrid Electric Vehicles.

SOC merge to same levels

<table>
<thead>
<tr>
<th>SOC</th>
<th>SOC Start [%]</th>
<th>SOC End [%]</th>
<th>Fuel Consumption [le/100km]</th>
<th>Net energy change [Vzc x Ah]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low initial SOC</td>
<td>51</td>
<td>60</td>
<td>2.78</td>
<td>-25.7</td>
</tr>
<tr>
<td>Charge balanced SOC</td>
<td>59</td>
<td>60.5</td>
<td>2.52</td>
<td>-5.7</td>
</tr>
<tr>
<td>High initial SOC</td>
<td>73</td>
<td>58.5</td>
<td>2.21</td>
<td>24.2</td>
</tr>
</tbody>
</table>
HYDROGEN CONSUMPTION CAN BE ESTIMATED USING THE IDEAL GAS LAW

PV = mRT

12-pack pressure is measured
Volume of 12 3AA2400 cylinders. Small portion of piping at the high pressure is unknown.
Total mass of H2 for the given conditions
Ideal gas constant
It was not possible to measure the gas temperature in the cylinders. The outside temperature on 12/5/17 was ~4°C

Pressure used for initial mass
Pressure used for end mass
Temperatures even out in a recovery phase between tests

Note: The compressibility factor should be included in the calculations, but was left out due to time constrained.

This analysis is only anecdotal. This was not a goal associate with the testing.

Air gas HYUHP300 which is a 12-pack of DOT 3AA2400 cylinders. The liquid volume for each cylinder is 49.8L. The H2 storage is exposed to outside temperature.
HYDROGEN CONSUMPTION BASED ON CYLINDER PRESSURE, VOLUME, AND "TEMPERATURE"

Note: To truly compare the two measurement methods, it would require to have a temperature controlled enclosure for the hydrogen storage and wait until the gas and cylinders stabilized at the enclosure temperature after the test before calculating the mass of hydrogen post test. The volume of high pressure piping should be known as well.
FUEL CELL SYSTEM OVERVIEW
FUEL CELL POLARIZATION CURVE

Stack Voltage [V] vs. Stack current [A]

Stack mapping data
• These data points come for the steady state mapping analysis (slide 16)

Stack 10Hz data
• Red data cloud
• The 10 Hz data to generate this graphs is from NEDCx2, UDDsx3, Highwayx2, US06x2, maximum acceleration x3, and steady state speed tests.

Stack and cell assumptions:
• 237 cm² active area (1)
• 370 cells in stack

Idle Voltage

Voltage under load

Cell Voltage [V]

Stack Voltage [V]

Current density [A.cm²]

0 0.42 0.83 1.27 1.69 2.11 2.53

0 50 100 150 200 250 300 350

0 2.53 0.42 0.83 1.27 1.69 2.11

(1) B. James, NREL, “Fuel Cell Systems Analysis”, 2017 DOE FCTO AMR, Project ID# FC163
Majority of UDDS and Highway cycle

The recirculation pump has to work harder at higher loads to overcome the higher hydrogen flow and pressure.

The air and hydrogen mass flow increase with the electric output or load.

The valve is open or closed. This graph shows the average over the test period. 0% is closed and 100% is open.

The air pressure is very low below 30 kW and increases with correlated with the FC air compressor power presented in a previous slide.

Plateau of hydrogen flow maybe an artefact of the high load testing.

The higher the load; the higher the water production; the higher the water drainage. The valve is open or closed. This graph shows the average over the test period. 0% is closed and 100% is open.

---

Toyota describes the modified their air supply system (1) which increases fuel economy and the 3D fine-mesh flow structure (2) which enables the humidifier-less fuel cell system.

FUEL CELL STACK OPERATING PARAMETERS AND HUMIDIFICATION CONTROL MECHANISMS

Majority of UDDS and Highway cycle

The recirculation pump has to work harder at higher loads to overcome the higher hydrogen flow and pressure.

The air and hydrogen mass flow increase with the electric output or load.

The higher the load; the higher the water production; the higher the water drainage.

The valve is open or closed. This graph shows the average over the test period. 0% is closed and 100% is open.

The air pressure is very low below 30 kW and increases with the FC air compressor power presented in a previous slide.

Plateau of hydrogen flow may be an artefact of the high load testing.
FUEL CELL IDLE OPERATION ON DRIVE CYCLE

~1 minute window of fuel cell ‘idle time’

FC stack open circuit voltage drops from 315V (0.85V@cell) to 282V (0.76V@cell) after 64 seconds

FC back up to OCV at startup

Fuel Cell stack making power

Fuel Cell stack making power

**Note:** This is an idle period from the NEDC drive cycle, which was used earlier to provide an overview of the vehicle operation.
Air flow is around 50 NLpm and the compressor slows to an average of 105 rpm. The hydrogen flow is stopped. Slower hydrogen decay is due to mechanical filter through flow dynamics in the metering system. Occasional hydrogen pressure peak from 19 kPa to 35 kPa. Each hydrogen pressure peak is coupled with some hydrogen flow. The hydrogen consumption is zero most of the time when the fuel cell ‘idles’. 

H2 “puff” of ~0.035 g

Note: This is an idle period from the NEDC drive cycle, which was used earlier to provide an overview of the vehicle operation.
SPECIAL 1 HOUR IDLE TEST TO QUANTIFY THE IDLE HYDROGEN CONSUMPTION

First 505 second of UDDS cycle (Phase1) to warm up the powertrain

Vehicle stopped, transmission in park, ignition ON. Scenario: waiting in parking lot.

The battery SOC drops as accessory loads draw power over time

Low SOC triggers restart of FC system

FC system reaches 1-2kW power level, which is enough power to maintain battery SOC

Vehicle stopped, transmission in park, ignition ON. Scenario: waiting in parking lot.

The battery SOC drops as accessory loads draw power over time

FC system recharge the battery at 5~6kW

Low power phase

Idle phase:
- FC voltage drops from 315V to 80V
- FC system has zero electric output

Idle phase:
- More on next slide
  - 1401 seconds duration,
  - 1.71 g of H2 consumed,
  - 74 V Stack voltage,
  - 0.00 Wh Stack electric output

Idle fuel flow rate → 4.39 g/hr

The fuel cell idle fuel flow rate is 4.39 g/hr.
That is low compared to 75.4 g consumption on the UDDS (23 minute test or 198 g/hr)
MORE DETAILS ON SPECIAL 1 HOUR IDLE TEST

- Hydrogen pressure bumps from 20 kPa to 35 kPa every ~40 seconds
- Hydrogen pumps step up from 20W to 60W for 10~12 seconds every 5 minutes
- Air flow steps up from 50 to 200 NLpm for 4 seconds every 3 minutes
- FC starts once the battery SOC drops to 45.5%
- 10 to 6 kW stack output until battery charge to 50%
- 1 to 2 kW stack output with fuel flow pulsing and it appear that the stack is air starved (compressor speed 660 rpm). 4 minutes later the FC settles to 500W to sustain accessory loads.

During the idle phases the FC system is starved of hydrogen to maintain a low open circuit voltage.
MAXIMUM POWER TESTING ON A 25% GRADE AT 72F

- FC stack peak output of 111.6kW
- FC stack output drops after ~30 seconds
- Drainage valve is open more often during peak power
- All 3 hydrogen injectors used for peak power
- Battery assist (26kW peak). Battery SOC drop from 62.5% to 39%
- Compressor peak speed 9,600 rpm, peak power 17 kW
- 27.3 mph is the final speed on a 25% grade

FC stack output settles at 73kW after 6 minutes. Higher relative air flow to the vehicle could increase the maximum continuous power output.

Note:
- Peak power is 110 kW for a limited time period.
- Continuous power is ~75 kW at 72F ambient conditions.

- This testing was performed at 72F test cell temperature.
- The test cell fan was matching the air flow to the vehicle speed.
MAXIMUM POWER TESTING ON A 25% GRADE AT 72F – NO FUEL STARVATION

Pressure drop due to higher flows

The actual low range pressure is above the low range target pressure

The graph shows the relationship between time and pressure, with various lines indicating different parameters such as Hydrogen power, Facility vehicle delivery pressure, and Low range hydrogen pressure. The diagram also includes a scatter plot correlating fuel cell stack output with hydrogen flow, indicating a quadratic relationship with a high R² value.

→ This is why two efficiency results were calculated for the FC stack and system efficiency analysis presented earlier.
MAXIMUM POWER TESTING ON A 25% GRADE AT 72F – THERMAL CONDITIONS

The available data appears to show that the fuel cell system was not limited by thermal conditions at the vehicle system level.

The water pump, the rotary valve, both fans switch to full cooling mode.

Note: Simplified cooling system. Some components are missing.
REPEATED MAXIMUM ACCELERATIONS TO 80 MPH AT 72F AMBIENT TEMPERATURE

The fuel cell system reliably and consistently produces peak power for repeat accelerations runs.

<table>
<thead>
<tr>
<th>Run</th>
<th>0-80 mph [s]</th>
<th>Peak Stack [kW]</th>
<th>Average Stack [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.7</td>
<td>109.9</td>
<td>100.6</td>
</tr>
<tr>
<td>2</td>
<td>18.7</td>
<td>112.6</td>
<td>103.0</td>
</tr>
<tr>
<td>3</td>
<td>20.2</td>
<td>113.5</td>
<td>103.8</td>
</tr>
<tr>
<td>4</td>
<td>20.3</td>
<td>114.0</td>
<td>104.6</td>
</tr>
</tbody>
</table>

Four repeated maximum acceleration tests

Battery assist is reduced as the battery state of charge drops.
IMPACT OF TEMPERATURES: 0F, 20F, 72F AND 95F+850W/M²
TESTING ACROSS A RANGE OF TEMPERATURES

Environmental Test Cell

Thermal testing
- The hood is closed in all cases
- The facility fan blows air dynamically across the front of the car at the same speed as the vehicle speed
- Cold start means that the vehicle was thermally ‘soaked’ at the target temperature for over 12 hours (typically 16 hours)

Test Sequence
- Cold start UDDS #1 + Hot start UDDS #2, & UDDS #3
- Pair of Highway cycles (except for 0F)
- Pair of US06 cycles (except for 0F)

<table>
<thead>
<tr>
<th>Hot testing</th>
<th>Standard testing</th>
<th>Cold testing</th>
<th>Cold testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>95F + 850 W/m² (35C)</td>
<td>72F (22C)</td>
<td>20F (-7C)</td>
<td>0F (-18C)</td>
</tr>
<tr>
<td>Climate control 72F auto</td>
<td>Climate control OFF</td>
<td>Climate control 72F auto</td>
<td>Climate control 72F auto</td>
</tr>
</tbody>
</table>
IMPACT OF AMBIENT TEMPERATURE AND CLIMATE CONTROL ON FUEL ECONOMY

Increasing operating temperature
Closer to target cabin temperature
Increasing driving intensity

Note: At 72F the climate control was off. At 20F and 95F the climate control was set to 72F auto.
WHERE DID THE ENERGY GO?

Climate control penalty is worst on initial test (cabin temperature pull up or pull down)

No electric heating used after some driving because enough power-train waste heat exists

HVAC AC is a permanent energy draw

Ambient test conditions:
- 20F
- 72F
- 95F+850W/m²

Climate control:
- At 72F the climate control was off.
- At 20F and 95F the climate control was set to 72F auto.
COMPARING A FUEL CELL VEHICLE TO A BATTERY ELECTRIC VEHICLE ACROSS TEMPERATURES

2017 Toyota Mirai

2012 Ford Focus BEV

Ambient test conditions:
- 20F
- 72F
- 95F+850W/m²

Climate control:
- At 72F the climate control was off.
- At 20F and 95F the climate control was set to 72F auto.
UDDS DRIVE CYCLES TEST SEQUENCE AT 0F, 20F AND 72F

Significant energy consumption increase on cold start at freezing temperatures

The heater is still needed after 2 hours of driving at 0F

Ambient test conditions:
- 0F
- 20F
- 72F

Climate control:
- the climate control was set to 72F auto in all cases
FUEL CELL SYSTEM SHUTDOWN AT 72F

Driver turns the car OFF after completing a UDDS drive cycle

FC voltage slowly decays

No FC stack power

A bit of hydrogen flow

Purpose of the shut down: Leave the FC (esp PEM) in a 'good' state especially from a water management perspective.
**FUEL CELL SYSTEM SHUTDOWN AT 20F**

Driver turns the car OFF after completing a UDDS drive cycle

Longer (70 seconds) air flow and hydrogen flow to dry out the stack

No stack power. No electric heater power.

---

**20F Ambient temperature**

Ignition off

Last ‘hill’ of the UDDS cycle

Time [s]

---

**Purpose of the shut down at freezing temperatures:** Evacuate the water within the FC stack to prevent internal freezing.

Periodically the vehicle may drain excess water. This can also be performed manually.

---

**Note:** When transitioning into freezing temperatures, the vehicle automatically ‘wakes up’ and performs a similar routine.
FUEL CELL SYSTEM SHUTDOWN AT 0F

- Driver turns the car OFF after completing a UDDS drive cycle
- Still 70 seconds of air flow and hydrogen flow to dry out the stack
- Higher air flow as compared to 20F
- Still no stack power and no electric heater power.

Graph showing ambient temperature at 0F with various sensor data points.
FC START UP ON COLD START IN FREEZING TEMPERATURES

Immediate and steady FC voltage on start up

FC voltage varies at low levels after start (for ~100 second). Large amount of H2 are pushed through the stack.

FC voltage low with minimal initial power output. FC voltage does not stabilized until 150 seconds.
FUEL CELL START UP ON COLD START AT 72F

Driver turn the car ON after an overnight soak at 72F

FC stack no producing power until the wheels spin

FC stack voltage is comes to OCV as soon it produces power

[Graph showing various parameters over time for the first 300 seconds of UDDS cold start test]
**FUEL CELL START UP ON COLD START AT 20F**

- Driver turn the car ON after an overnight soak at 20F
- Large increase in H2 flow compared to 72F cold start
- FC stack voltage is low for the first 100 seconds
- FC stack voltage is back to normal operating ranges

Graph showing:
- **20F**
- **First 300 seconds of UDDS cold start test**
- **Time [s]**

Key points:
- FC produces power before wheels spin
- Electric heater power consumption

Graph lines indicating:
- Dyno_Spd [mph]
- Dyno power [kW]
- Test Cell temperature [C]
- Fuel Cell temperature [C]
- Fuel Cell power [kW]
- Fuel Cell voltage [V]/10
- FC 'Reactor' temperature [C]
- Battery power [kW]
- Battery SOC [%]
- Compressor power [kW]
- Hydrogen power [kW] - metered
- HVAC power [kW]
FUEL CELL START UP ON COLD START AT 0F

Driver turn the car ON after 2+ days of 0F temperatures. The wheel spin after 20 seconds.

Intermittent power delivery. Driver reported ‘bucking’ of vehicle on dyno.

FC stack voltage back to ‘normal’

Note#1: Due to time constraints this test could not be repeated. It is unclear if is repeatable.

Note#2: A 0F cold start UDDS test which only 16 hours of soak was performed as well. No drive quality issues were reported on that test.
MAXIMUM ACCELERATION AT 0F

**Note:** Force cooling @ 0F for 2 hours after the 5 UDDS cycles

<table>
<thead>
<tr>
<th>Run @72F</th>
<th>0-80 mph [s]</th>
<th>Peak Stack [kW]</th>
<th>Average Stack [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.7</td>
<td>109.9</td>
<td>100.6</td>
</tr>
<tr>
<td>2</td>
<td>18.7</td>
<td>112.6</td>
<td>103.0</td>
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</tr>
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<td>4</td>
<td>20.3</td>
<td>114.0</td>
<td>104.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run @72F</th>
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<th>Peak Stack [kW]</th>
<th>Average Stack [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29</td>
<td>98.3</td>
<td>86.0</td>
</tr>
<tr>
<td>2</td>
<td>20.6</td>
<td>113.8</td>
<td>104.4</td>
</tr>
<tr>
<td>3</td>
<td>18.5</td>
<td>113.8</td>
<td>105.5</td>
</tr>
</tbody>
</table>
HILL CLIMB WITH SOLAR LOAD

The Mirai maintained the 62 mph speed target in these conditions

Continuous power of 63kW after 30 minutes

95°F + 850 W/m²

*Note:* This is higher continuous power compared to the 25% grade test. The vehicle speed in grade test was 27 mph. That low speed resulted in low air flow from the facility fan in front the vehicle and therefore in a lower heat rejection potential.

Hill Climb test
- 62 mph (100 km/h)
- 6% grade
- At 4810 lbs test weight (GVW)
- 95°F ambient temperature
- 850 W/m² solar load
- Climate control set to 72°F auto
→ Realistic worst case scenario
CONCLUSION AND TAKEAWAYS FROM TESTING A 2017 TOYOTA MIRAI FUEL CELL VEHICLE

Fuel Cell Stack and System Efficiency Analysis

- Fuel Cell Stack Output vs. Efficiency
- Fuel Cell peak efficiency: Stack 66.0%, System 63.7%
- Corelated FC system parameters and operation to output.

Energy Analysis Across Temperatures

- Ambient test conditions: 0F, 20F, 72F, 95F
- Power output of the FC system conditioning to 0F is limited initially

0F to 95F Testing Completed

- Contrary to BEVs, FCVs have enough waste heat to keep a cabin warm.
- 10Hz data will be available publicly at www.anl.gov/d3

Key Takeaways:

- The FC is starved of H₂ when not used. The fuel cell idle fuel flow rate is 4.39 g/hr.
- Peak power is 110 kW for a limited time period. Continuous power will vary from ~50 kW to ~75 kW depending on thermal conditions and vehicle speed.
TECHNOLOGY ASSESSMENT OF A FUEL CELL VEHICLE: 2017 TOYOTA MIRAI

HENNING LOHSE-BUSCH, MICHAEL DUOBA, KEVIN STUTENBERG, SIMEON ILIEV, MIKE KERN
Argonne National Laboratory

BRAD RICHARDS, MARTHA CHRISTENSON
Transport Canada
AARON LOISELLE-LAPOINTE
Environment and Climate Change Canada

June 2018 (v10)
Argonne National Laboratory, IL
Advanced Powertrain Research Facility
4WD Chassis Dynamometer Thermal Test Cell

“Research and Data Driven Lab”
“Independent Public Data”

• Test cell specifications
  ✓ 4WD chassis dynamometer
    - Variable wheel base (180 inches max)
    - 250 hp/axle
    - 300 to 12,000 lb inertia emulation
  ✓ Radiant sun energy emulation
    of 850W/m² (adjustable)
  ✓ Variable speed cooling fan (0–62 mph)
  ✓ Gaseous fuel and hydrogen capable
  ✓ Diesel: Dilution tunnel, PM, HFID

• Thermal chamber
  ✓ EPA 5 cycle capable
    (20°F, 72°F and 95°F + 850W/m² solar load)
  ✓ Demonstrated as low as 0°F
  ✓ Intermediate temperatures possible

• Research features
  ✓ Modular and custom DAQ with real time data display
  ✓ Process water available for cooling of experiment components
  ✓ Available power in test cell
    - 480VAC @ 200A
    - 208VAC @ 100A
  ✓ ABC 170 Power supply capable to emulate electric vehicle battery
  ✓ Custom Robot Driver with adaptive learning
  ✓ Several vehicle tie downs
    - chains, low profile, rigid,...
    - 2, 3 and 4 wheel vehicle capable
  ✓ Expertise in testing hybrid and plug-in hybrid electric vehicles, battery electric vehicles and alternative fuel vehicles

• Special instrumentation
  ✓ High precision power analyzers (testing and charging)
  ✓ CAN decoding and recording
  ✓ OCR scan tool recording
  ✓ Direct fuel flow metering
  ✓ Infrared temperature camera
  ✓ In cylinder pressure indicating systems
  ✓ In-situ torque sensor measurement
  ✓ 5 gas emissions dilute bench with CVS (modal and bag emissions analysis)
  ✓ FTIR, Mobile Emissions unit
  ✓ Raw and Fast HC and NOx bench
  ✓ Aldehyde bench for alcohol fuels
HOW ARE VEHICLES TESTED FOR ENERGY CONSUMPTION

Chassis dynamometer test cell

A driver accelerates and brakes to follow a drive trace

Simple physics are used to emulate the proper load at the wheel to emulate the real world

\[
\text{Power}_{\text{propulsion}} = m \times \frac{\partial (V)}{\partial t} + F_{\text{roadload}} \times V
\]

- **Inertia force:** overcome change in momentum
- **Road load force:** caused by wind resistance and other vehicle losses
  \[
  F_{\text{roadload}} = A + B \times V + C \times V^2
  \]

A drive trace is a defined speed profile as a function of time
EPA’S 5 CYCLES TESTS FOR FUEL ECONOMY LABEL

EPA implemented the new 5 Cycle Fuel Economy Label to close the gap to real world fuel economy the consumer can expect.

- **Classic cycles!**
  - FTP UDDS @ 75
    - #1 Cold start
    - #2 Hot start
  - HWFET @ 75 F

- **Aggressive cycle!**
  - US06 @ 75 F

- **Extreme Temperatures!**
  - SC03 @ 95 F
    - +850 W/m²
  - UDDS @ 20 F

CAFE (only city and highway)

City FE computed by a formula incorporating the various effects of

Parts of these cycles compute into a City and a Highway Fuel Economy.
PSYCHOLOGY OF FUEL ECONOMY VS. FUEL CONSUMPTION

Fuel Economy = Distance / Fuel

Fuel consumption = Fuel / Distance

If little fuel is used, FE ‘explodes’ to a large number and becomes misleading.

FC is a better scale for very efficient vehicles!

‘The MPG illusion’

125 gal saved over 10,000 mi

~84 gal saved over 10,000 mi
ELECTRIFICATION COMPLICATES EFFICIENCY CALCULATIONS

Conventional Vehicle

2012 Focus 2L

Fuel → Engine → Irreversible power flow → Tire

2013 Focus BEV

Motor → Battery

Bi-directional power flow

Efficiency = \frac{Energy_{out}}{Energy_{in}}

Regenerative braking reverses the power flow and charges the high voltage battery (In & Out reverse)

→ SAE J2951 defines “Cycle Energy” as the integration of positive power at the wheel over the cycle (regenerative braking = “free” energy)
HIGHER EFFICIENCY POWERTRAIN ARE MORE SENSITIVE

Conventional

Hybrid Electric

Battery Electric (incl. charger)

Observations:
• Everything matters down to the accessory loads in electric vehicles.

Data note: UDDS hot start

<table>
<thead>
<tr>
<th>SAE J2951 definition</th>
<th>Vehicle efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20F</td>
<td>1.2</td>
</tr>
<tr>
<td>72F</td>
<td>1.0</td>
</tr>
<tr>
<td>95F+sun</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Degree of Hybridization (M/(M+E))

Conventional
- 2012 Ford Focus
- 2013 Jetta TDI
- 2013 Chevy Cruze Diesel

Hybrid Electric
- 2013 Chevy Malibu Eco
- 2013 VW Jetta HEV
- 2010 Prius
- 2013 Ford Cmax HEV
- 2014 Honda Accord HEV

Battery Electric
- 2012 Nissan Leaf BEV
- 2013 Nissan Leaf BEV
- 2015 BMW i3 BEV
- 2015 Chevy Spark BEV
- 2013 Ford Focus BEV

Peak ICE eff + regen
Peak ICE eff

Peak ICE eff + regen
Peak ICE eff

UDDS (City Driving)
NET ENERGY CHANGE OF THE BATTERY DETERMINES IF A HEV IS CHARGE SUSTAINING OVER THE TEST CYCLE

- Net energy change (NEC) = net battery energy delta over the test cycle
- A test is considered charge sustaining when the NEC of battery is less than 1% of fuel energy used over the test cycle
- If an HEV discharges its battery over a test cycle, the fuel consumption will be increased.

Sample data - 11 Sonata HEV - UDDS

<table>
<thead>
<tr>
<th>Battery Discharging</th>
<th>Battery Charging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net Energy Change</td>
<td></td>
</tr>
<tr>
<td>Battery Charging</td>
<td></td>
</tr>
<tr>
<td>Fuel Consumption</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
</tbody>
</table>

Sample data - 11 Sonata HEV - UDDS

- 1% CS limit
- 20F
- 72F
- Linear (72F NEC)
- 95F
- 72F NEC

y = -0.0229x + 4.8238
R² = 0.6315
SAFETY AND METERING PANEL

Quick connect fitting

Vent lines to the roof

Hydrogen sensor

Over pressure relief valve

Quick connect fitting

Manul valves

Manual pressure regulator (removed for Mirai testing before of pressure drop – pressure set @ the outside panel)

Pressure gage

Over pressure sensor

Vehicle delivery pressure sensor

Flexible fuel hose to vehicle with manual valve

Vehicle delivery pressure sensor

Flexible fuel hose to vehicle with manual valve
BOOST CONVERTER OPERATION

![Graph showing voltage vs. dyno power](image)

- Boosted voltage [V]
- Battery Voltage [V]
RIPPLE AND PULSES IN STEADY OPERATION

H2 flow ripple correlated to drainage valve

Note Air compressor power pulses at low FC loads
61712006 SSS @ 72F 15, 30, 45, 60, 75 MPH

Check periodic air compressor power pulses (parallel h2o drainage)
25% GRADE @ 95F WITH 850 W/M²

Max FC system power

25% grade @ 95F with 850W/m²

De-rating power to 50 kW