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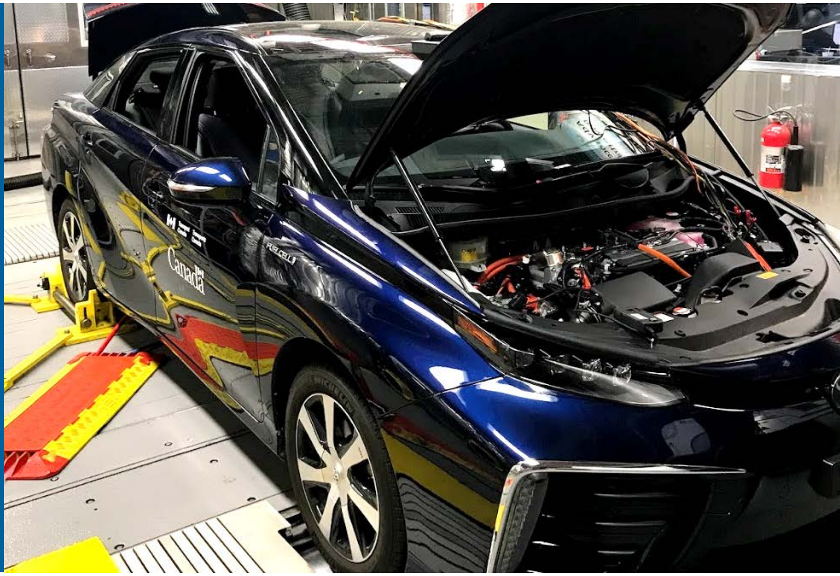
# TECHNOLOGY ASSESSMENT OF A FUEL CELL VEHICLE: 2017 TOYOTA MIRAI



PRINCIPAL INVESTIGATOR: **HENNING LOHSE-BUSCH**
Vehicle System Research Group,

Project ID# TV149



2018 U.S. DOE Fuel Cell Technologies Program Annual Merit Review and Peer Evaluation Meeting, June 13th, 2018

# OVERVIEW

## Timeline

- September 2017: Proposal to test the Fuel Cell Vehicle Proposal
- Fall 2017: Instrumentation
- December 2017: Testing
- Winter 2018: Analysis
  - See Milestone on slide 6

## Budget

- FY18  $93k

## DOE barriers addressed:

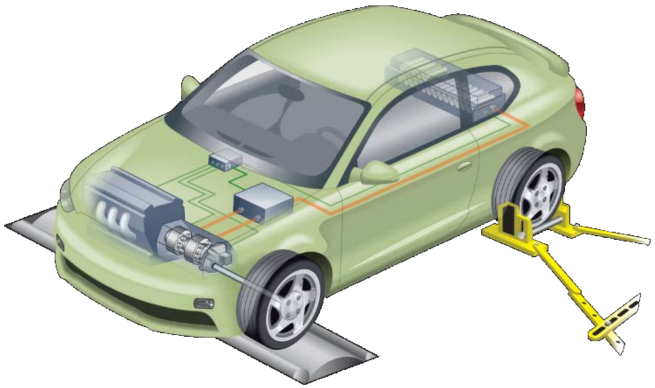
- Lack of public and independent data on automotive fuel cell system data

## Partners:

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


Transport
Canada

# RELEVANCE: PUBLIC AND INDEPENDENT IN-DEPTH POWERTRAIN DATA FOR RESEARCH COMMUNITY



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

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## Research Oriented Test Facilities

**4WD chassis dynamometer**

- Thermal Chamber: 0F to 95F
- Solar emulation

*opened 2002, upgraded 2011*

**2WD chassis dynamometer**

- Up to medium duty

*opened 2009*

## Vehicle Technology Assessment

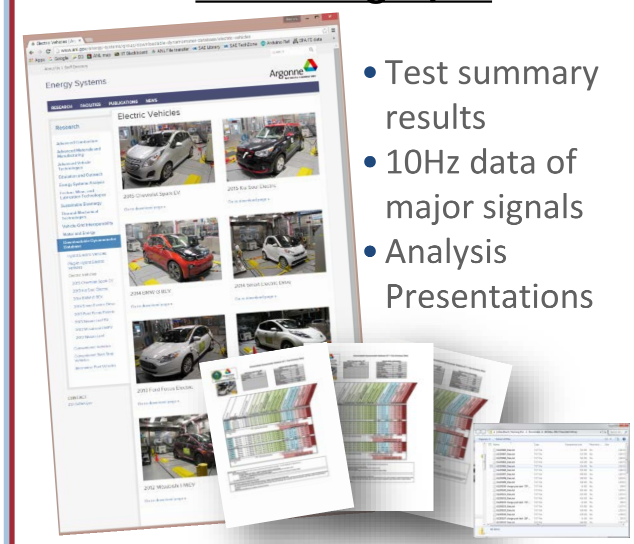
**Vehicle level**

- 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

# RELEVANCE: HIGHLY LEVERAGED DATA AND ANALYSIS YIELD REAL OUTCOMES

Openly shared public data on advanced technology vehicles is very rare. The data may exist within the largest industry labs, but this data is confidential and closely guarded.

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Independent and Public

Data and Analysis

**Dynamometer Downloadable Database**

www.anl.gov/D3/

**DOE Partner Data Sets**

Full data sets with more signals and more tests available

**Analysis and Insights**

→ Quantifies technology challenges

→ Leads to innovation in basic research

→ **Enable petroleum displacement through technology assessment & data dissemination**

### Technology Assessment

- Technology trends at component and system level
- Inform research goals
- Find efficiency opportunities

### Modeling and Simulation

- Component mapping
- Thermal analysis
- Climate control system
- Data for validation

### Codes and Standards

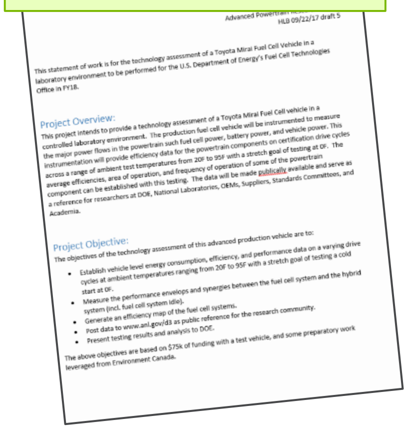
- Procedures development and validation
- Technology neutral
- Informed decision making

### Independent Public Data and Knowledge Base

- Academia, national laboratories, startups, suppliers, and OEMs

# MILESTONES: VEHICLE LABORATORY TECHNOLOGY ASSESSMENT TIMELINE

1 **Proposal to DOE**
**September 2017**


Advanced Powertrain Research
HLB 09/22/17 draft 5

This statement of work is for the technology assessment of a Toyota Mirai Fuel Cell Vehicle in a laboratory environment to be performed for the U.S. Department of Energy's Fuel Cell Technologies Office in FY18.

Project Overview:
This project intends to provide a technology assessment of a Toyota Mirai Fuel Cell vehicle in a controlled laboratory environment. The production fuel cell vehicle will be instrumented to measure the major power flows in the powertrain such fuel cell power, battery power, and vehicle power. This instrumentation will provide efficiency data for the powertrain components on certification drive cycles across a range of ambient test temperatures from 20F to 95F with a stretch goal of testing at 0F. The average efficiencies, area of operation, and frequency of operation of some of the powertrain component can be established with this testing. The data will be made publically available and serve as a reference for researchers at DOE, National Laboratories, OEMs, Suppliers, Standards Committees, and Academia.

Project Objective:
The objectives of the technology assessment of this advanced production vehicle are to:

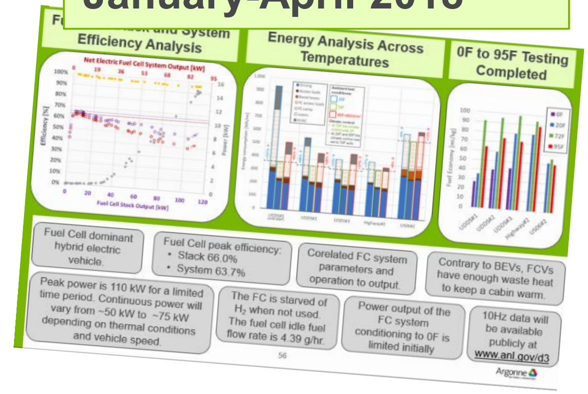
- Establish vehicle level energy consumption, efficiency, and performance data on a varying drive cycles at ambient temperatures ranging from 20F to 95F with a stretch goal of testing a cold start at 0F.
- Measure the performance envelops and synergies between the fuel cell system and the hybrid system (incl. fuel cell system idle).
- Generate an efficiency map of the fuel cell systems.
- Post data to www.anl.gov/d3 as public reference for the research community.
- Present testing results and analysis to DOE.

The above objectives are based on $75k of funding with a test vehicle, and some preparatory work leveraged from Environment Canada.

2 **Instrumentation**
**October-November 2017**


3 **Laboratory testing**
**December 2017**

4 **Analysis and reporting**
**January-April 2018**



# APPROACH: WELL-ESTABLISHED AND EFFECTIVE TEST METHODS ADJUSTED TO INDIVIDUAL TECHNOLOGIES

The vehicle benchmark activity has been refined during the past decade, which has resulted in:

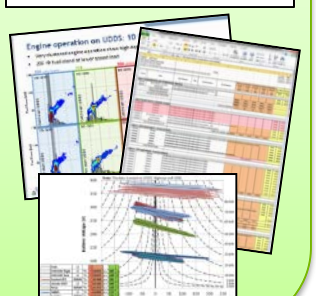
- Advanced and unique facilities and instrumentation
- Continuous improvement of testing procedures
- Standardization of test plans including instrumentation and drive cycles which are adjusted for individual vehicles
- Significant knowledge of advanced vehicles and testing methods

## Baseline Dynamometer Testing

1. Preparation and instrumentation

2. Dyno testing

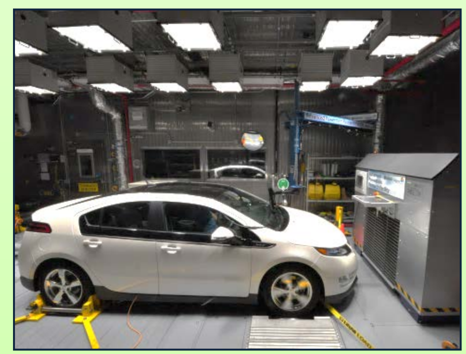
3. Analysis



## Argonne's Vehicle Testing Facilities

The right tools for the task:

- 4WD chassis dynamometer cells
- Custom DAQ, flexible, module-driven, used in both cells
- Thermal chamber which is 5-Cycle compliant (+)



**4WD chassis dyno with thermal chamber**

Drive cycles and test conditions

- Standard drive cycles + technology specific cycles, performance tests, vehicle and component mapping cycles
- Thermal test conditions: 0ºF to 95ºF with 850 $W/m^2$ radiant solar energy (full "5-Cycle")



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# APPROACH: HYDROGEN MEASUREMENT FOR THE MIRAI

### 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

**Different metering technics:**

- Integrated mass flow meter → **Yes**
- Ideal gas law → **Possible** *but more complicated*
- ~~Gravimetric~~ → **No** (too expensive)



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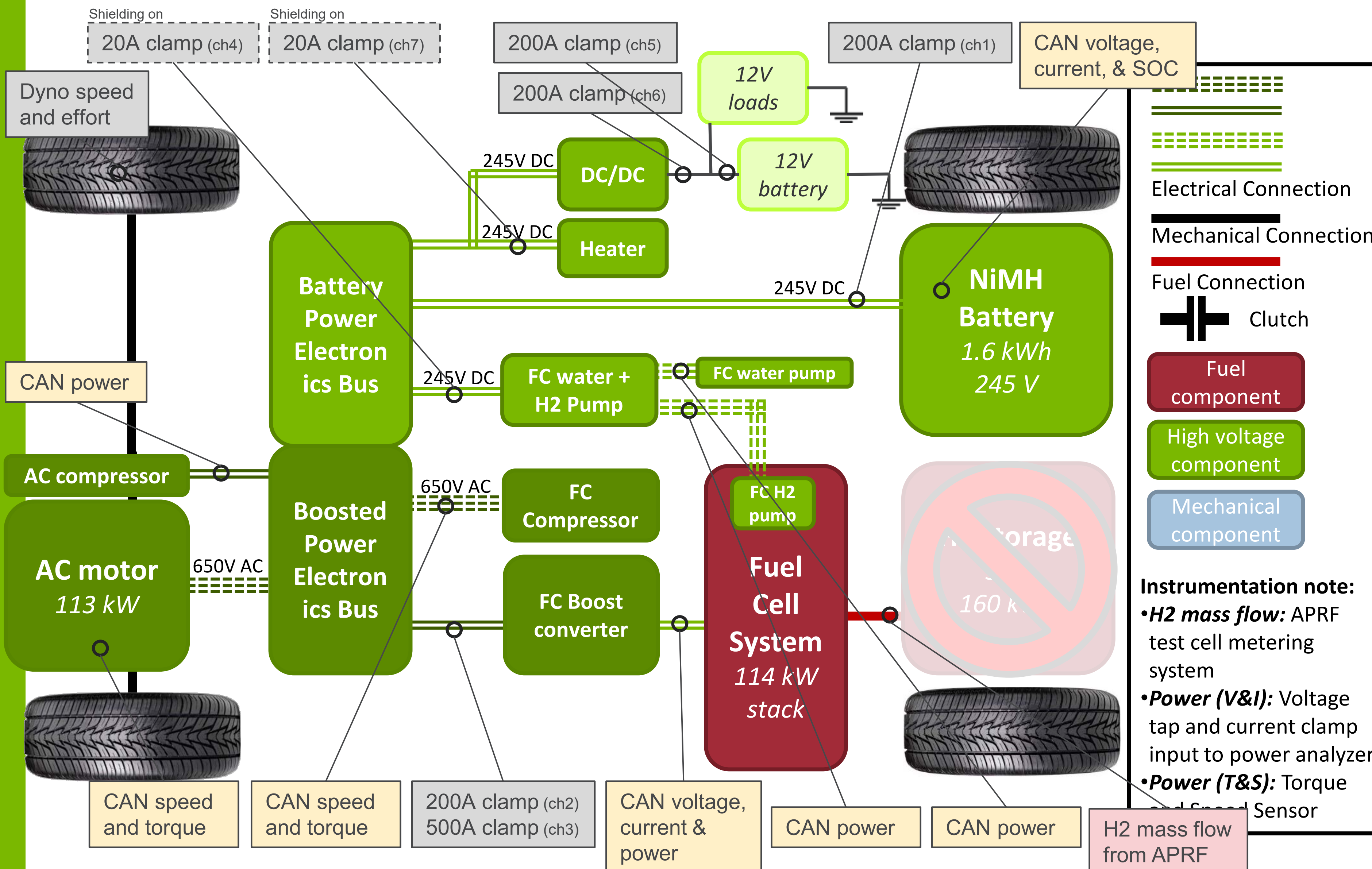
# APPROACH: POWERTRAIN INSTRUMENTATION



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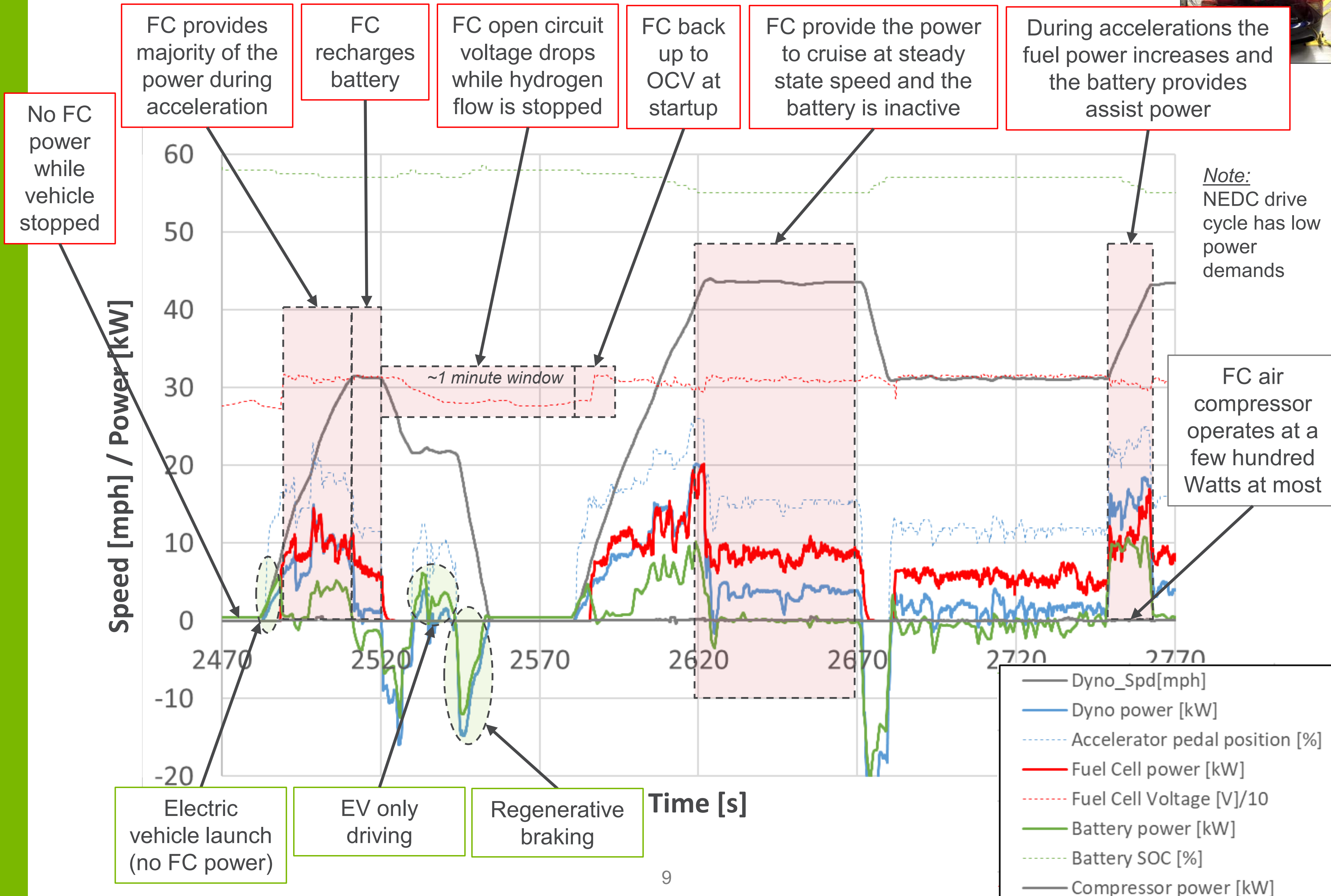
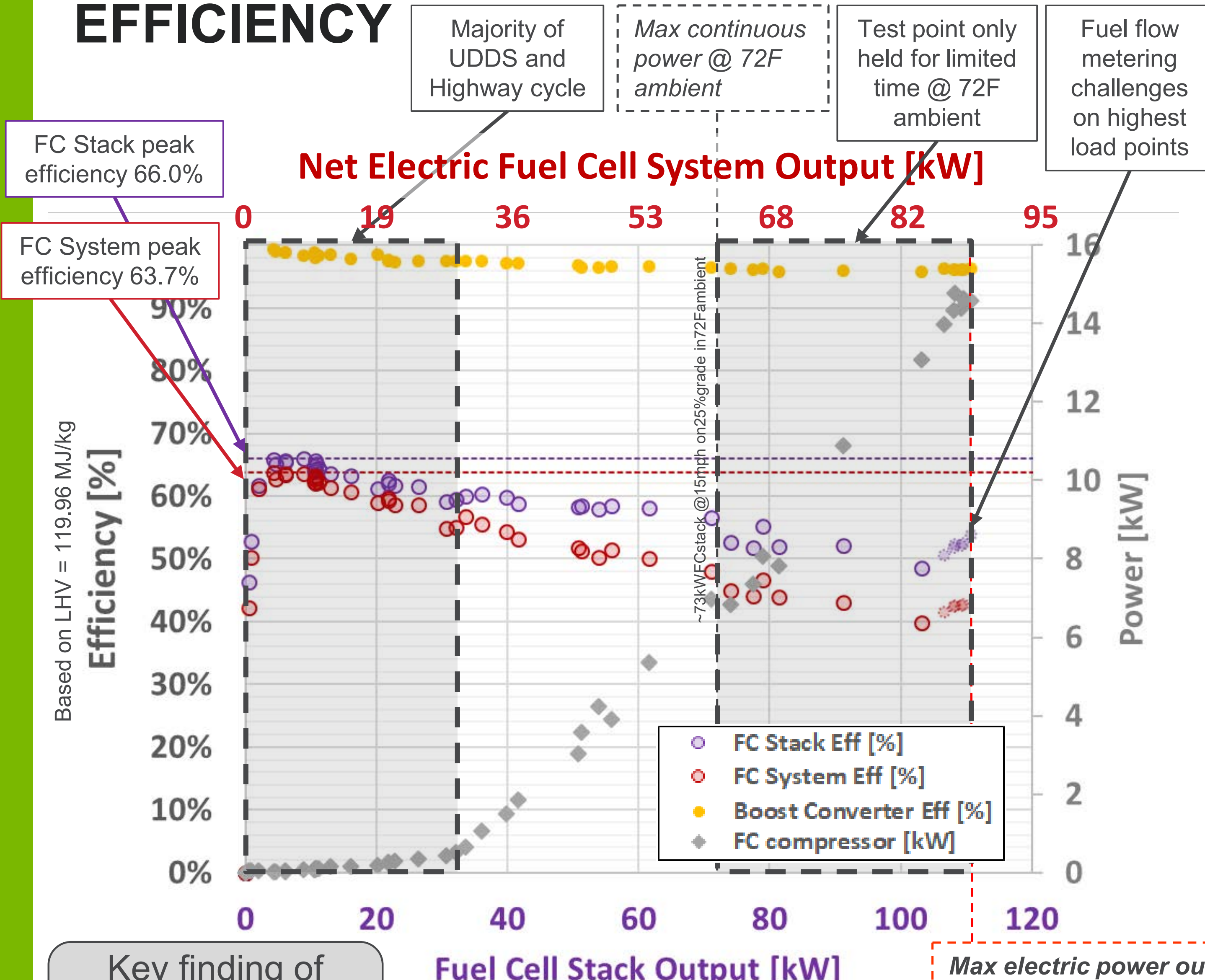
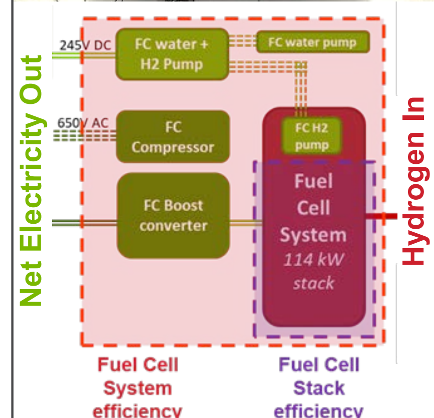
# ACCOMPLISHMENTS: BASIC SYSTEM OPERATION

# ACCOMPLISHMENTS: FUEL CELL STACK AND SYSTEM EFFICIENCY




2017 Toyota Mirai test data




***Note:*** Analysis based on steady state speed tests with 0%, 3% and 6% grade + WOT at 72F ambient temperatures

Key finding of efficiency based on laboratory data

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



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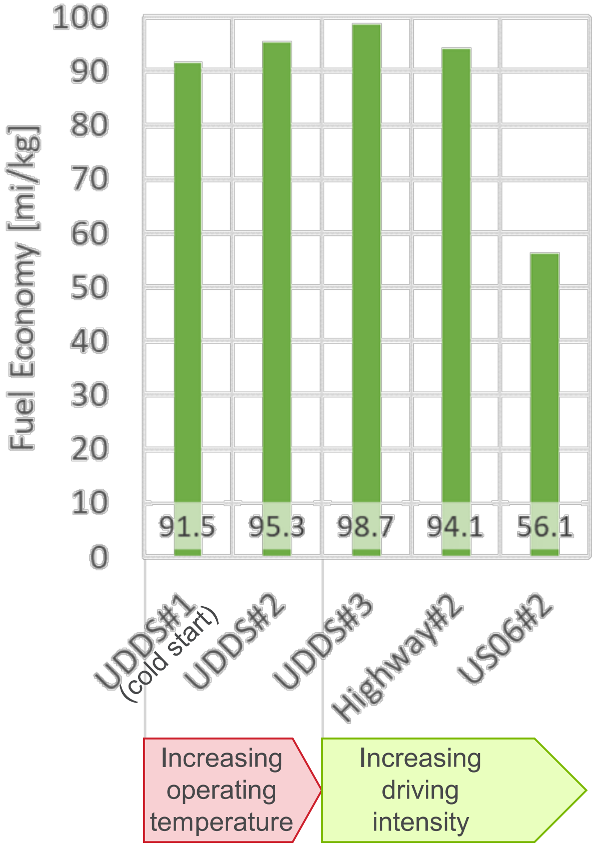
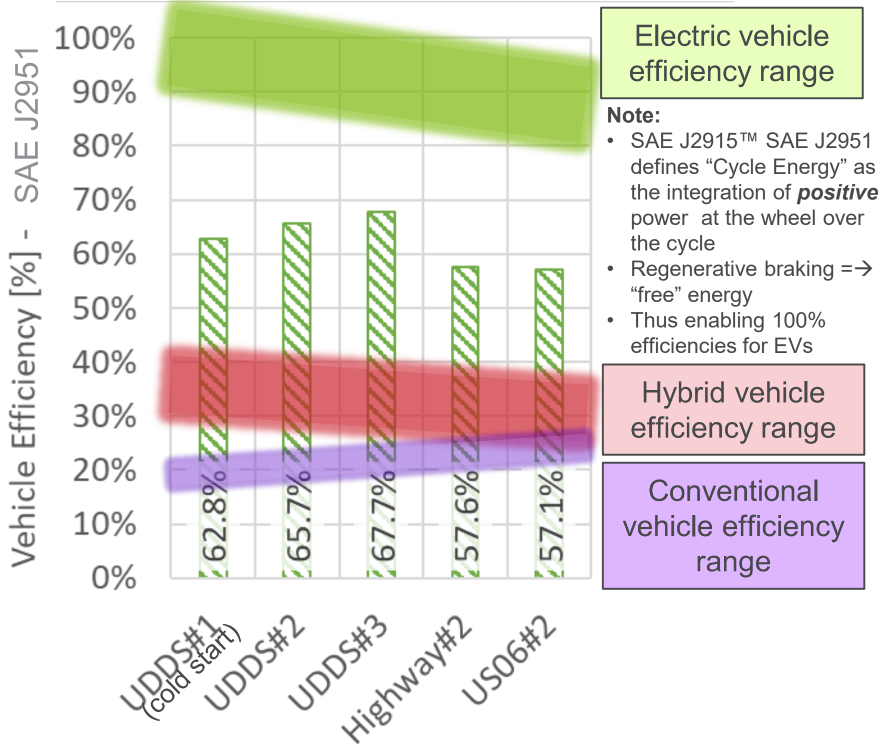
# ACCOMPLISHMENTS: CERTIFICATION CYCLES TEST RESULT AT 72F


High fuel economy.

*Caution: MPG illusion area.*




**Note:**
- SAE J2915™ 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

Overall high powertrain efficiencies.

Efficiency drops for higher driving intensity contrary to conventional vehicles.

# ACCOMPLISHMENTS: SPECIAL 1 HOUR IDLE TEST TO QUANTIFY THE IDLE HYDROGEN AT 72F


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

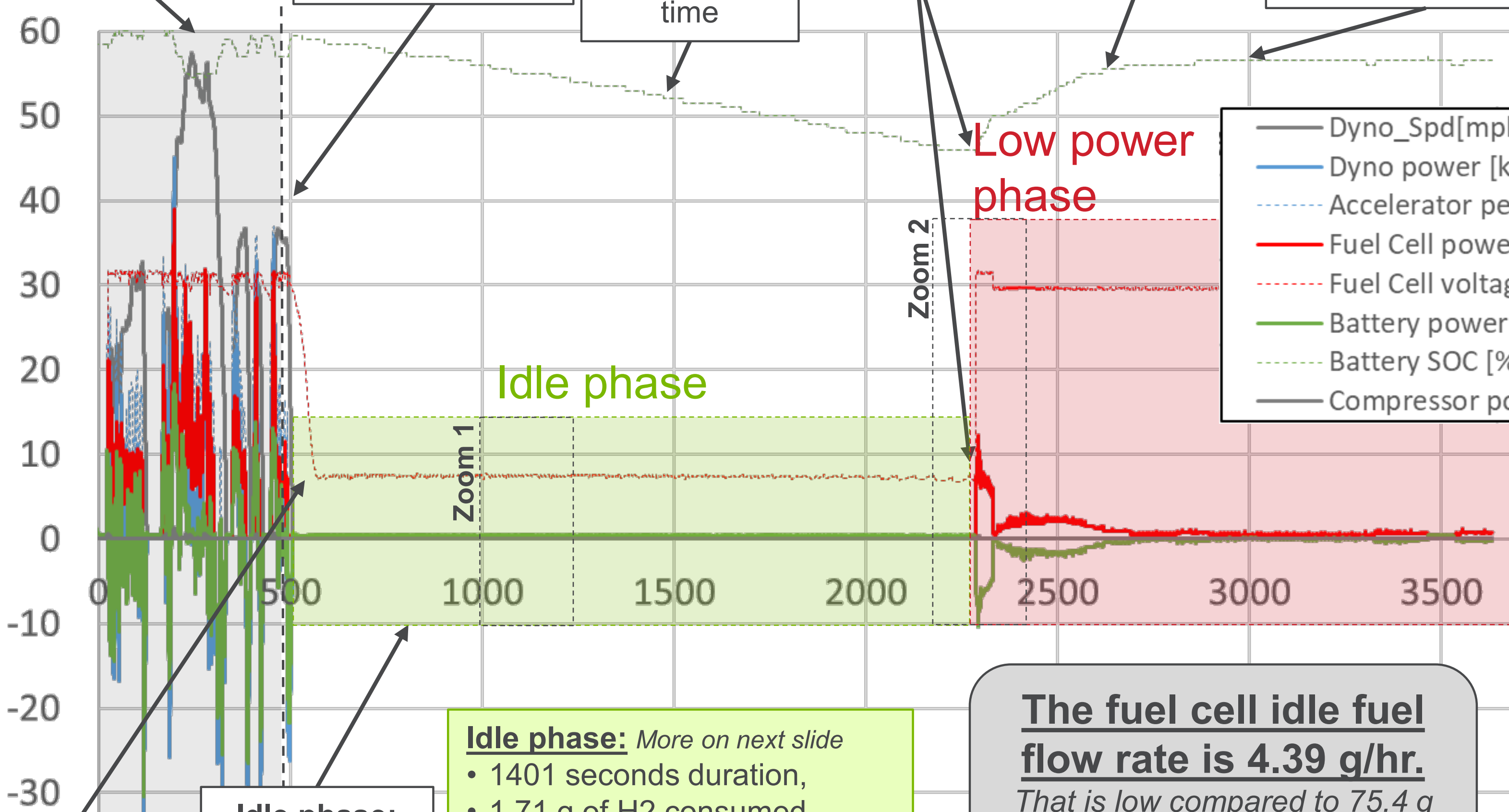
Vehicle stopped, transmission in park, ignition ON. Scenario: waiting in parking lot.

The battery SOC drops as accessory loads draw power over time

Low SOC triggers restart of FC system

FC system recharge the battery at 5~6kW

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




FC voltage drops from 315V to 80V

**Idle phase:** 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)*

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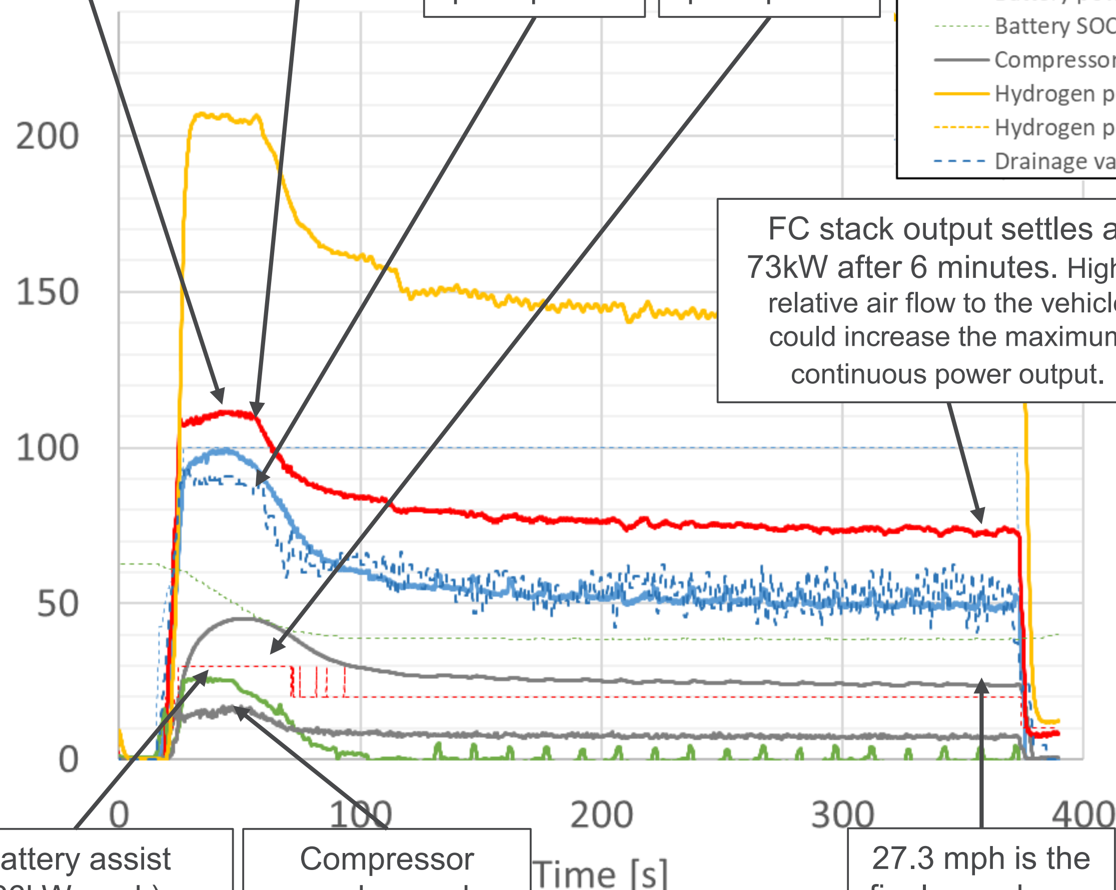
# ACCOMPLISHMENTS: MAXIMUM POWER TESTING ON A 25% GRADE AT 72F

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




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

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

*Test note:*

- This testing was performed at 72F test cell temperature.
- The test cell fan was matching the air flow to the vehicle speed.


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

# <u>ACCOMPLISHMENTS:</u> TESTING ACROSS A RANGE TEMPERATURES


Environmental Test Cell

| Hot testing<br>95F + 850 W/m$^2$<br>(35C) | Standard testing<br>72F<br>(22C) | Cold testing<br>20F<br>(-7C) | Cold testing<br>0F<br>(-18C) |
|---|---|---|---|
| Climate control<br>72F auto | Climate control<br>OFF | Climate control<br>72F auto | Climate control<br>72F auto |

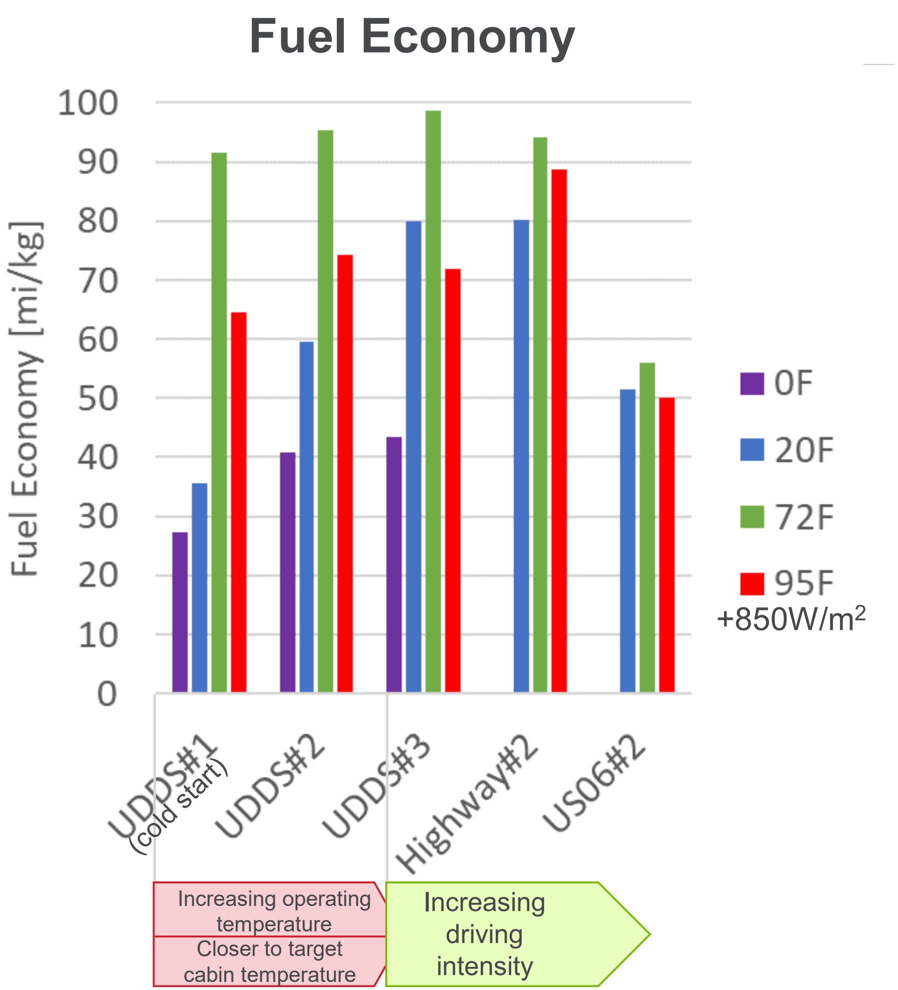
## Thermal testing

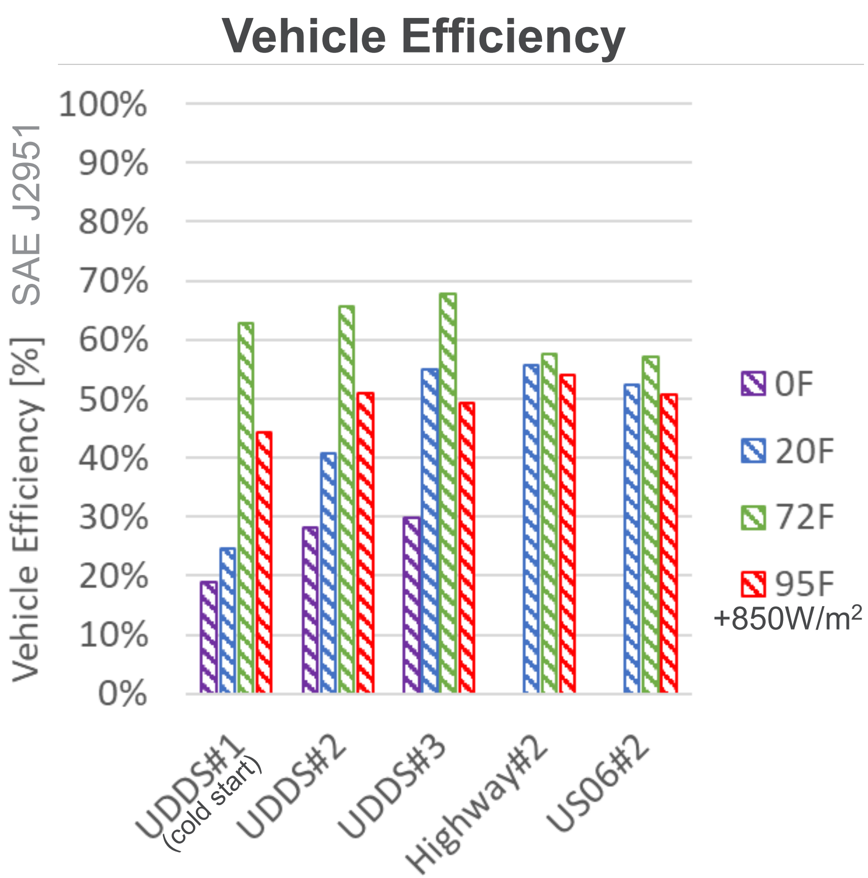
- The hood is closed in all cases
- The facility fan blows air dynamically across the front of the car at the same speed as the vehicle speed
- Cold start means that the vehicle was thermally ‘soaked’ at the target temperature for over 12 hours  (typically 16 hours)

## Test Sequence

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

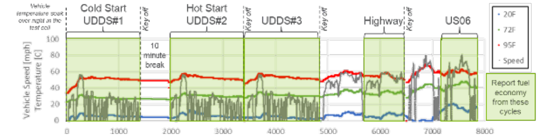

# ACCOMPLISHMENTS: IMPACT OF AMBIENT TEMPERATURE AND CLIMATE CONTROL ON FUEL ECONOMY

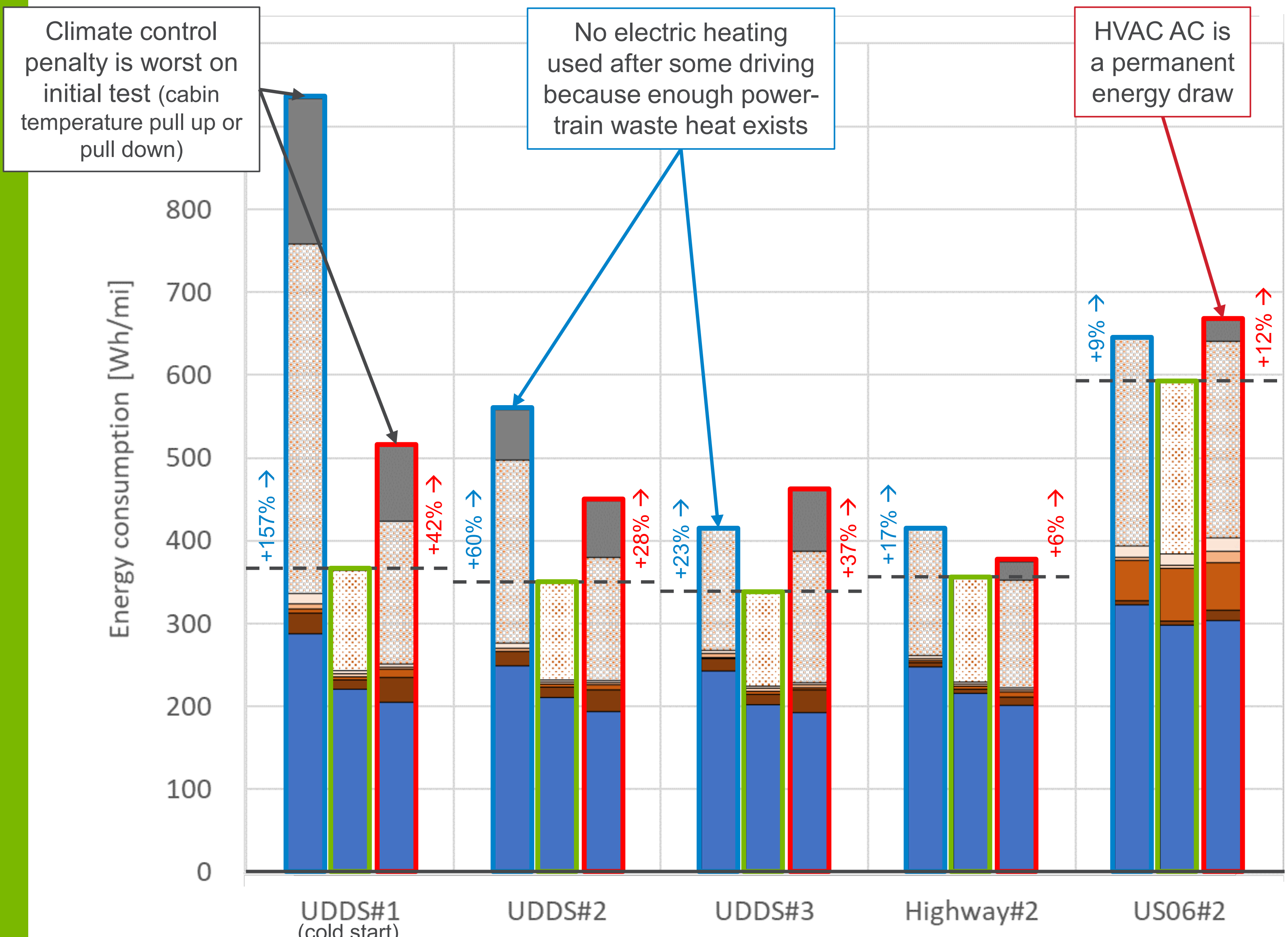



**Note:** At 72F the climate control was off. At 20F and 95F the climate control was set to 72F auto.

# WHERE DID THE ENERGY GO?





- Driving
- Access loads
- Boost losses
- FC access loads
- FC comp
- Losses
- HVAC

**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.

# COORDINATION AND COLLABORATIONS WITH OTHER INSTITUTIONS


*Collaboration with*

Transport Canada

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

# FUTURE WORK: THE PROJECT IS COMPLETED

Any proposed future work is subject to change based on funding levels

**APRF**

Independent and Public

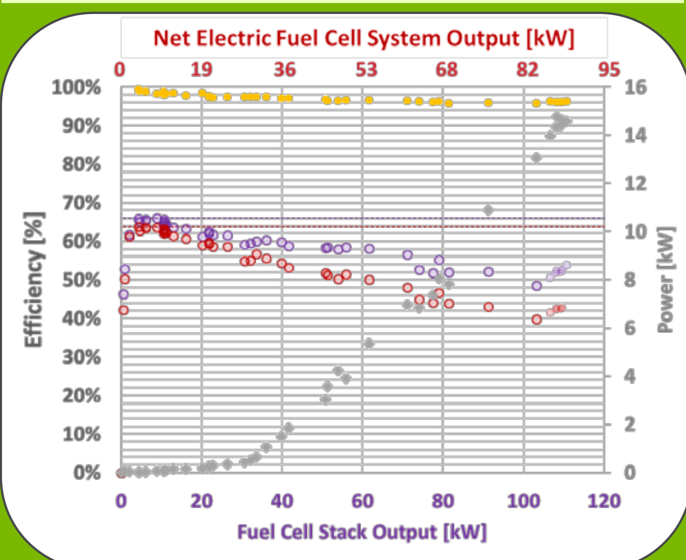
Data and Analysis

**DOE Evaluation Activities**
- National lab analysis
- Technology evaluation

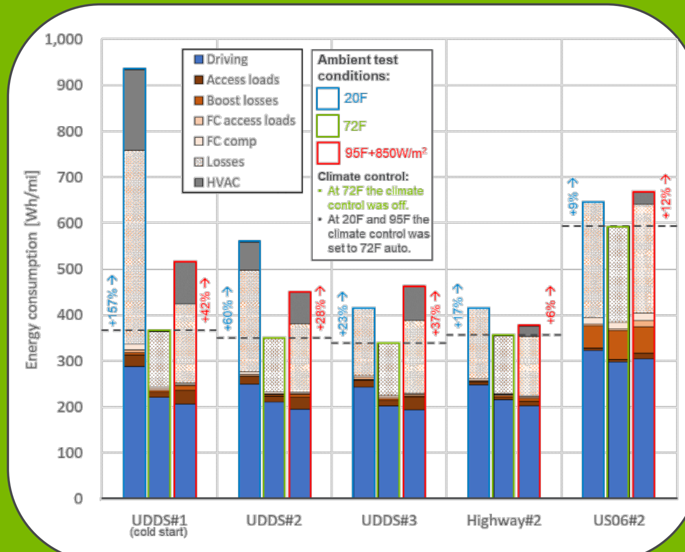
NREL, ORNL (Oak Ridge National Laboratory), INL (Idaho National Laboratory), Argonne National Laboratory

# CONCLUSION AND TAKEAWAYS FROM TESTING A 2017 TOYOTA MIRAI FUEL CELL VEHICLE

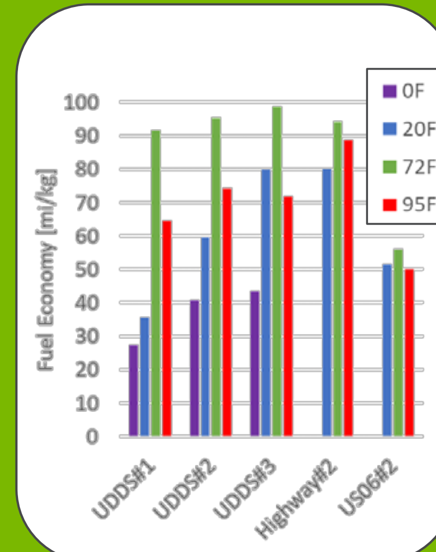

## Fuel Cell Stack and System Efficiency Analysis




## Energy Analysis Across Temperatures




## 0F to 95F Testing Completed




Fuel Cell dominant hybrid electric vehicle.

Fuel Cell peak efficiency:
- Stack 66.0%
- System 63.7%

Corelated FC system parameters and operation to output.

Contrary to BEVs, FCVs have enough waste heat to keep a cabin warm.

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.

The FC is starved of $H_2$ when not used. The fuel cell idle fuel flow rate is 4.39 g/hr.

10Hz data will be available publicly at www.anl.gov/d3



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# TECHNICAL BACK-UP SLIDES

# ADVANCED POWERTRAIN RESEARCH FACILITY
# 4WD CHASSIS DYNAMOMETER THERMAL TEST CELL

Argonne NATIONAL LABORATORY — U.S. DEPARTMENT OF ENERGY

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

- **Test cell features**
  - ✓ 4WD chassis dynamometer
    - Variable wheel base (180inches max)
    - 250 hp/axle
    - 300 to 12,000 lbs.. inertia emulation
  - ✓ Radiant sun energy emulation 850W/m$^2$ (adjustable)
  - ✓ Variable speed cooling fan (0–62mph)
  - ✓ Gaseous fuel and hydrogen capable
  - ✓ Diesel: Dilution tunnel, PM, HFID
- **Thermal chamber**
  - ✓ EPA 5 cycle capable (20°F, 72°F and 95°F + 850W/m$^2$ solar load)
  - ✓ Demonstrated as low as 0°F
  - ✓ Intermediate temperatures possible


*APRF (Advanced Powertrain Research Facility)*

- **Research aspects**
  - ✓ 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
  - ✓ Infra Red 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