Report # ANL/ESD-18/12

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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Prepared for U.S. Department of Energy, Fuel Cell Technologies Office

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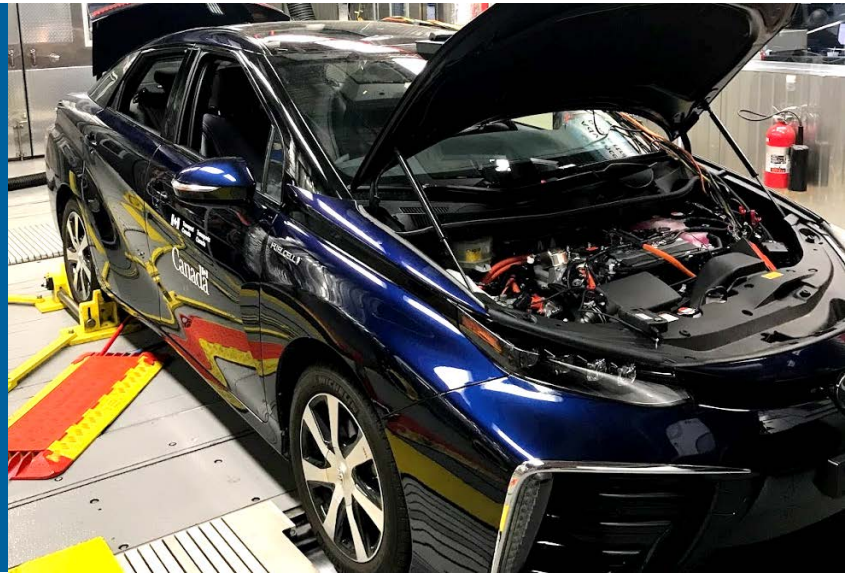
TECHNOLOGY ASSESSMENT OF A FUEL CELL VEHICLE: 2017 TOYOTA MIRAI



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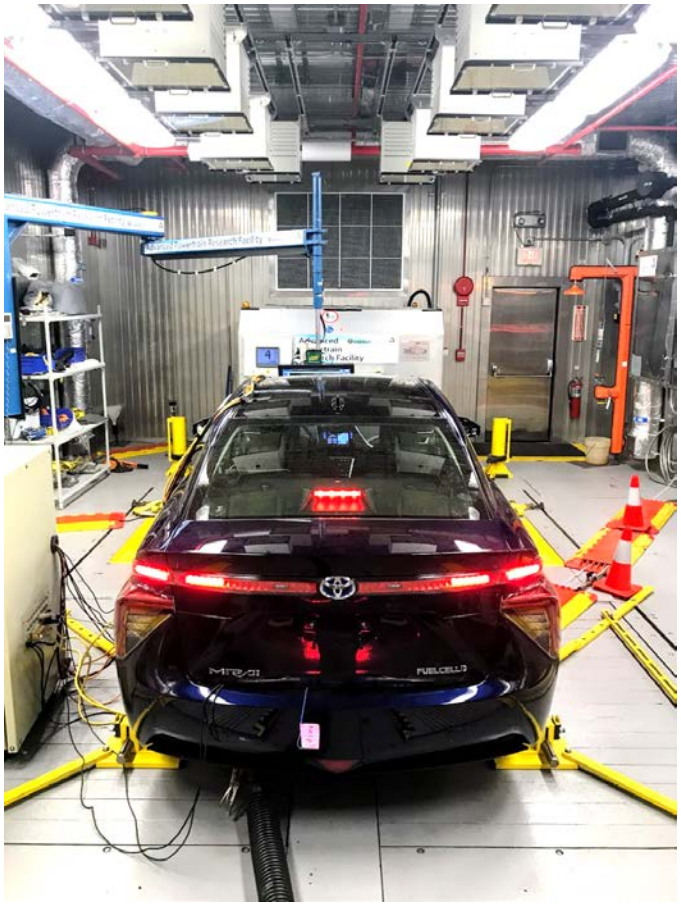
June 2018 (v10)
Argonne National Laboratory, IL

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

Vehicle overview and instrumentation	Link
Fuel cell hybrid powertrain operation overview • On cycles • By components	Link
Fuel cell stack and system efficiency (steady load mapping)	Link
Certification drive cycle testing and results at 72F • Results with average efficiencies • Energy analysis	Link
Fuel cell system operation • Air & hydrogen as function of power output • FC idle testing • FC maximum power output (continuous and peak pulses)	Link
Impact of temperatures: 0F, 20F, 72F and 95F+850W/m^2 • Fuel economy results and energy analysis ults for UDDS, Highway and US06 across temperatures • Fuel cell system shut down from 72F to 0F • Fuel cell system cold start from 72F to 0F • Power delivery of FC conditioned at 0F • Hill climb test' at 95F with solar load	Link
Summary and take away points	Link

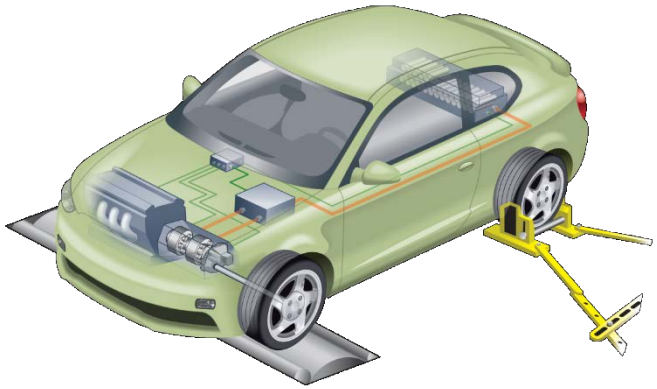
Collaboration with

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"

U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

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

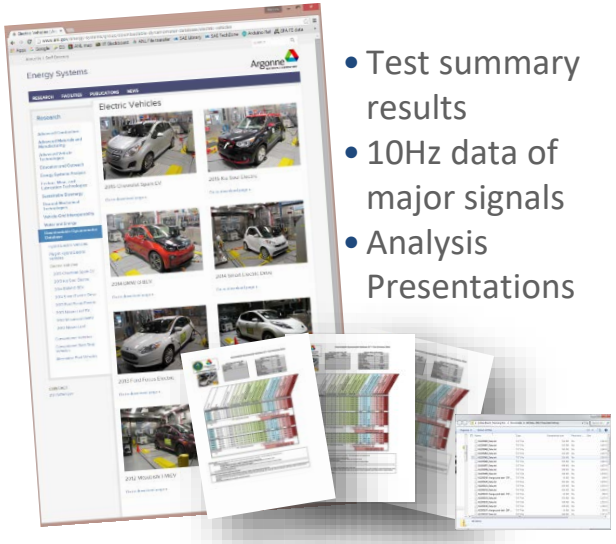
Vehicle level

- 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

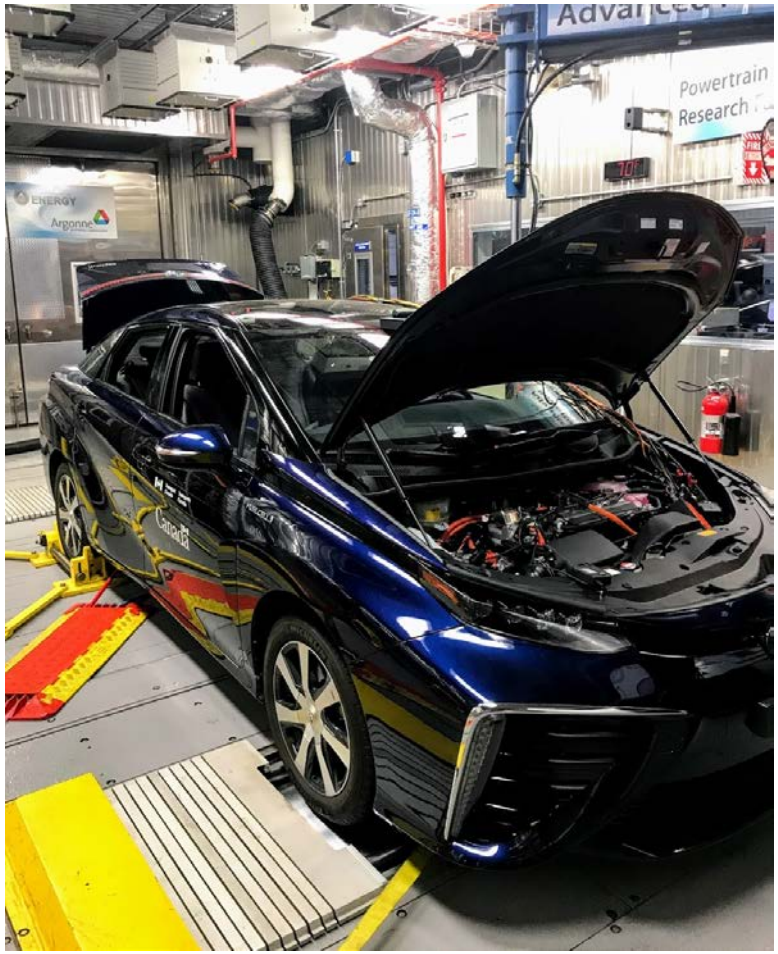
Downloadable Dynamometer Database www.anl.gov/d3



- Test summary results
- 10Hz data of major signals
- Analysis Presentations

VEHICLE OVERVIEW AND INSTRUMENTATION

2017 TOYOTA MIRAI FUEL CELL VEHICLE



2017 Toyota Mirai Fuel Cell Vehicle	
Vehicle architecture	Fuel Cell Series Hybrid Vehicle
Test weight	4250 lbs
Power plant	Fuel Cell Solid Polymer Electrolyte Fuel Cell* 370 cells in stack 114kW*, 3.1 kW/L, 2.0 kW/kg Flow channel: 3D fine-mesh flow field (cathode) Humidification: Internal circulation system (humidifier-less)
Hydrogen storage	10,000 psi, 5 kg of H2
Battery	Nickel-metal Hydride, 1.6 kWh, 245V *
Climate control	Electrical AC compressor Electric heater
EPA Label Fuel Economy (mpge)	66 City /66 Hwy /66 Combined+
Performance	Reported 0-60 Time: 9.0s^

*Manufacturer data
+www.fueleconomy.gov
^www.zeroto60times.com

Transport Canada

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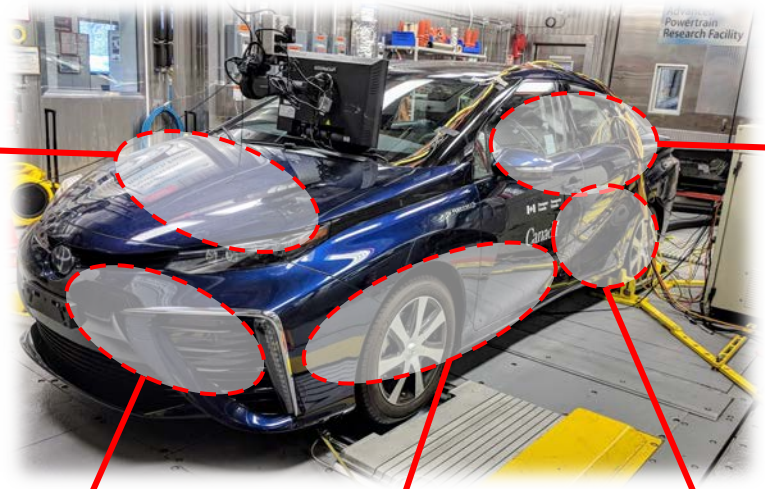
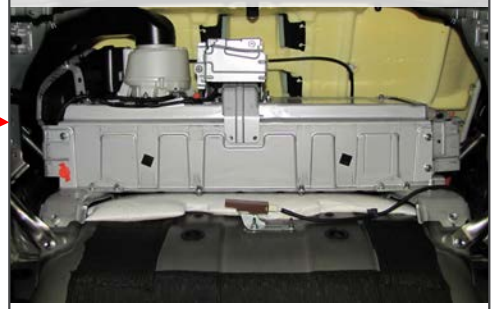
TOYOTA MIRAI POWERTRAIN COMPONENT LAYOUT

Power Electronics

The high voltage power distribution system is under the hood along with the inverters for the motors.



Battery Pack



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

Electric motors

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

Fuel Cell System

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

On-board hydrogen Storage

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

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.

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:

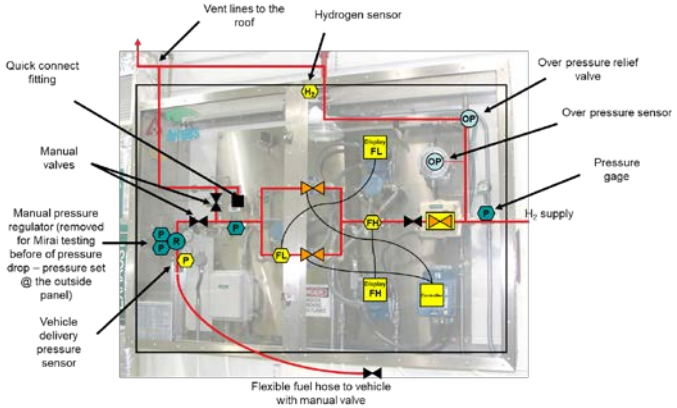
- Integrated mass flow meter → **Yes**
- Ideal gas law → **Possible** *but more complicated and not the intension of this work*
- ~~Gravimetric~~ → **No** *too expensive for the budget of this work*

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
- Further specifications: http://www.emerson.com/en-us/catalog/micro-motion-elite-coriolis



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 additional to ethernet.
- Further Specifications: https://www.hioki.com/en/products/detail/?product_key=6413

High voltage tap

Power analyzers

Current clamps

SAMPLE OF HIGHLIGHTED CAN MESSAGES (TOTAL 400+)

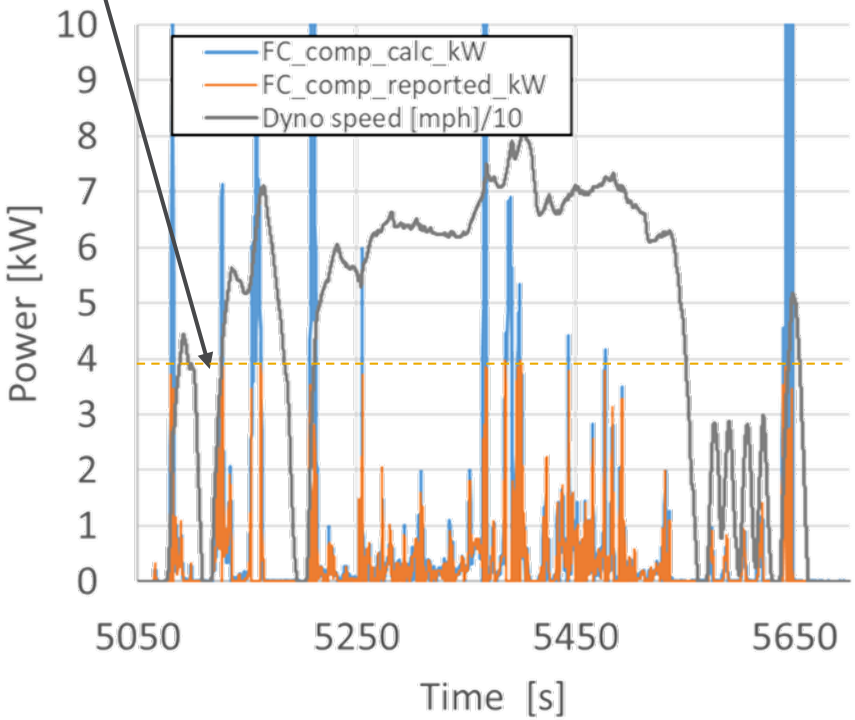
Data from idling the vehicle

Possible Vehicle Communication Signal	Value	Unit
FC Voltage before Boosting	239.1	V
FC Voltage after Boosting	345.5	V
FC Current	2.9	A
Target FC Output Power	4.7	kW
FC output Power	0.94	KW
FC Stack Air Temperature (FC Stack Inlet)	38	C
FC Stack. Air Pressure (FC Stack Inlet)	-0.91	kPa(gauge)
Intake Air Temperature	26	C
Mass Air Flow Value	300.9	NL/min
Air Compressor Revolution	639.5	rpm
Air Compressor Consumption Power	0	W
FC Stack Coolant Temperature (Radiator Outlet)	29	C
FC Stack Coolant Temperature (FC Stack Outlet)	45	C
FC Water Pump Revolution	735.25	rpm
FC Water Pump Consumption Power	19	V
Radiator Fan 1 Driving Request	0	%
Radiator Fan 2 Driving Request	0	%
Estimated Radiator Rotary 'Valve Position	0	%
FC Stack Air Temperature (FC Stack Inlet)	38	C
FC Stack Air Pressure (FC Stack Inlet)	-1.35	kPa(gauge)
Mass Air Flow Value	299.7	NL/min
Hydrogen Pump Revolution	607.35	rpm
Hydrogen Pump Consumption Power	19	W
Smoothed Value of Low-range Hydrogen Pressure	54.5	kPa(gauge)
Hydrogen Injector Injection Number	1	
FC Voltage before Boosting	293.9	
FC Current	3.35	
FC Mode	FC Working	
Low Temperature Mode	2	
FC Stack Power Generation Mode	*Intermittent*	
FC Stack Cell Average Minimum Voltage	0.02	V
FC Stack Cell Minimum Voltage	0	V
FC Stack Cell Minimum Average Voltage Cell Channel No	31	ch
FC Stack Cell Minimum Voltage Cell Channel No	1	ch
FC Total Voltage	293.9	
FC Stack Internal Resistance	0.11	ohm
Hydrogen Pump Motor Temperature	38	ch
Hydrogen Injector I Injection Request	Off	
Hydrogen Injector 2 Injection Request	Off	
Hydrogen Injector 3 Injection Request	Off	

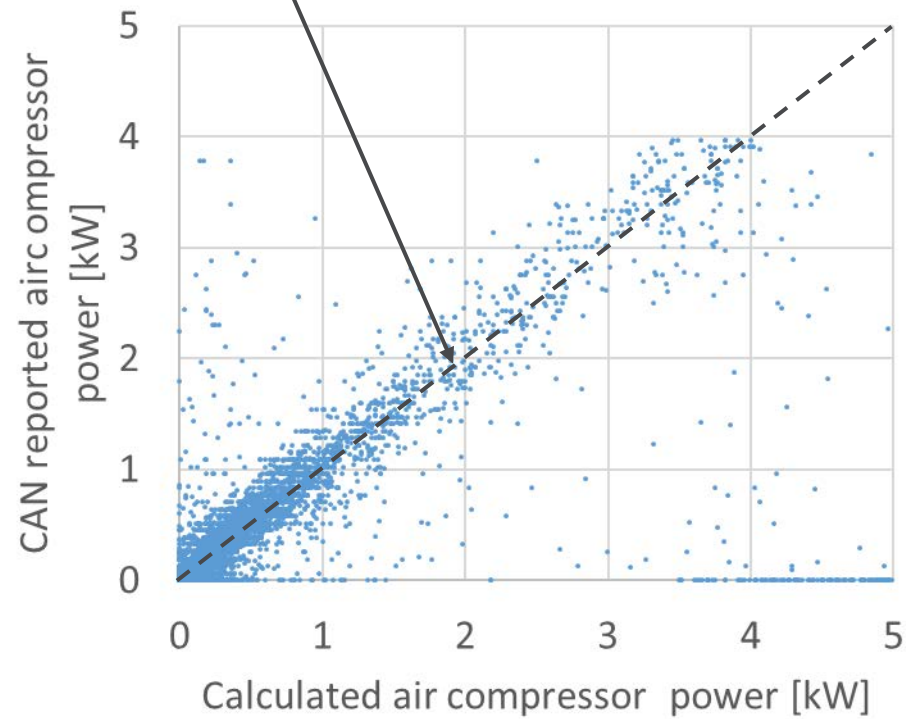
Exhaust Drainage Valve Driving Request	Off	
Low-range Hydrogen Pressure	29.07	kPa(gauge)
Internal Resistance ROB	0.019	ohm
Internal Resistance RI17	0.019	ohm
Battery Pack Current Value (1B Correction)	-1.97	A
Delta SOC	0	%
SOC IG-ON	64	%
Status of Charge Min	45.5	%
Cooling Fan Mode 1	0	
Drive Motor Revolution	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	500	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	%

AIR COMPRESSOR POWER CALCULATIONS

The CAN reported air compressor power message ('*air_compressor_consumption_power_FC_W*') clips at the value of ~3.97kW



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.

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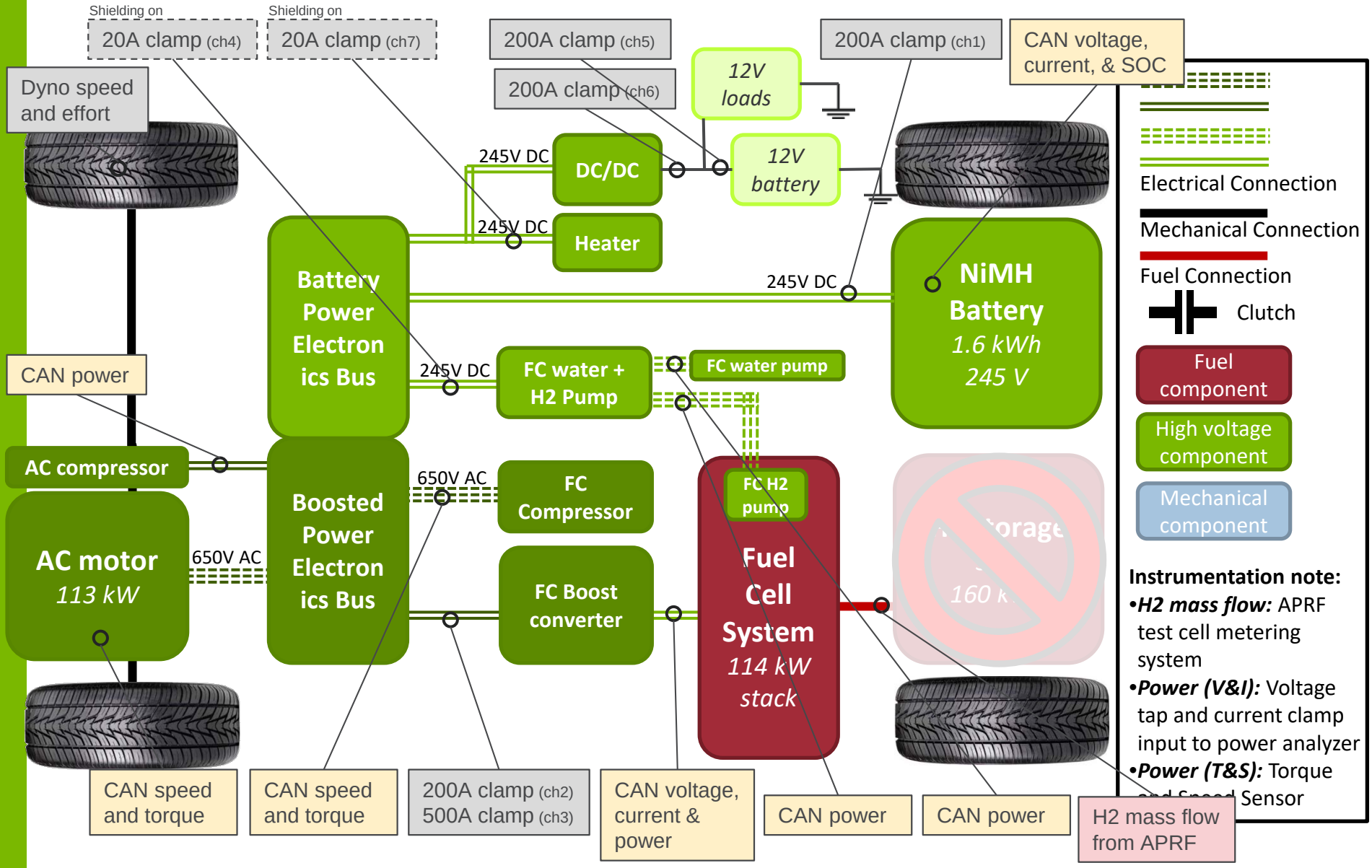
POWERTRAIN ARCHITECTURE AND MEASUREMENTS



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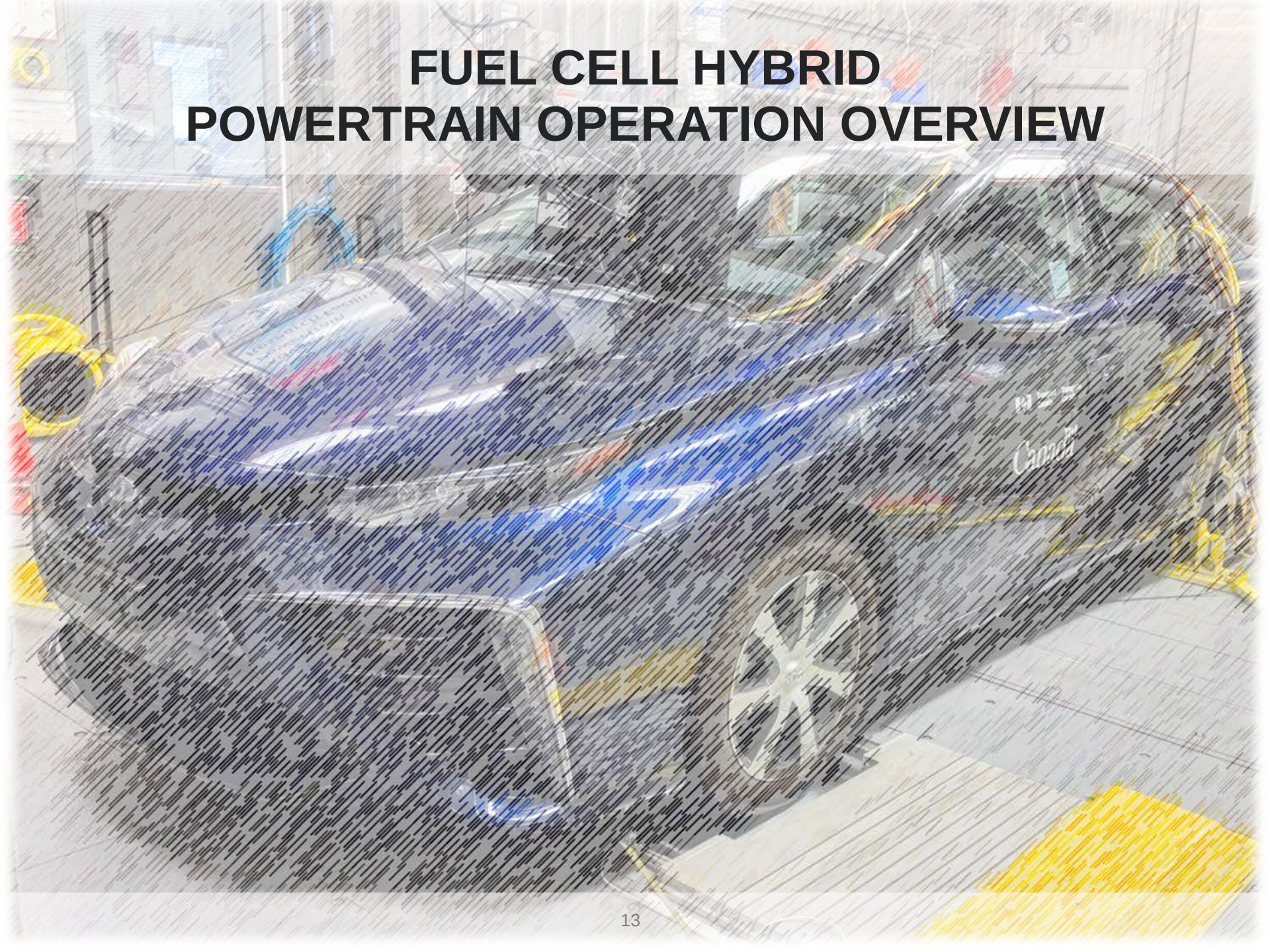
FUEL CELL HYBRID POWERTRAIN OPERATION OVERVIEW



BASIC FUEL CELL HYBRID SYSTEM OPERATION

No FC power while vehicle stopped

FC provides majority of the power during acceleration

FC recharges battery

FC open circuit voltage drops while hydrogen flow is stopped

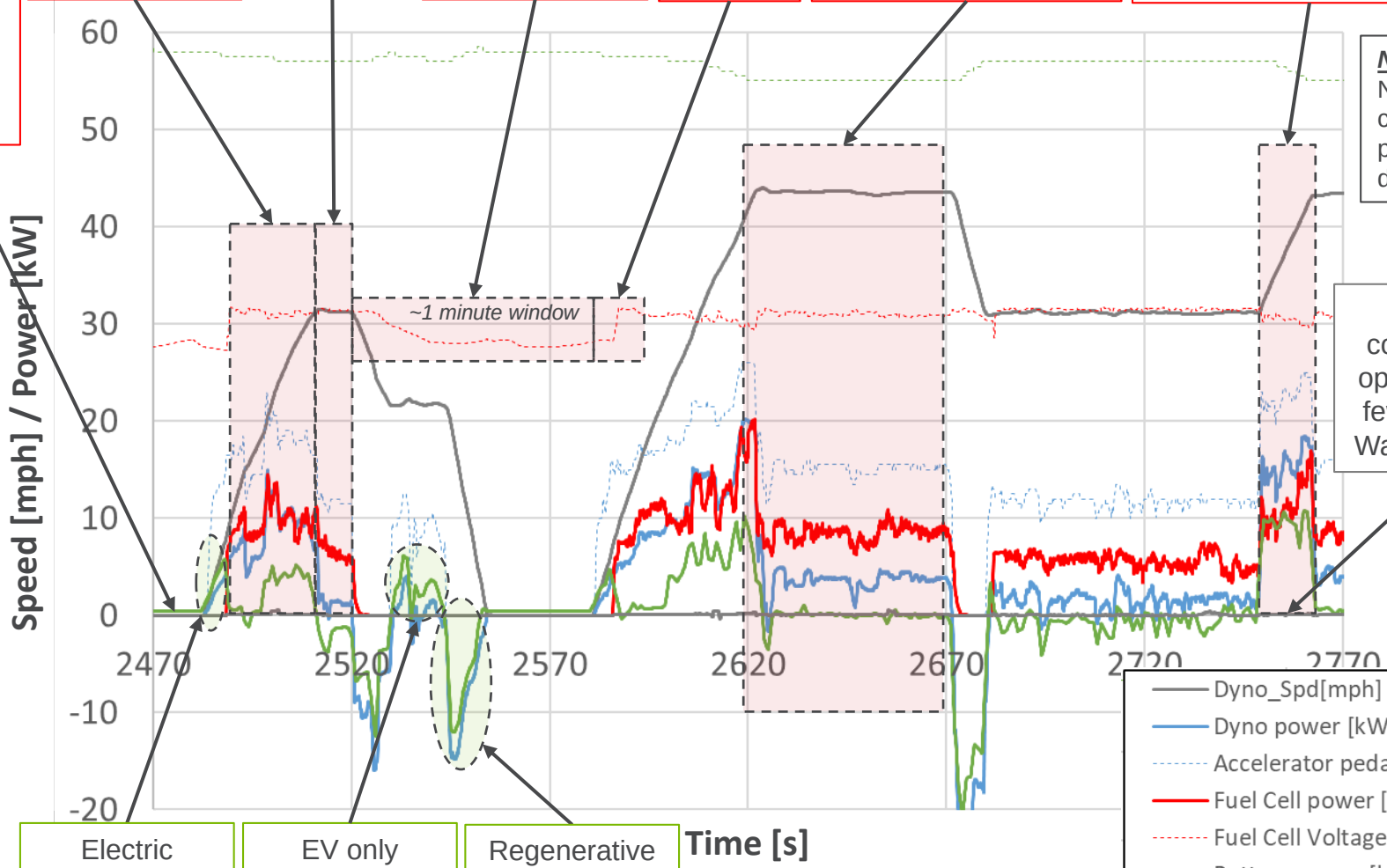
FC back up to OCV at startup

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

Note: NEDC drive cycle has low power demands

FC air compressor operates at a few hundred Watts at most



Electric vehicle launch (no FC power)

EV only driving

Regenerative braking

FUEL CELL OPERATION ON AGGRESSIVE DRIVING

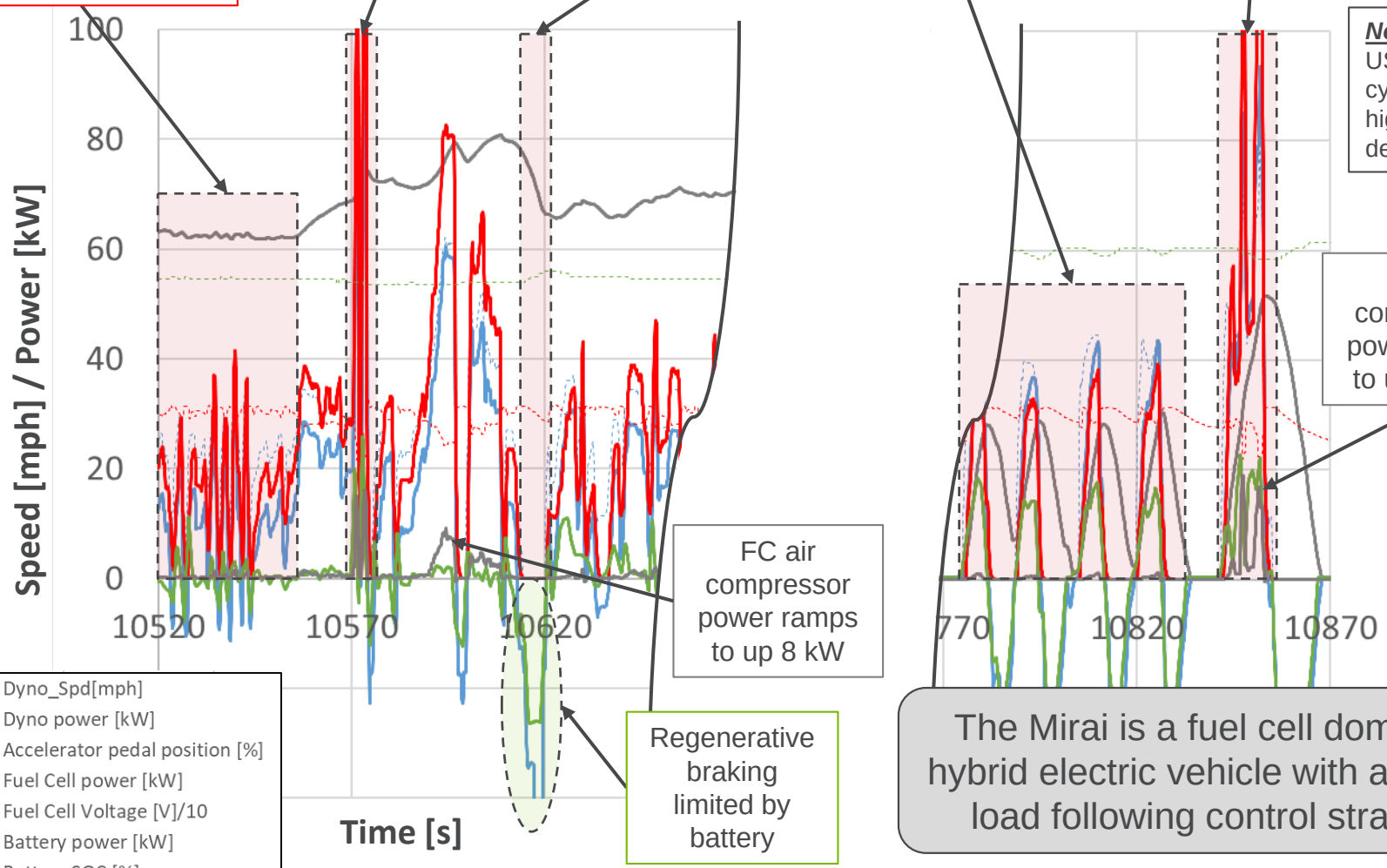
Highly dynamic speed changes while cruising and the FC power follows the dynamic load changes

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



Note: US06 drive cycle has high power demands

FC air compressor power ramps to up 15 kW

FC air compressor power ramps to up 8 kW

Regenerative braking limited by battery

The Mirai is a fuel cell dominant hybrid electric vehicle with a strong load following control strategy

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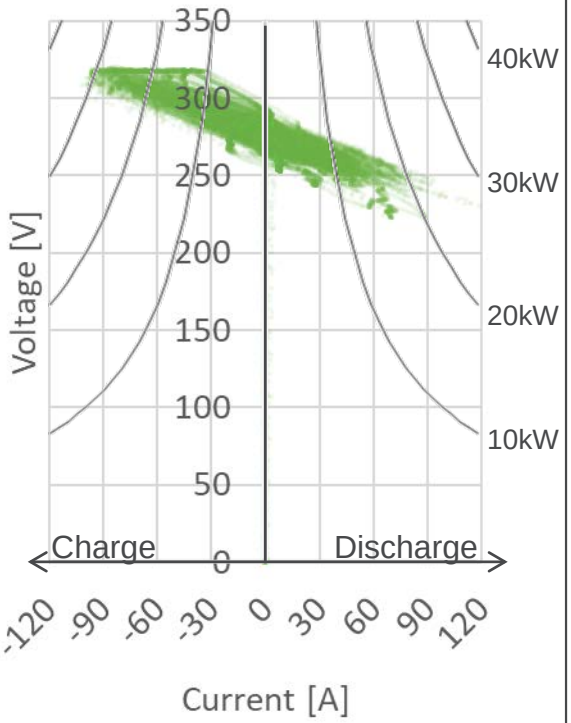
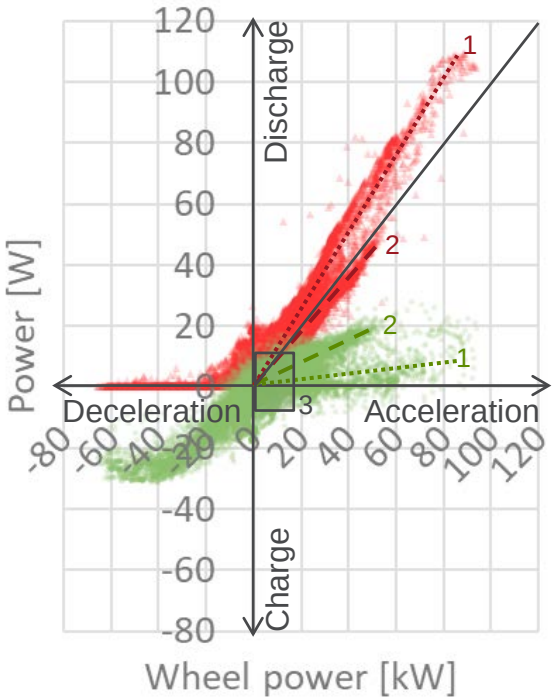
FUEL CELL AND BATTERY USAGE ENVELOPS

Battery polarization curve



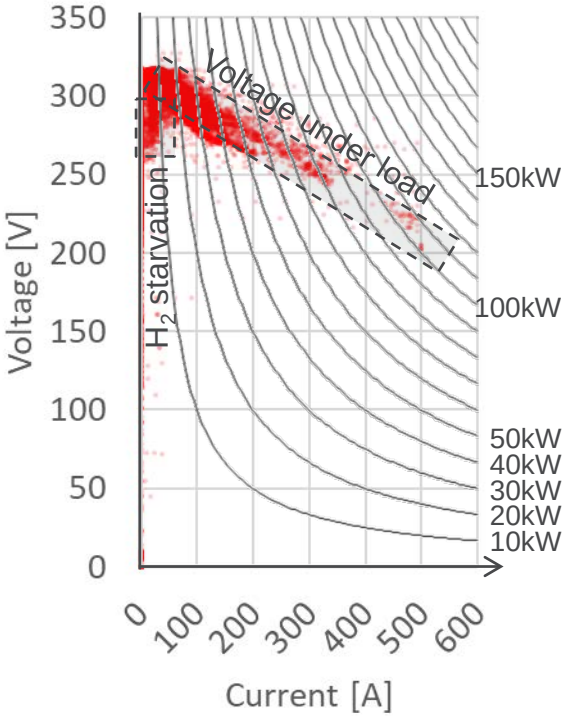
Compared to gasoline HEVs the battery polarization curves is more extensive on the charging side for the fuel cell hybrid.

FC vs Battery power



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.

Fuel Cell polarization curve



Open Circuit Voltage is around 315V. The voltage drop while the fuel cell is idled is apparent.

Note:
The 10 Hz data to generate these graphs is from NEDCx2, UDDSx3, Highwayx2, US06x2, maximum acceleration x3, and steady state speed tests.

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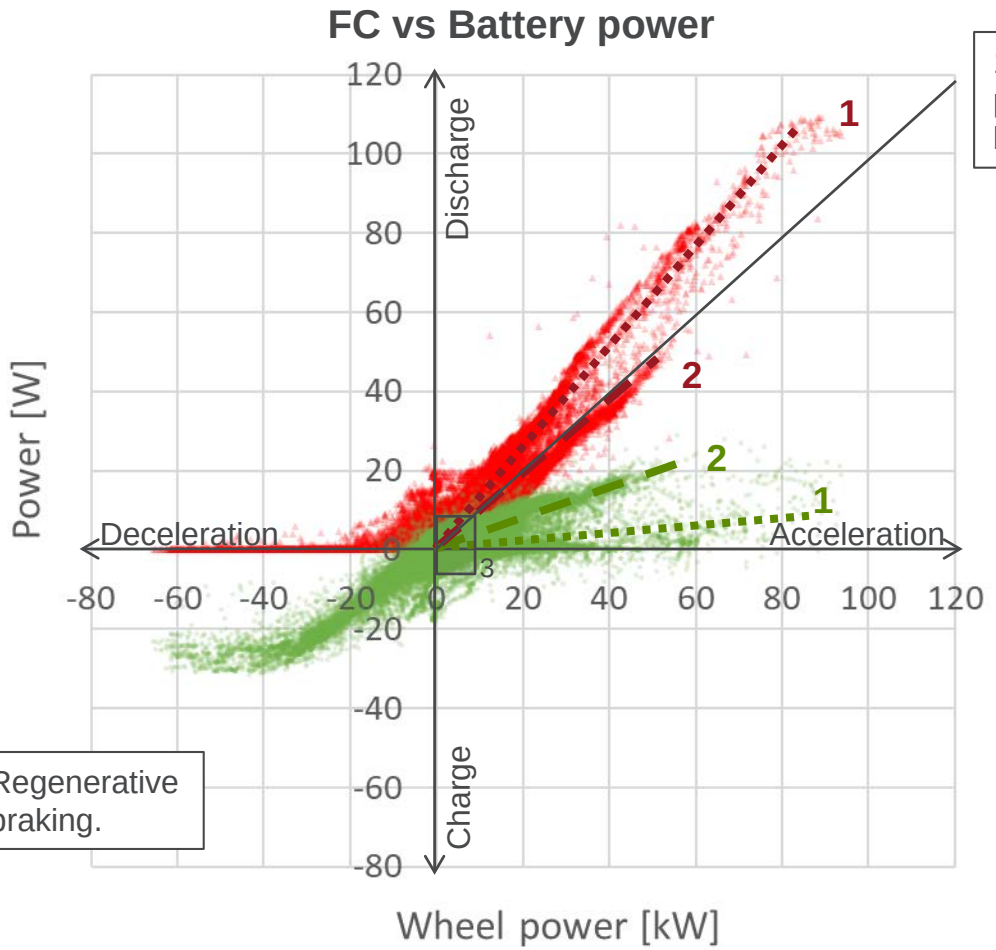
FUEL CELL AND BATTERY USAGE ENVELOPS



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.

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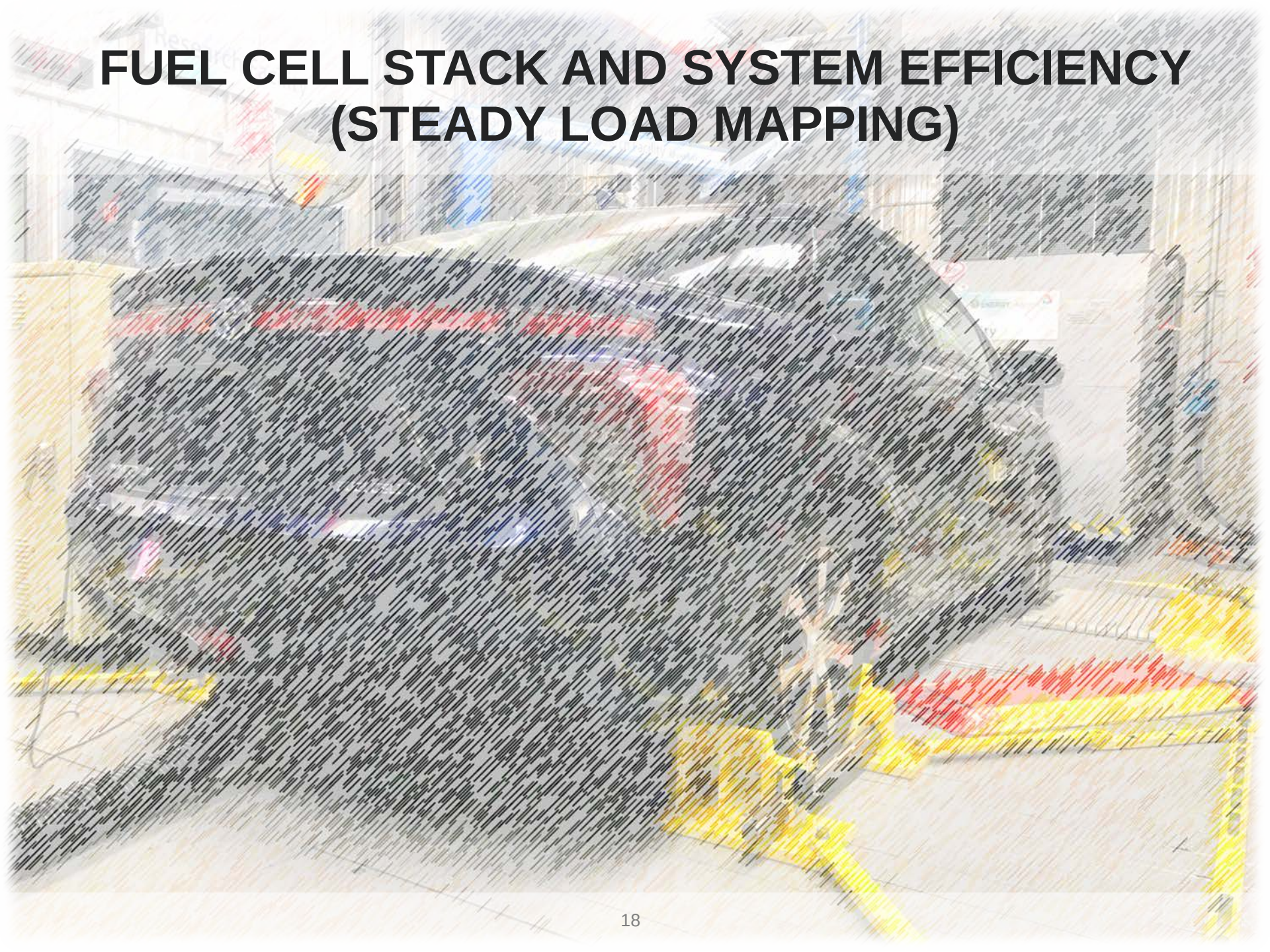
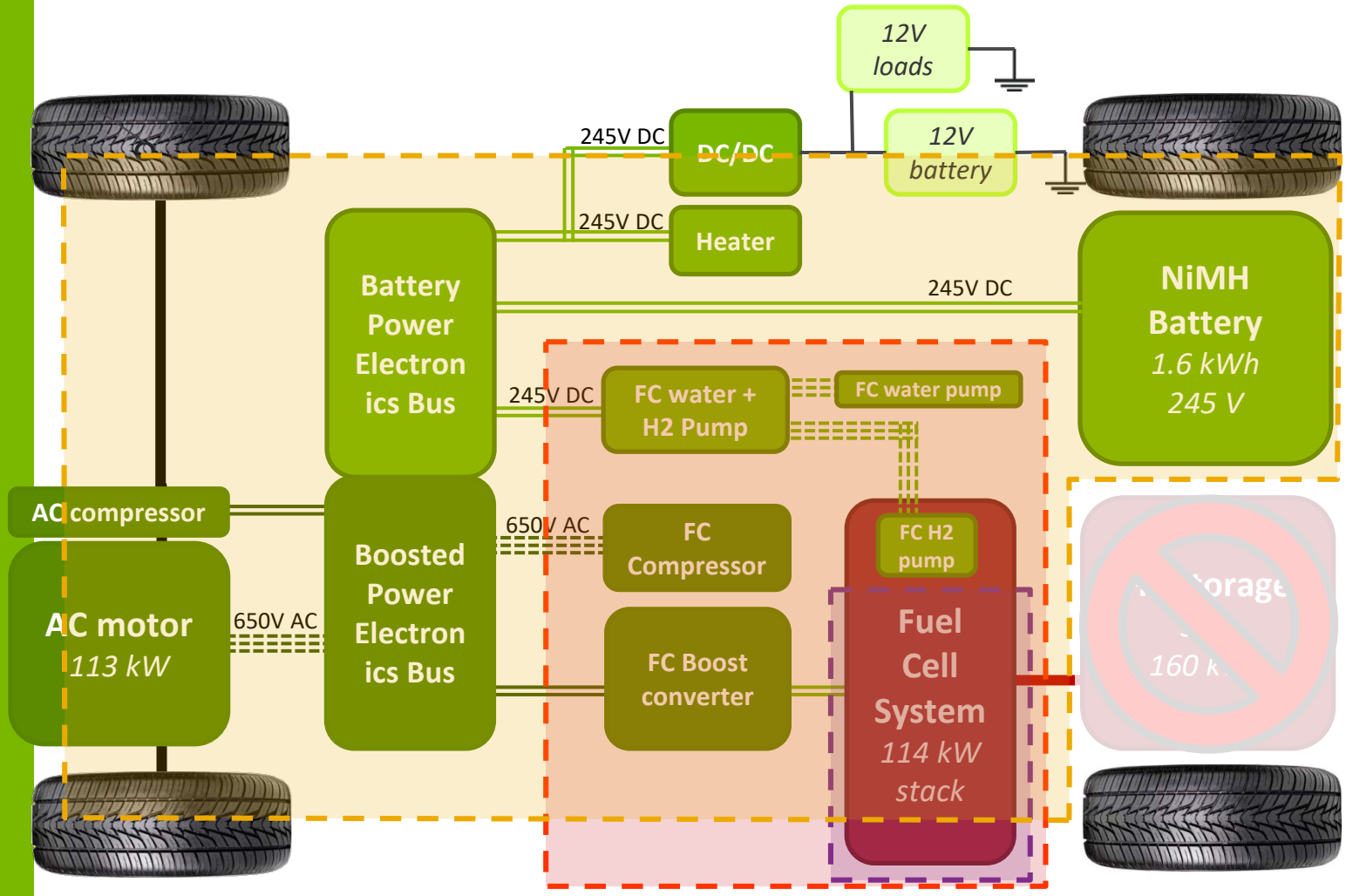
FUEL CELL STACK AND SYSTEM EFFICIENCY (STEADY LOAD MAPPING)



DEFINING THE SYSTEM BOUNDARIES FOR EFFICIENCY CALCULATIONS



Electrical Connection

Mechanical Connection

Fuel Connection

Clutch

Fuel component

High voltage component

Mechanical component

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

Vehicle Efficiency
(SAE J2951™ positive cycle energy based)

Fuel Cell System Efficiency

Fuel Cell Stack Efficiency

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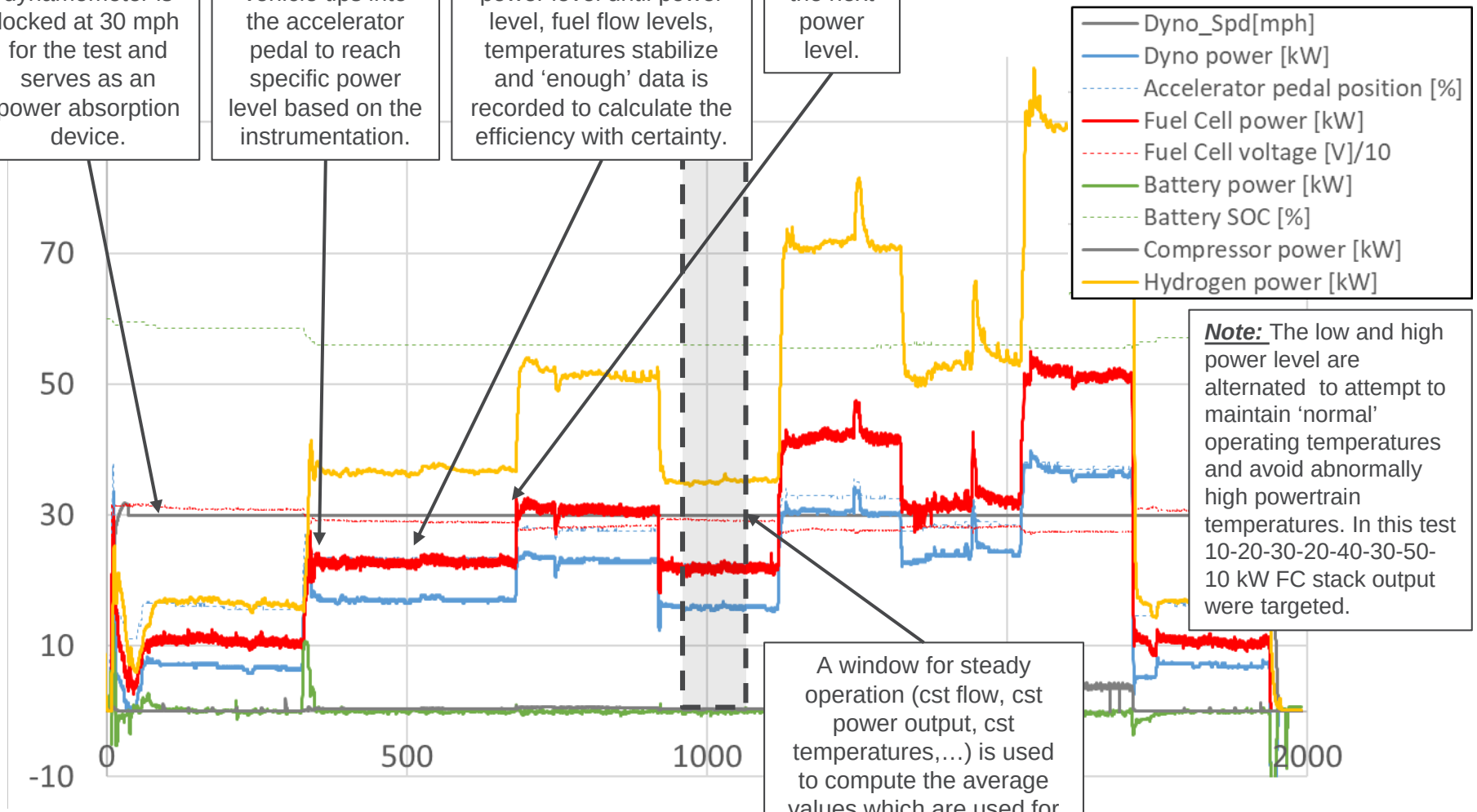
FUEL CELL SYSTEM MAPPING IN VEHICLE ON CHASSIS DYNAMOMETER

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

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FUEL CELL STACK AND SYSTEM EFFICIENCY

Majority of UDDS and Highway cycle

Max continuous power @ 95F ambient + solar

Max continuous power @ 72F ambient

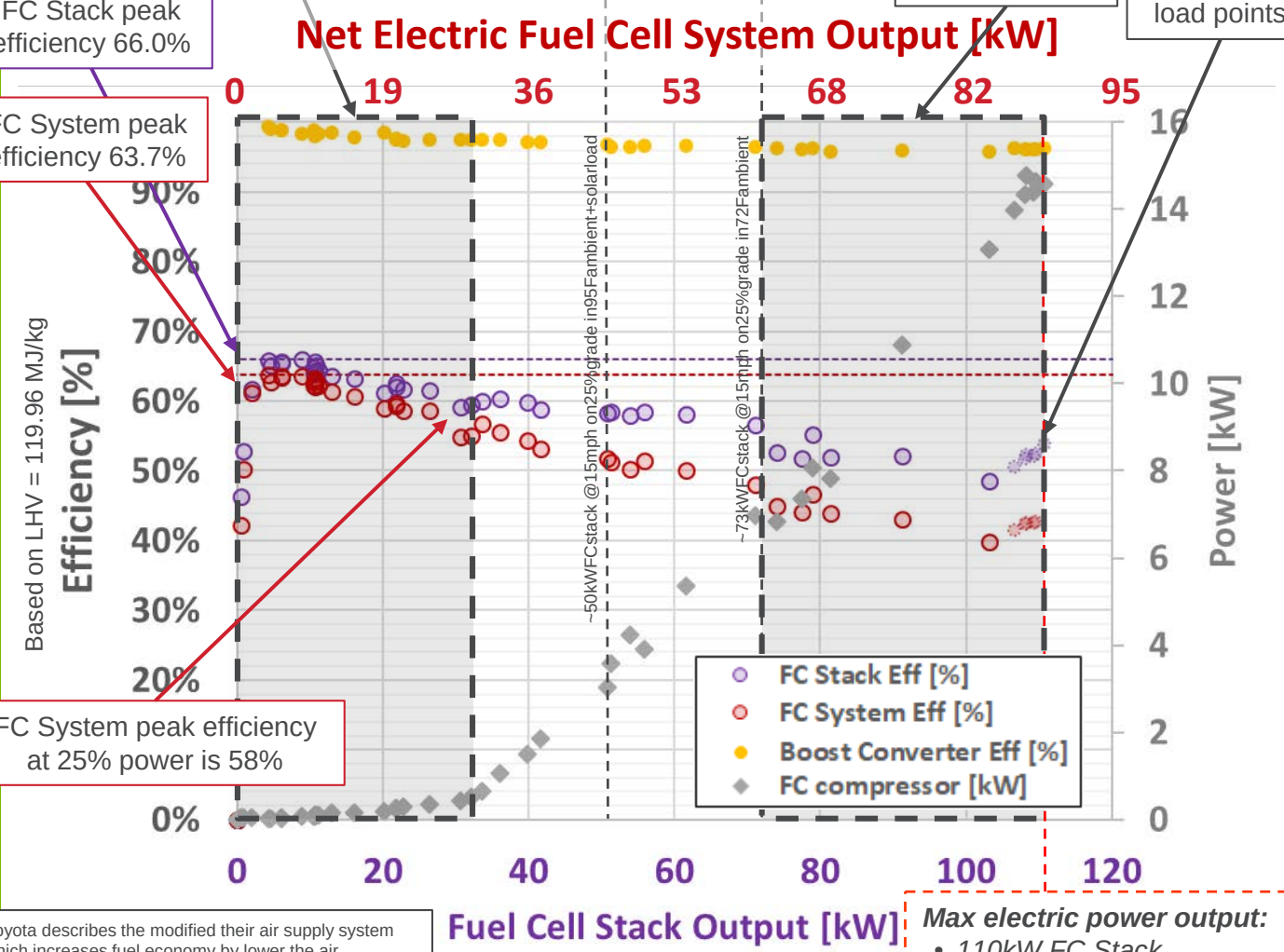
Test point only held for limited time @ 72F ambient

Fuel flow metering challenges on highest load points

FC Stack peak efficiency 66.0%

FC System peak efficiency 63.7%

FC System peak efficiency at 25% power is 58%

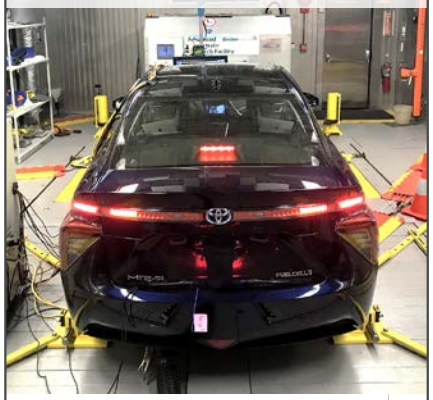


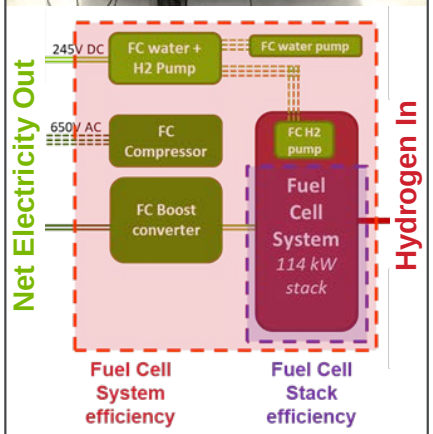
Toyota describes the modified their air supply system which increases fuel economy by lower the air compressor power at low loads. Hasegawa, T., Imanishi, H., Nada, M., and Ikogi, Y., "Development of the Fuel Cell System in the Mirai FCV," SAE Technical Paper 2016-01-1185, 2016, doi:10.4271/2016-01-1185.

Max electric power output:

- *110kW FC Stack*
- *105kW FC Boost converter*
- *90kW FC System*

2017 Toyota Mirai test data





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.

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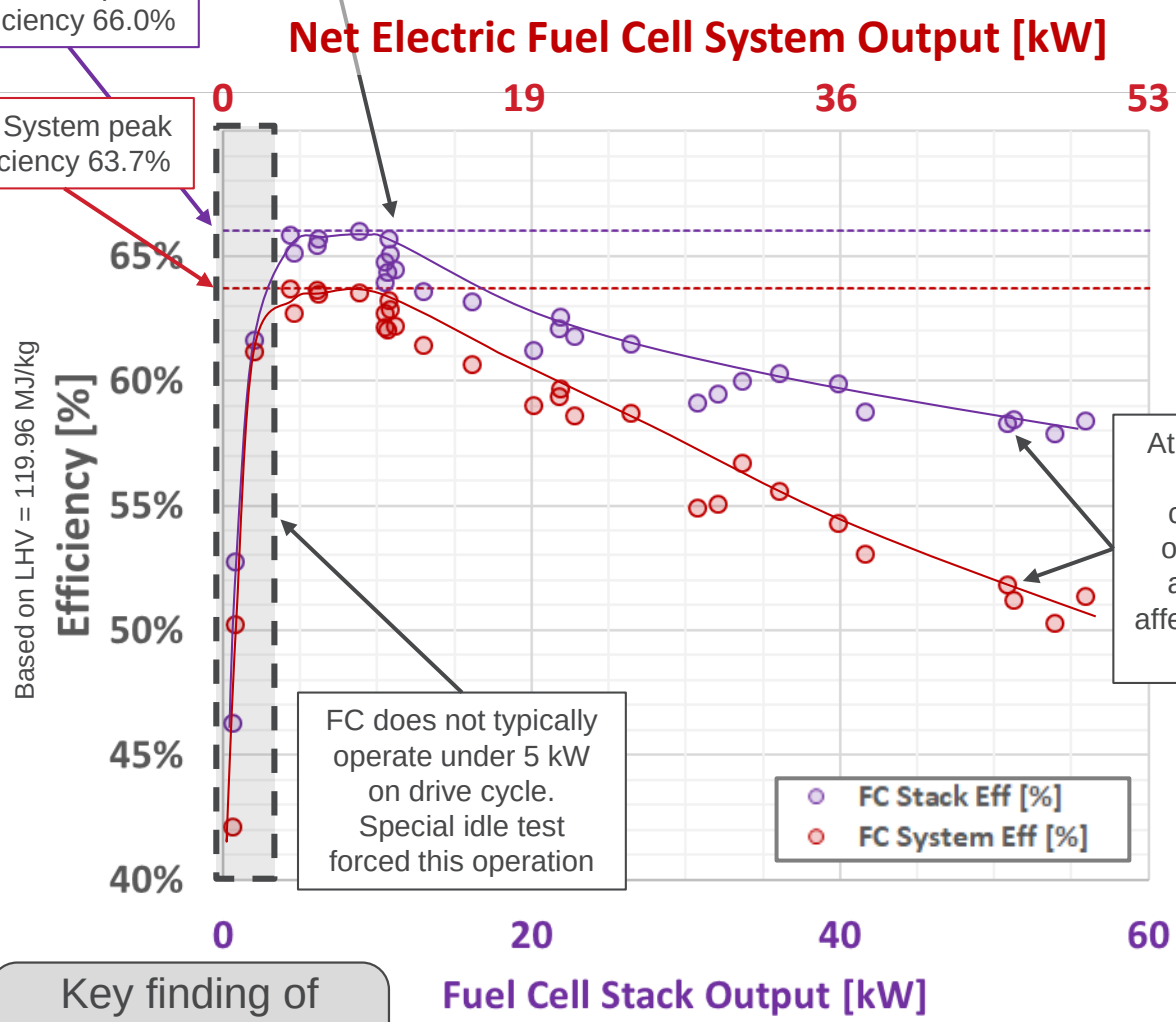
FUEL CELL EFFICIENCY IN OPERATING ZONE

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%

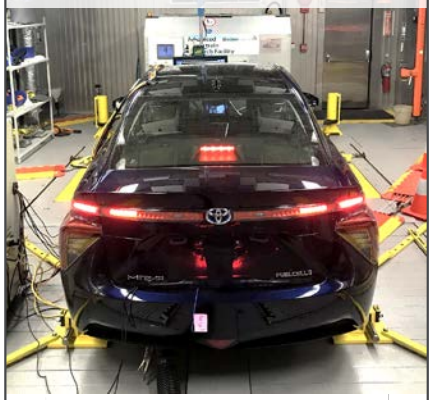


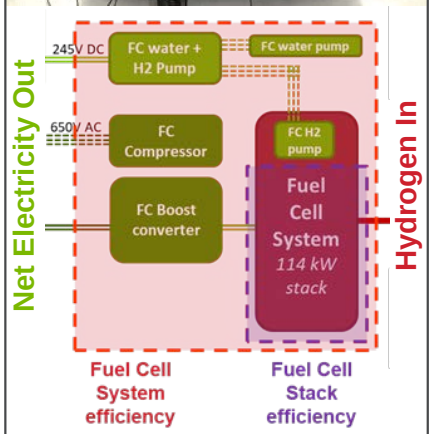
At higher loads the air compressor other system accessories affect the system efficiency

FC does not typically operate under 5 kW on drive cycle. Special idle test forced this operation

Key finding of efficiency based on laboratory data

2017 Toyota Mirai test data





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.

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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]

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

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.
c W. Sung, Y. Song, K. Yu, and T. Lim, "Recent Advances in the Development of Hyundai-Kia's Fuel Cell Electric Vehicles," SAE Int. J. Engines 3.1 (2010): 768–772, doi: 10.4271/2010-01-1089.

Table from https://www.energy.gov/eere/fuelcells/doe-technical-targets-fuel-cell-systems-and-stacks-transportation-applications on April 2018

"*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,

	2008 Hyundai Borrego	2017 Toyota Mirai
Weight	2300 kg reported in paper	1930 kg test weight
Fuel Cell Peak power	PEM 100 kW	PEM 114 kW
Fuel Economy on FTP 72 (aka UDDS)	72 mpge	Cold start 91.5 mpge Hot start 95.3 mpge
FC stack efficiency at 60 mph	65%	63.2%
FC system efficiency at 60 mph	62%	60.6%
Peak FC stack efficiency	65%	66.0% @ 5 to 10 kW stack output
Peak FC system efficiency	62%	63.7% @ 5 to 10 kW stack output

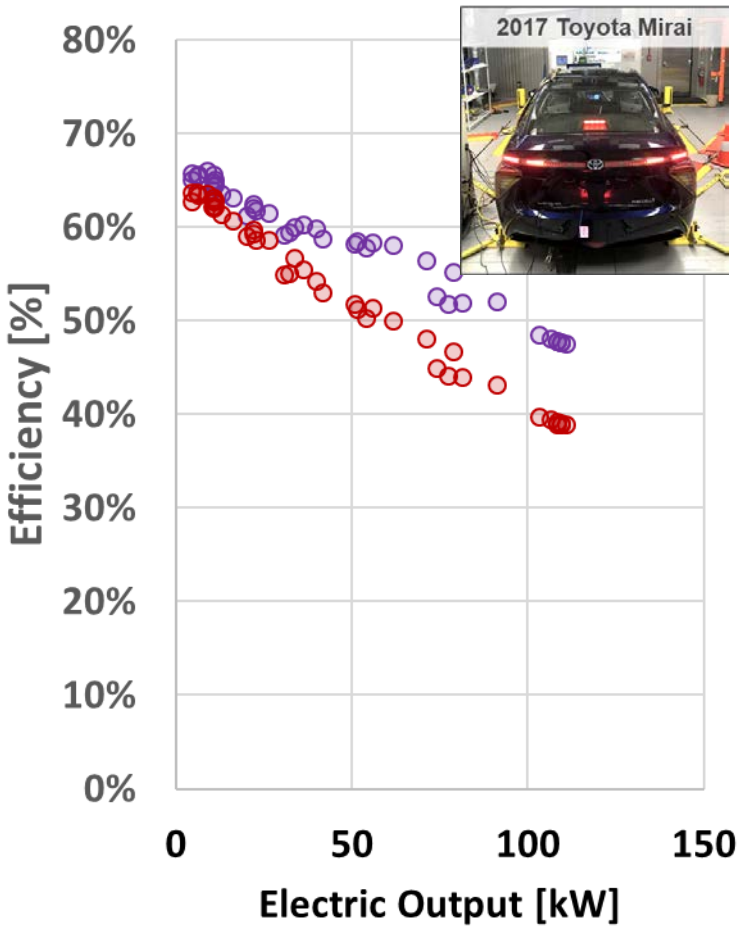
COMPARISON OF SERIES HYBRID "GENERATORS"

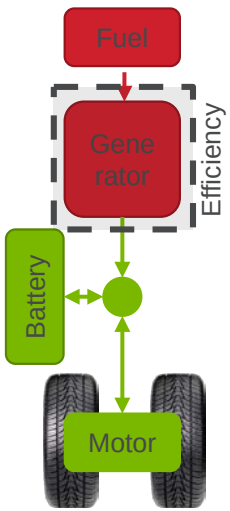
Fuel Cell Hybrid Electric Vehicle:

- Charge sustain
- Fuel Cell dominant
- Generator max output 114 kW

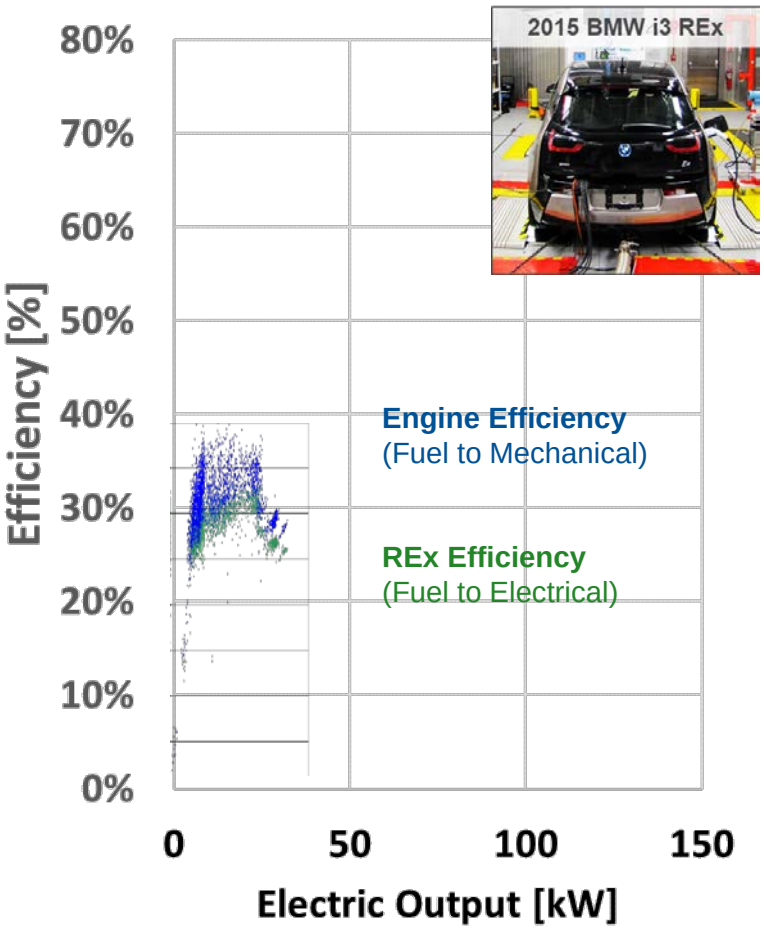
Battery Electric Vehicle with range extender:

- Primarily BEV
- Small 649cc 2cyl engine
- Generator max output 25 kW





Series Hybrid Architecture



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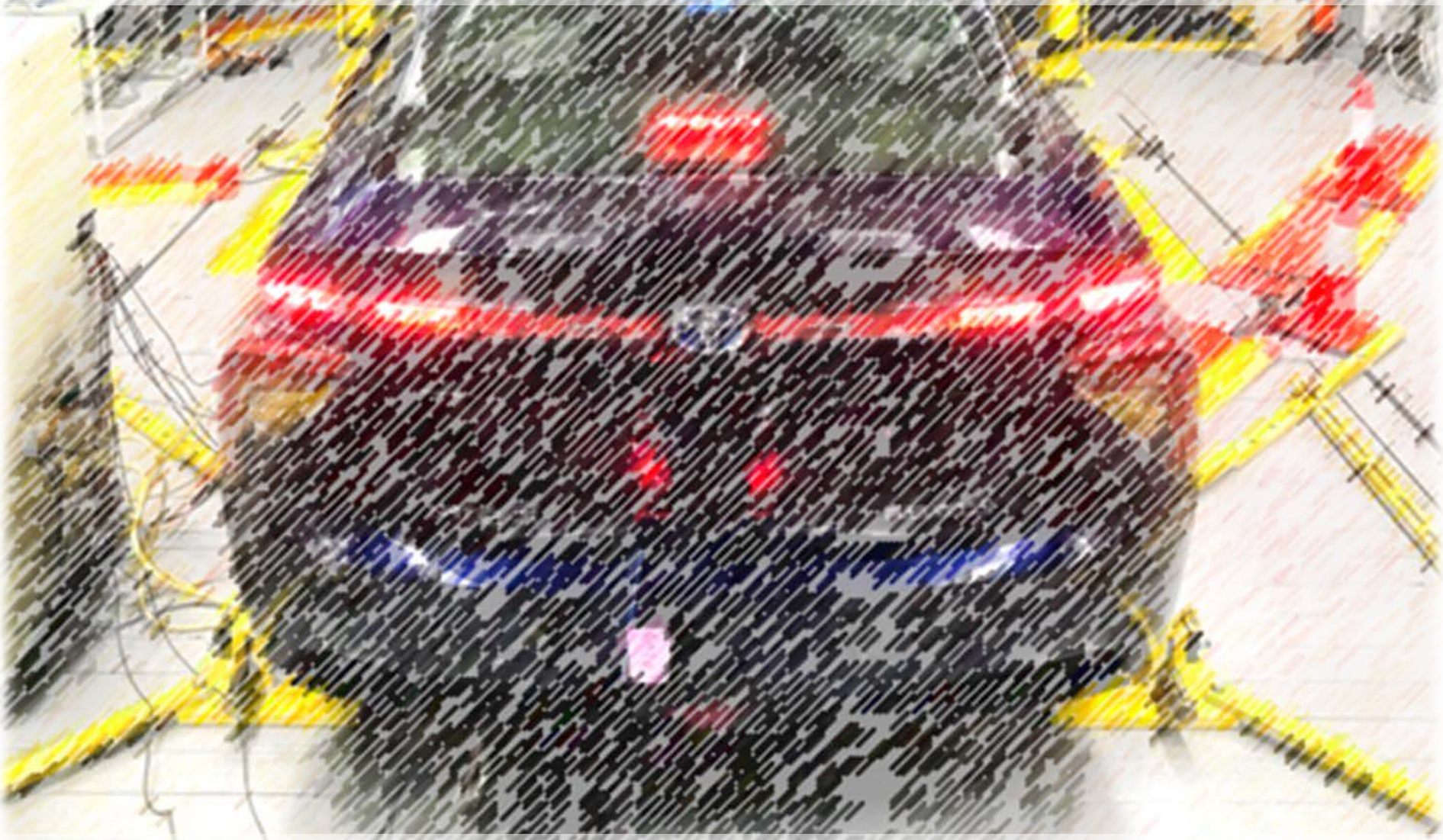
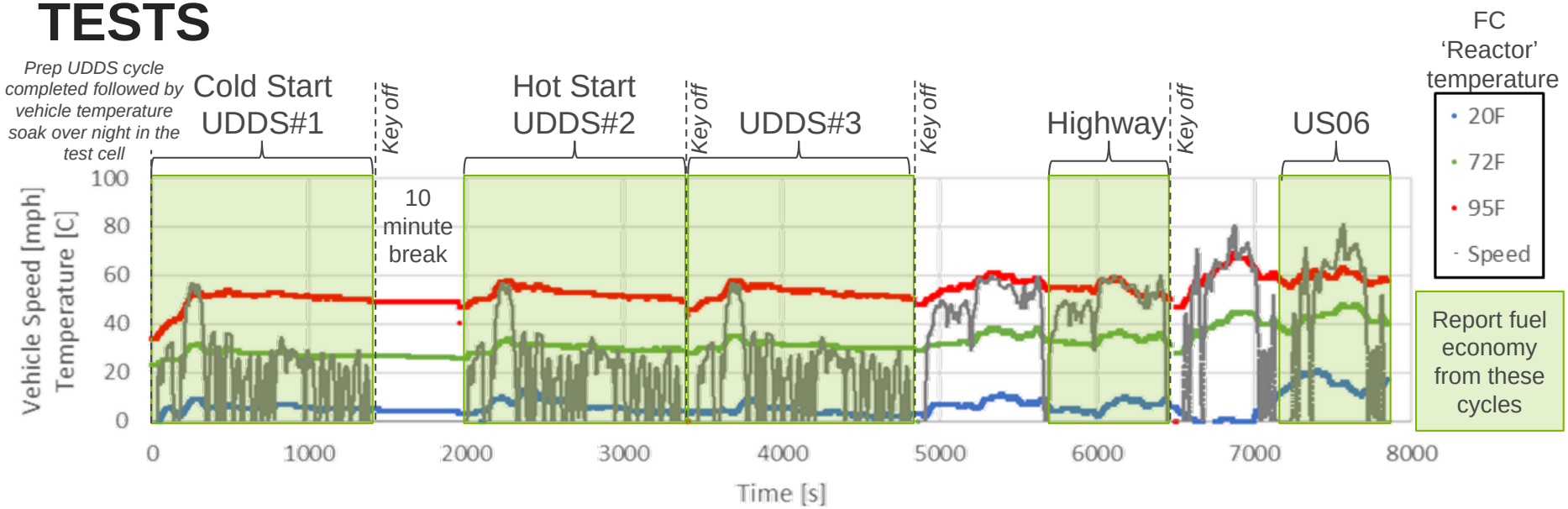
CERTIFICATION DRIVE CYCLE TESTING AND RESULTS AT 72F AMBIENT TEMPERATURE



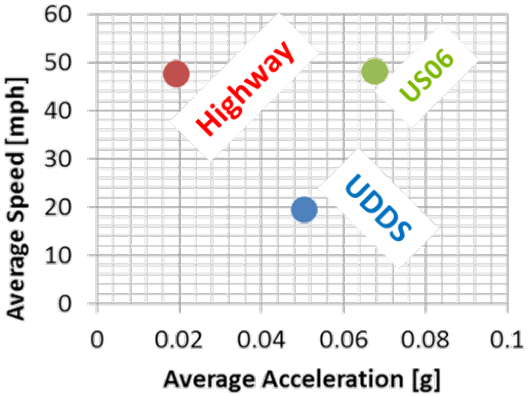
STANDARD TEST SEQUENCE FOR CERTIFICATION TESTS



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.



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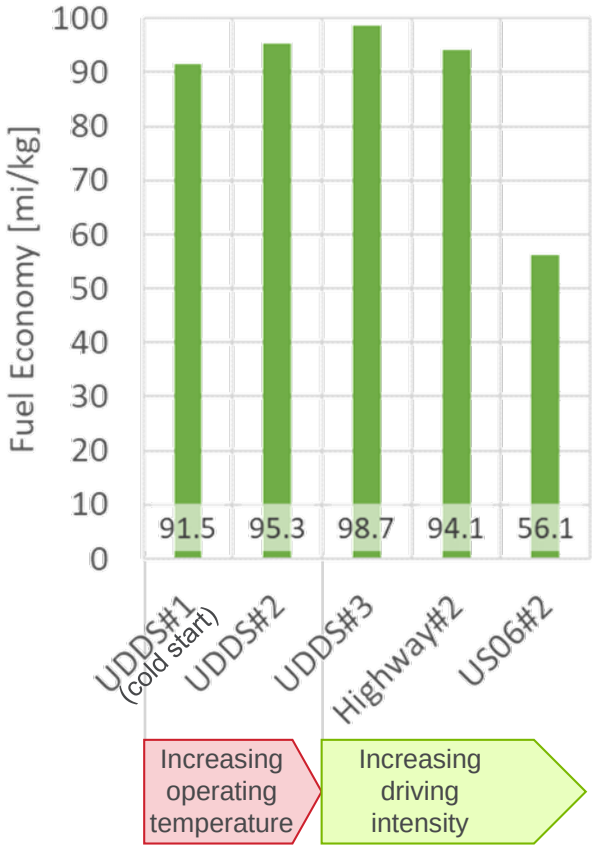
CERTIFICATION CYCLES TEST RESULT AT 72F AMBIENT TEMPERATURE

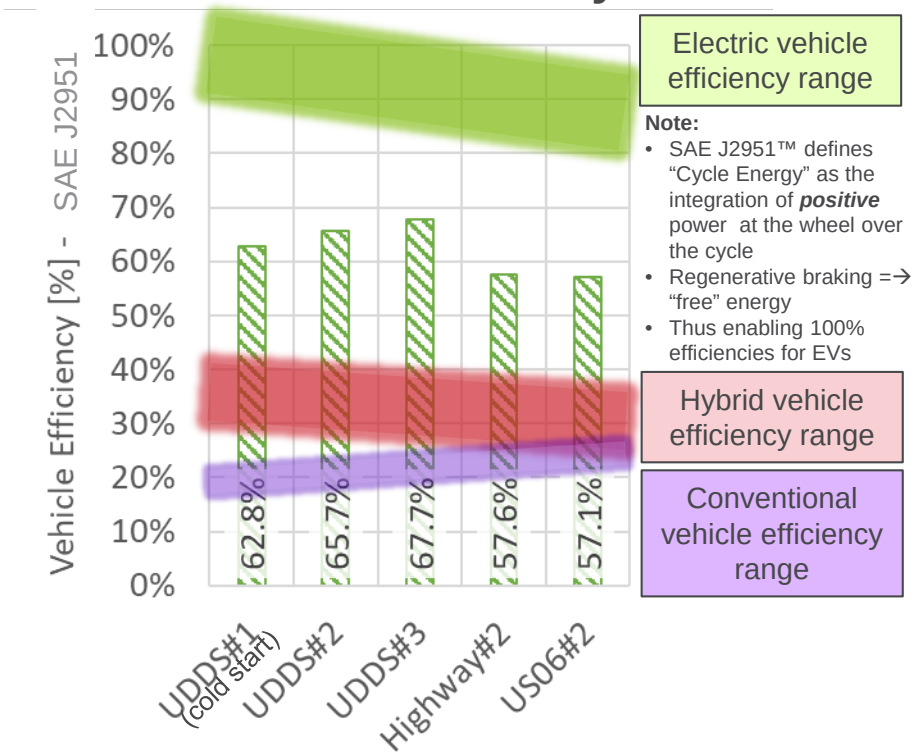
Fuel Economy



High fuel economy.

Caution: MPG illusion area.

Vehicle Efficiency



Overall high powertrain efficiencies.

Efficiency drops for higher driving intensity contrary to conventional vehicles.

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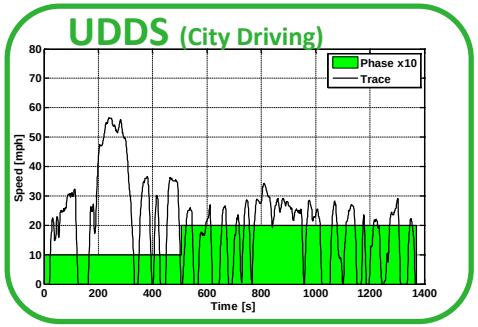
FUEL ECONOMY COMPARISON TO EPA RESULTS

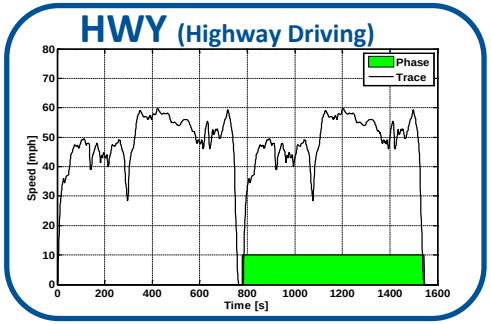
Argonne test results appear to match the EPA published test results

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

[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 (H_2 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.





2017 Toyota Mirai Label Fuel Economy Data

2018 Toyota Mirai

	mates		
Fuel Economy (mi/kg)	66 comb	66 city	66 hwy
Range (miles)	312		
Annual Fuel Cost *	$1,250		
Vehicle Class	Subcompact Car		
Motor	AC Induction (113 kW)		
Battery	245 V NiMH		
Availability	Select dealers in California & Hawaii (sale or lease)		

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.

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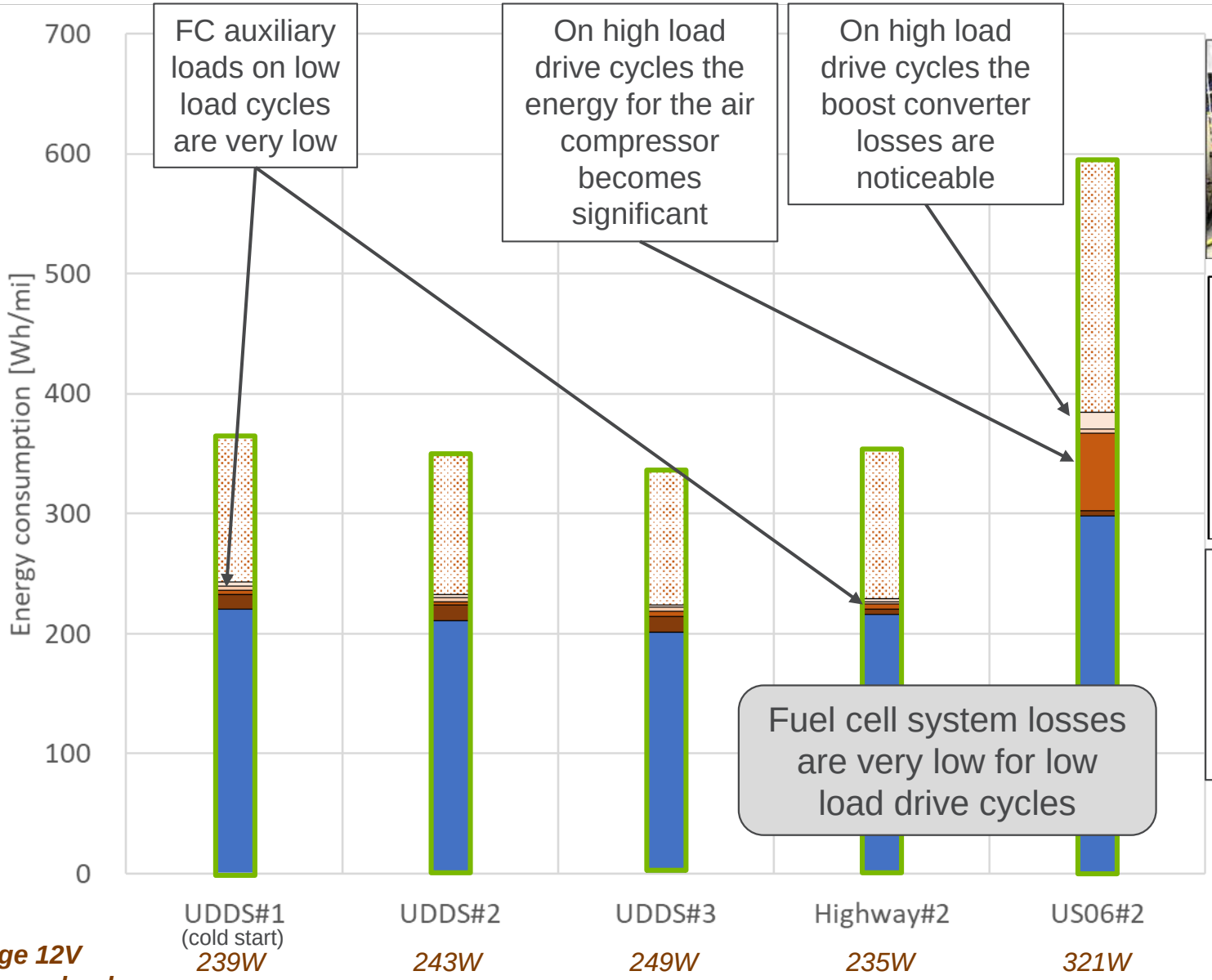
WHERE DID THE ENERGY GO?

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



Ambient test conditions:

72F

Climate control:

- At 72F the climate control was off.

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

Average 12V accessory loads

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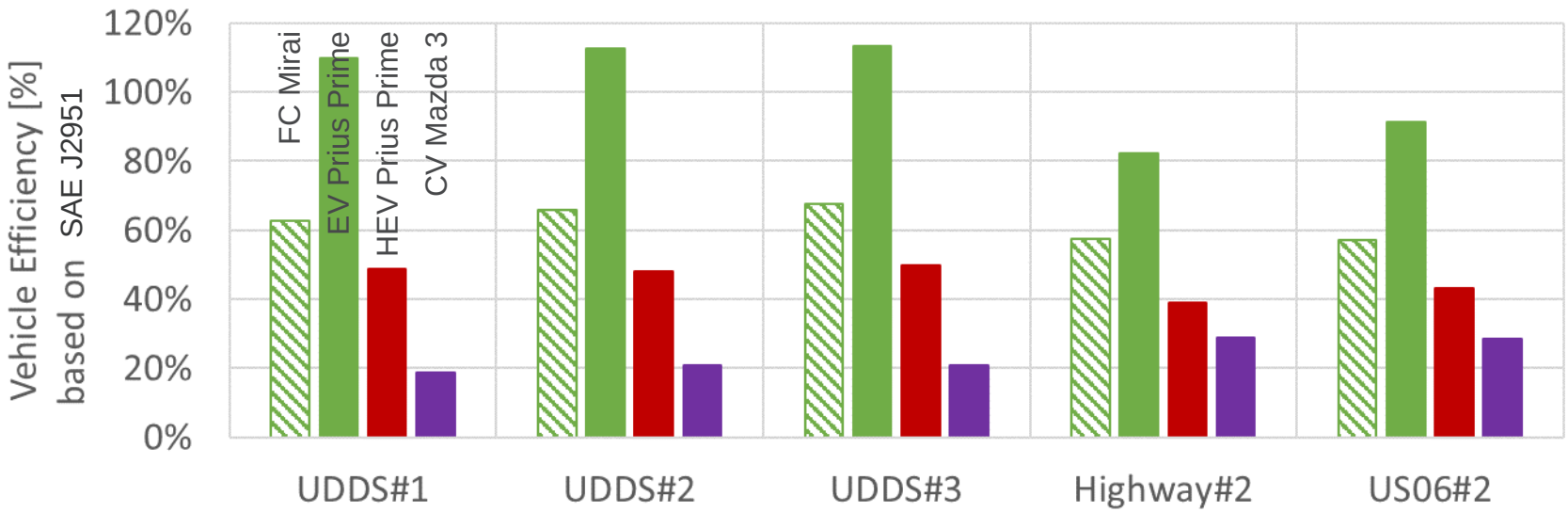
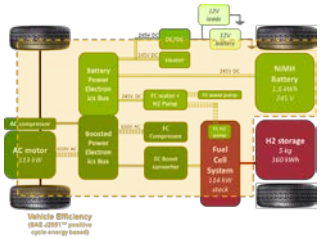
FUEL CELL VEHICLE EFFICIENCY CONTEXT





The fuel cell vehicle efficiency is higher compared to vehicles that use an internal combustion engine.

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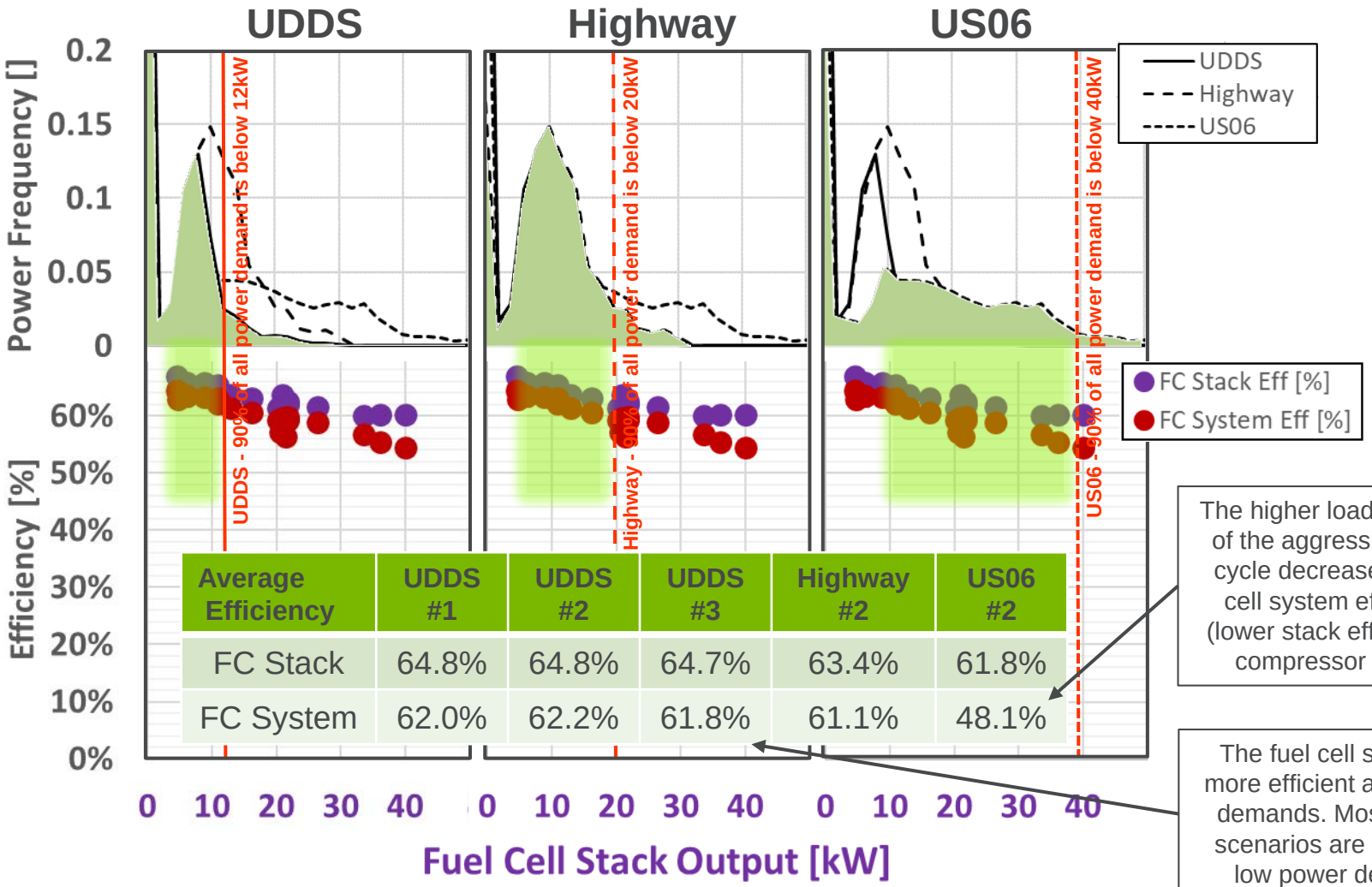
FUEL CELL SYSTEM PEAK EFFICIENCY CORRELATES WITH VEHICLE DEMANDS



Average Efficiency	UDDS #1	UDDS #2	UDDS #3	Highway #2	US06 #2
FC Stack	64.8%	64.8%	64.7%	63.4%	61.8%
FC System	62.0%	62.2%	61.8%	61.1%	48.1%

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.

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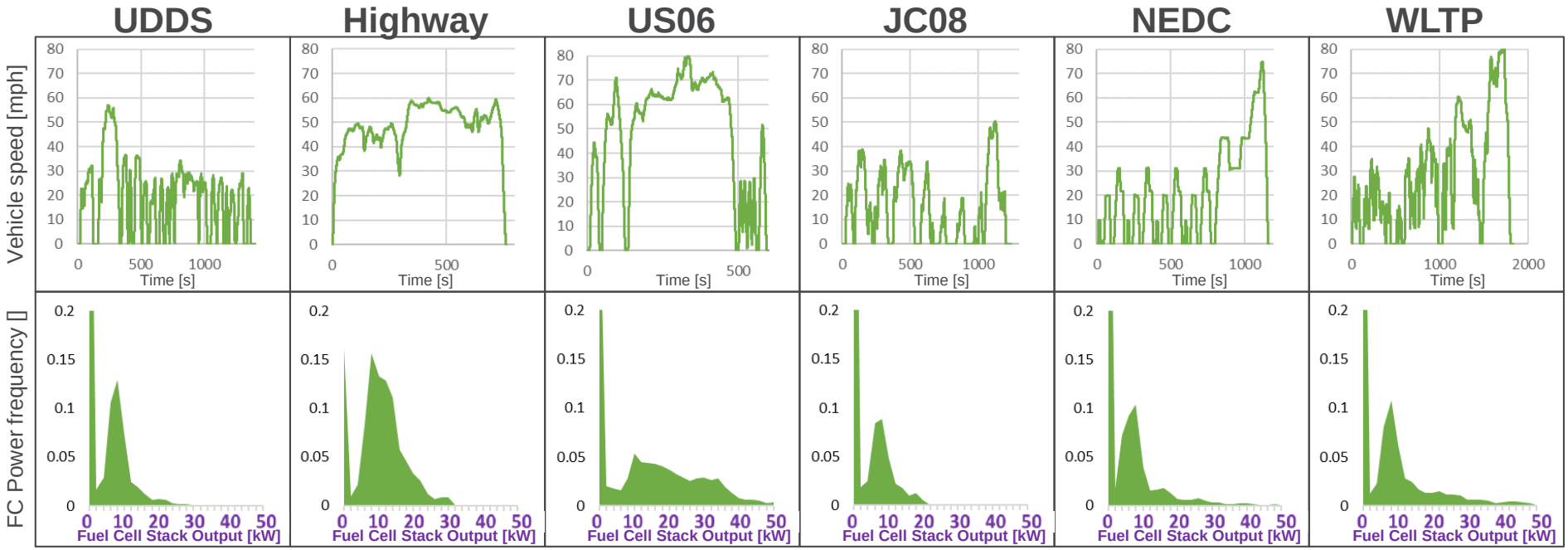
FURTHER DRIVE CYCLE RESULTS AT 72F AMBIENT TEMPERATURE

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



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%)

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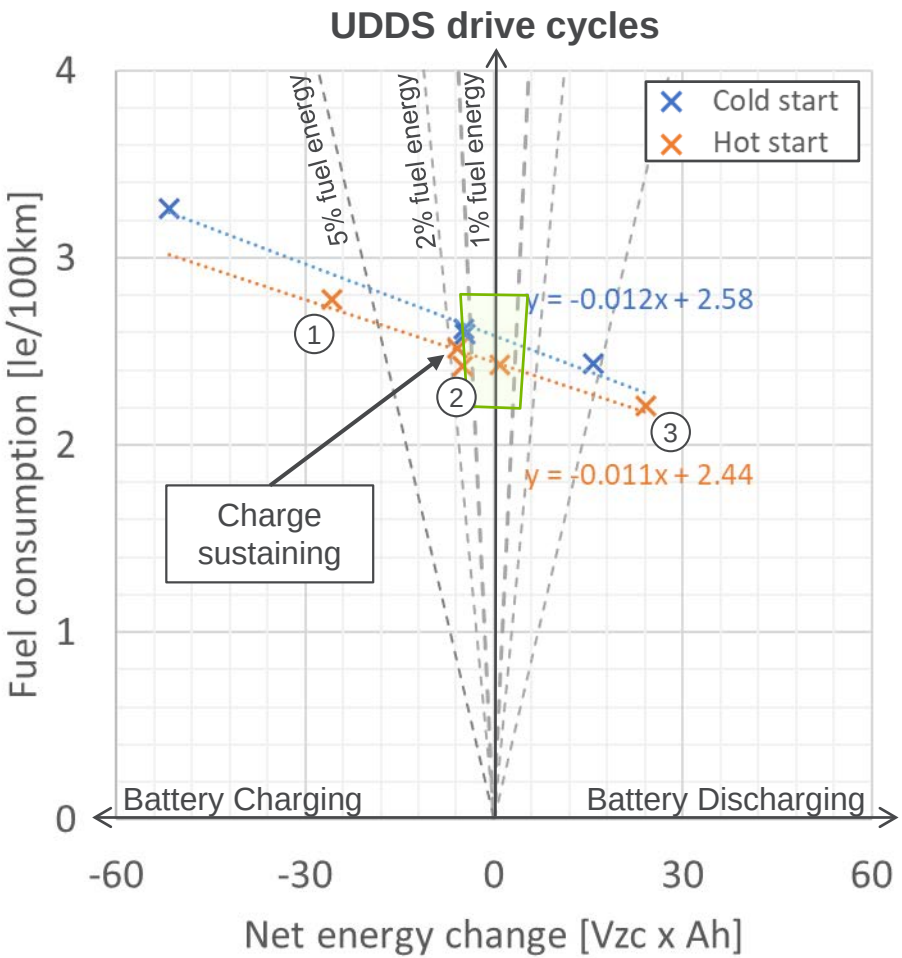
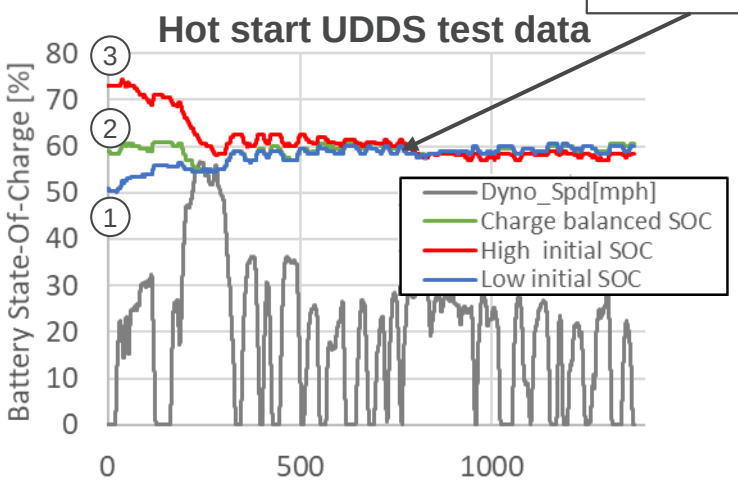
FUEL CONSUMPTION WITH BATTERY STATE OF CHARGE CORRECTION

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





	SOC Start [%]	SOC End [%]	Fuel Consumption [le/100km]	Net energy change [Vzc x Ah]
Low initial SOC	51	60	2.78	-25.7
Charge balanced SOC	59	60.5	2.52	-5.7
High initial SOC	73	58.5	2.21	24.2

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HYDROGEN CONSUMPTION CAN BE ESTIMATED USING THE IDEAL GAS LAW

Ideal Gas Law Equation

$$PV = mRT$$

12-pack pressure is measured

Volume of 12 3AA2400 cylinders. S mall 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 ~4C

High pressure sensor enclosure

Outside H2 Storage

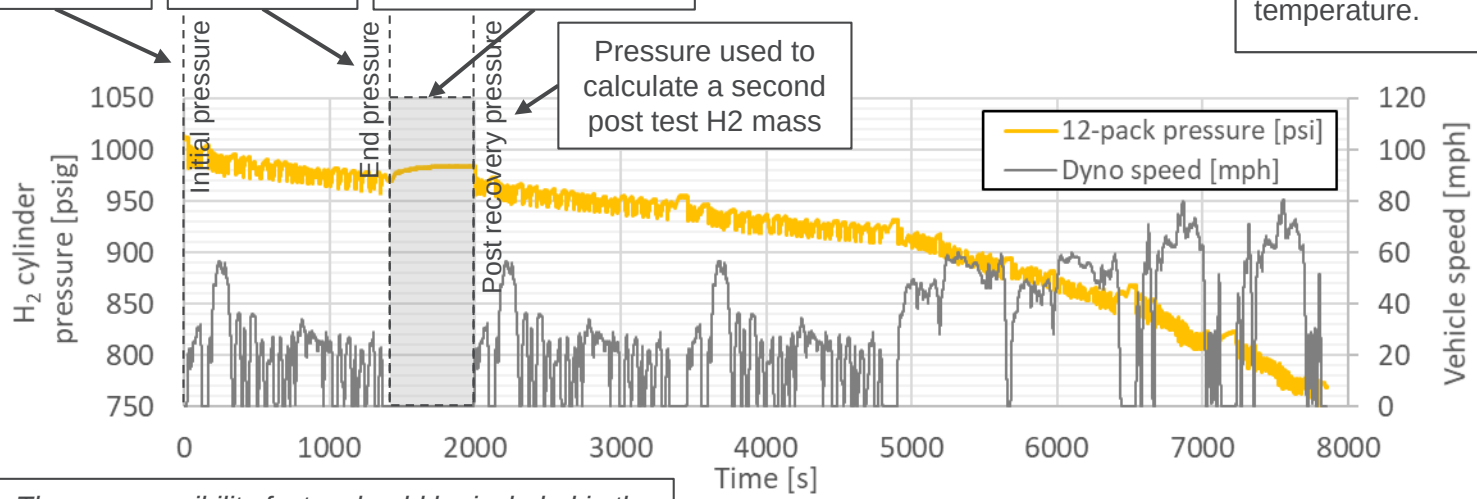
Air gas HYUHP300 which is a 12-pack of DOT 3AA2400 cylinders. The liquid volume for each cylinder is 49.8L. The H2 storage is exposed to outside temperature.

Pressure used for initial mass

Pressure used for end mass

Temperatures evens out in a recovery phase between tests

Pressure used to calculate a second post test H2 mass



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

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

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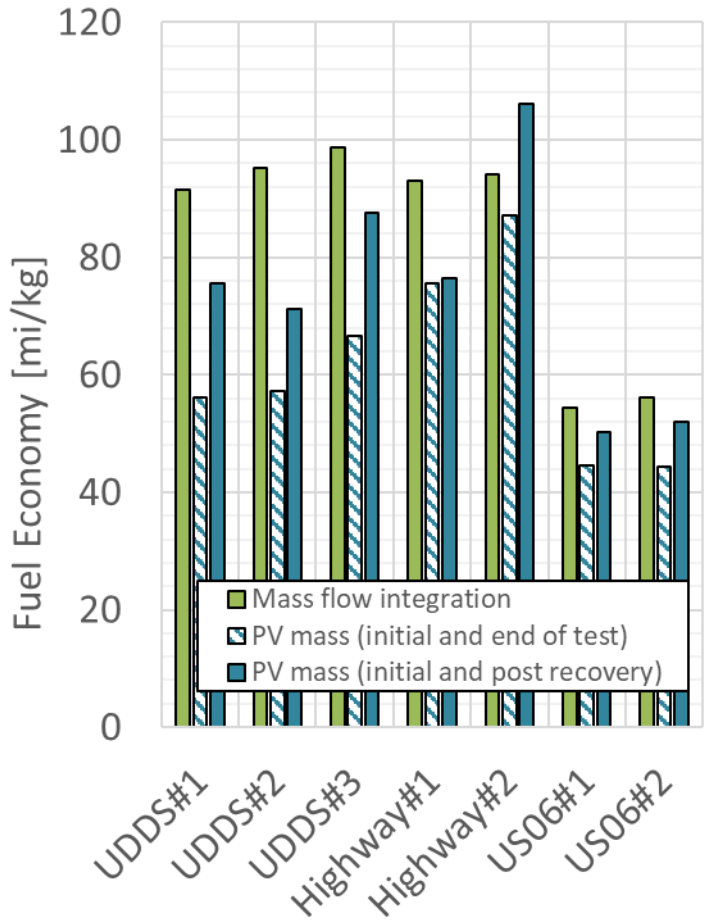
HYDROGEN CONSUMPTION BASED ON CYLINDER PRESSURE, VOLUME, AND "TEMPERATURE"



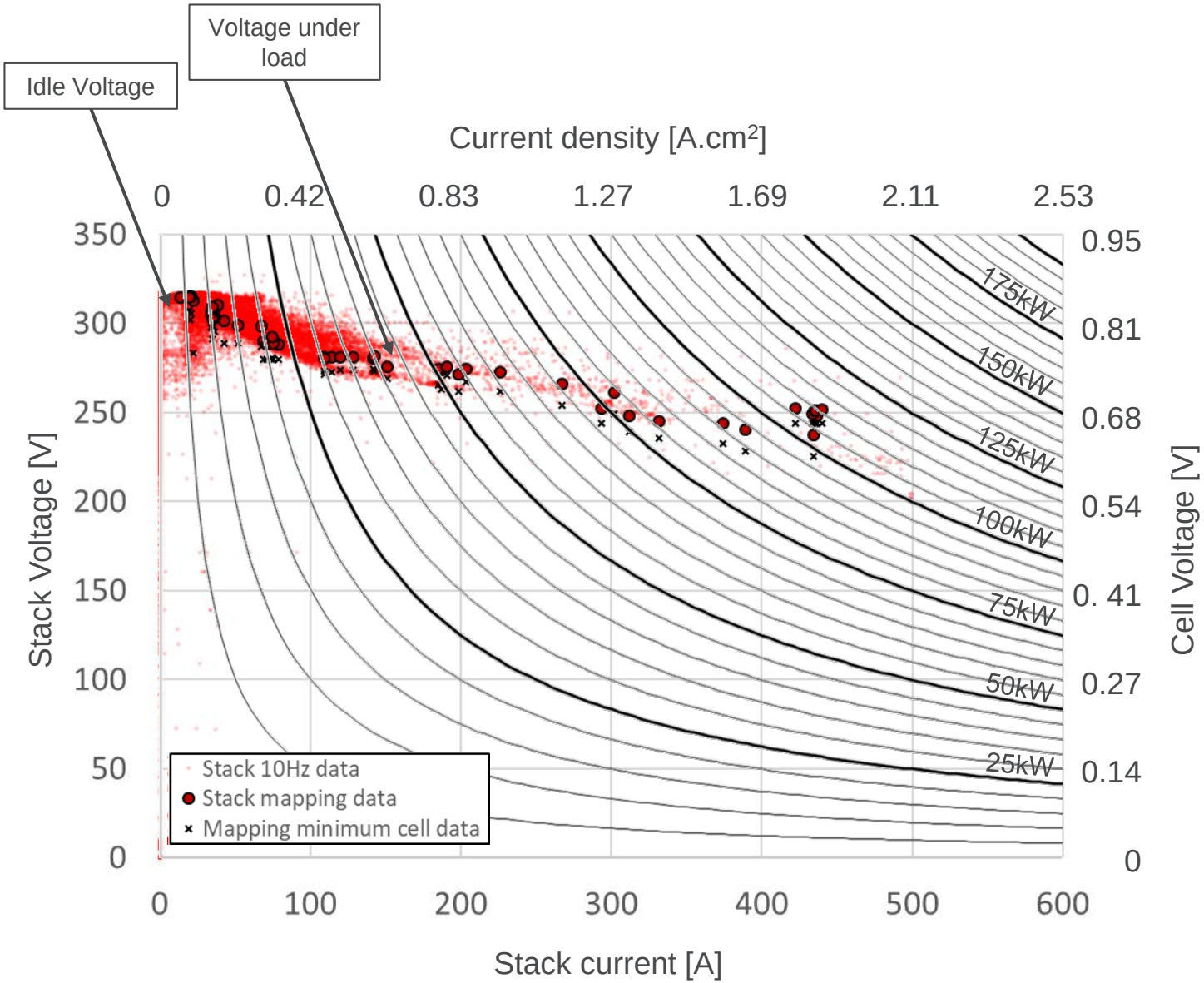
	Initial pressure [psig]	End pressure [psig]	Post-recovery pressure [psig]	Recovery time [min]	Mass flow meter [g]	PV mass end of test [g]	PV mass post recovery [g]
UDDS#1	1011	974	984	10	81.7	133.2	98.9
UDDS#2	984	948	955	3	78.1	130.1	104.4
UDDS#3	955	924	931	10	75.7	112.1	85.4
Highway#1	931	894	894	0.25	110.4	135.9	134.0
Highway#2	894	861	867	17	109.0	117.7	96.8
US06#1	867	817	823	1.5	147.4	180.1	159.4
US06#2	823	773	780	341	143.0	180.8	154.4
Total sequence	1011	N/A	780	N/A	745.3	N/A	833.3

The hydrogen consumed based on the ideal gas law is 12% high than the integrated hydrogen mass flow meter.

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 mapping data
Mapping minimum cell 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 cm^2 active area [1]
- 370 cells in stack

[1] B. James, NREL , "Fuel Cell Systems Analysis", 2017 DOE FCTO AMR, Project ID# FC163

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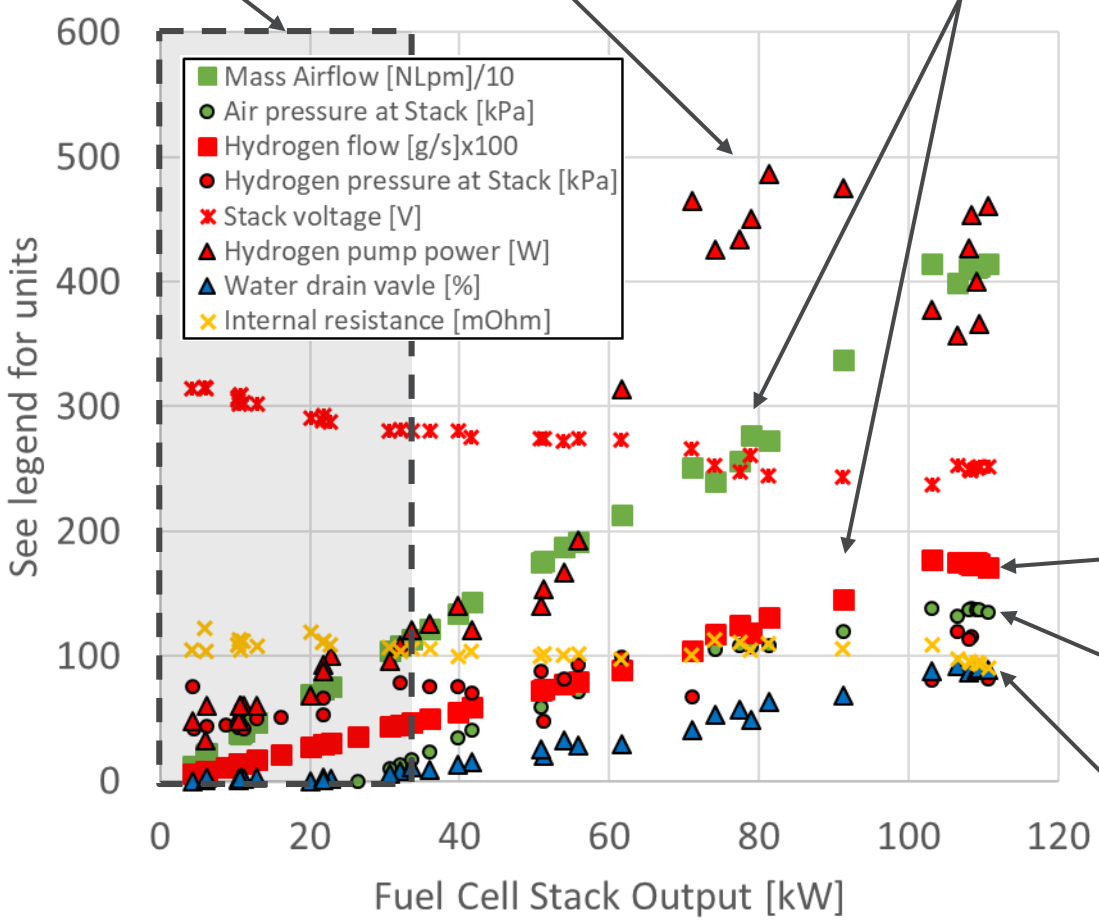
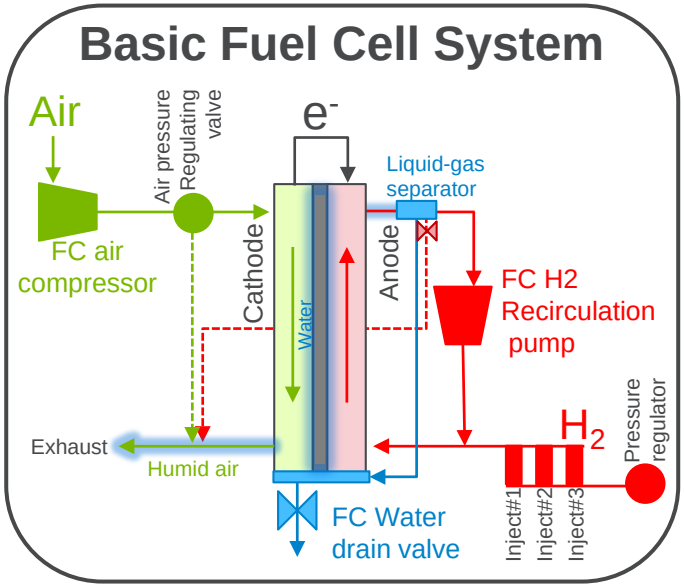
FUEL CELL STACK OPERATING PARAMETERS AND HUMIDIFICATION CONTROL MECHANISMS

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.





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

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

The higher the load; the higher the water production; the higher the water drainage.
The valve is open or closed. This graph show 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.

1. Hasegawa, T., Imanishi, H., Nada, M., and Ikogi, Y., "Development of the Fuel Cell System in the Mirai FCV," SAE Technical Paper 2016-01-1185, 2016, doi:10.4271/2016-01-1185.
2. Konno, N., Mizuno, S., Nakaji, H., and Ishikawa, Y., "Development of Compact and High-Performance Fuel Cell Stack," SAE Int. J. Alt. Power. 4(1):2015, doi:10.4271/2015-01-1175.

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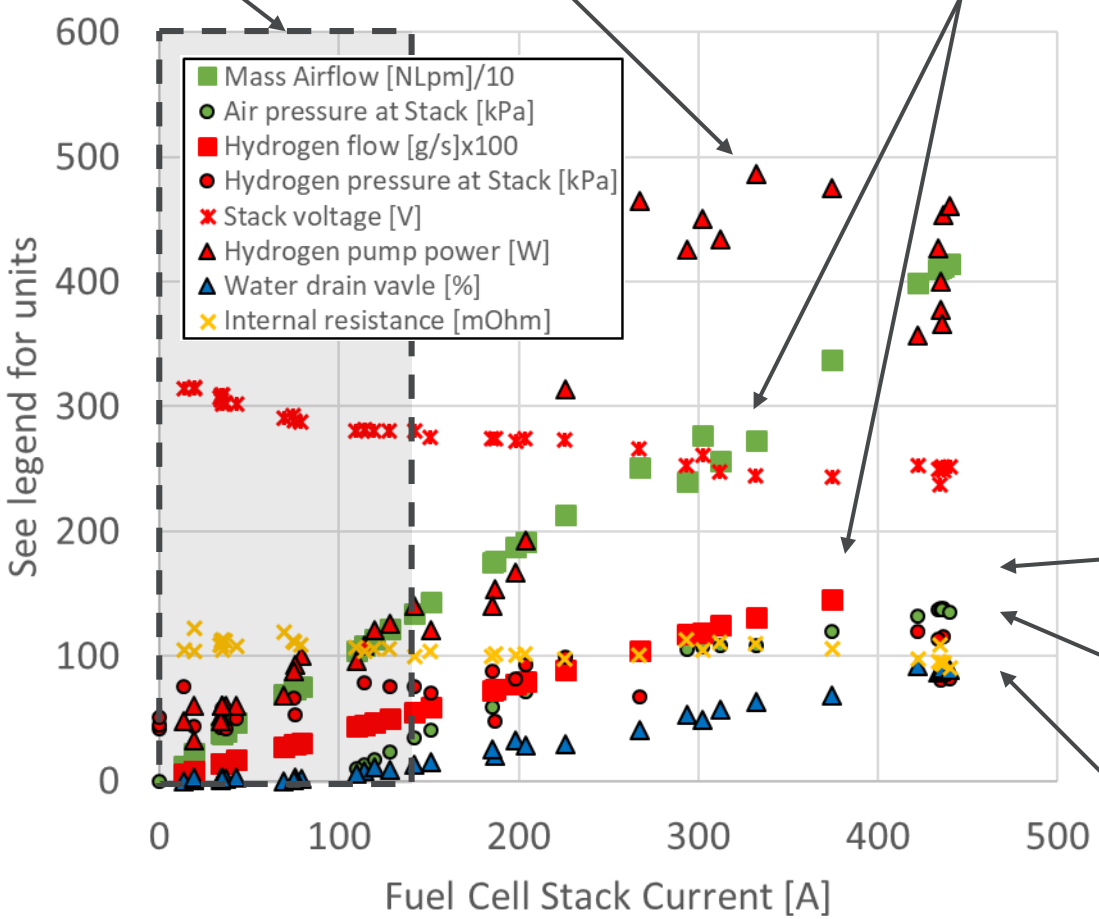

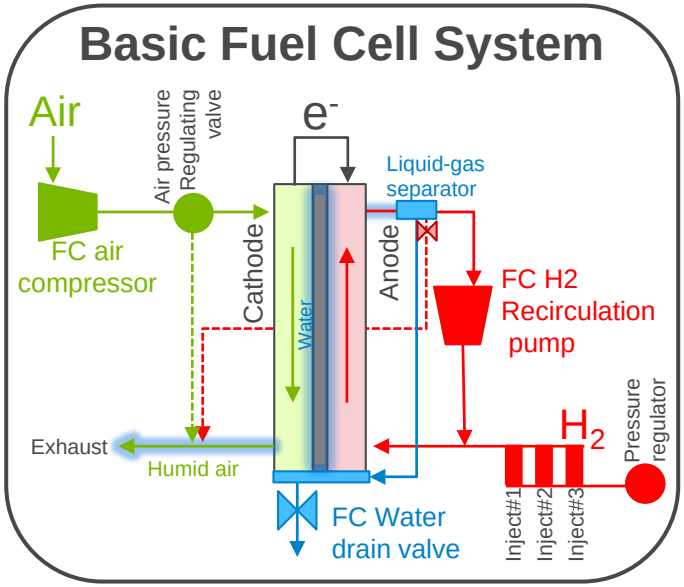

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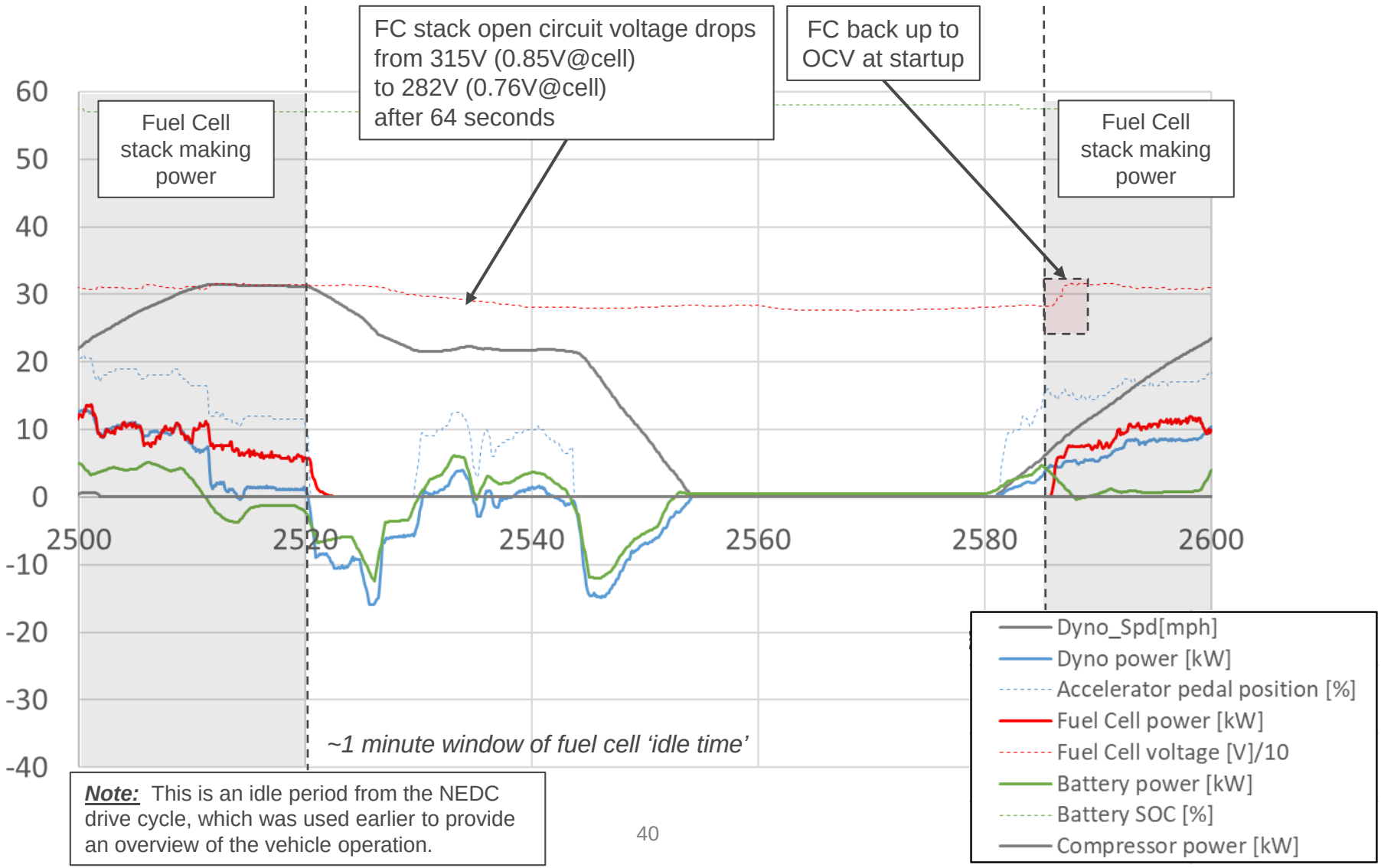
FUEL CELL IDLE OPERATION ON DRIVE CYCLE



Note: This is an idle period from the NEDC drive cycle, which was used earlier to provide an overview of the vehicle operation.

FUEL CELL IDLE OPERATION ON DRIVE CYCLE

Stack stops producing power. The hydrogen flow is stopped.

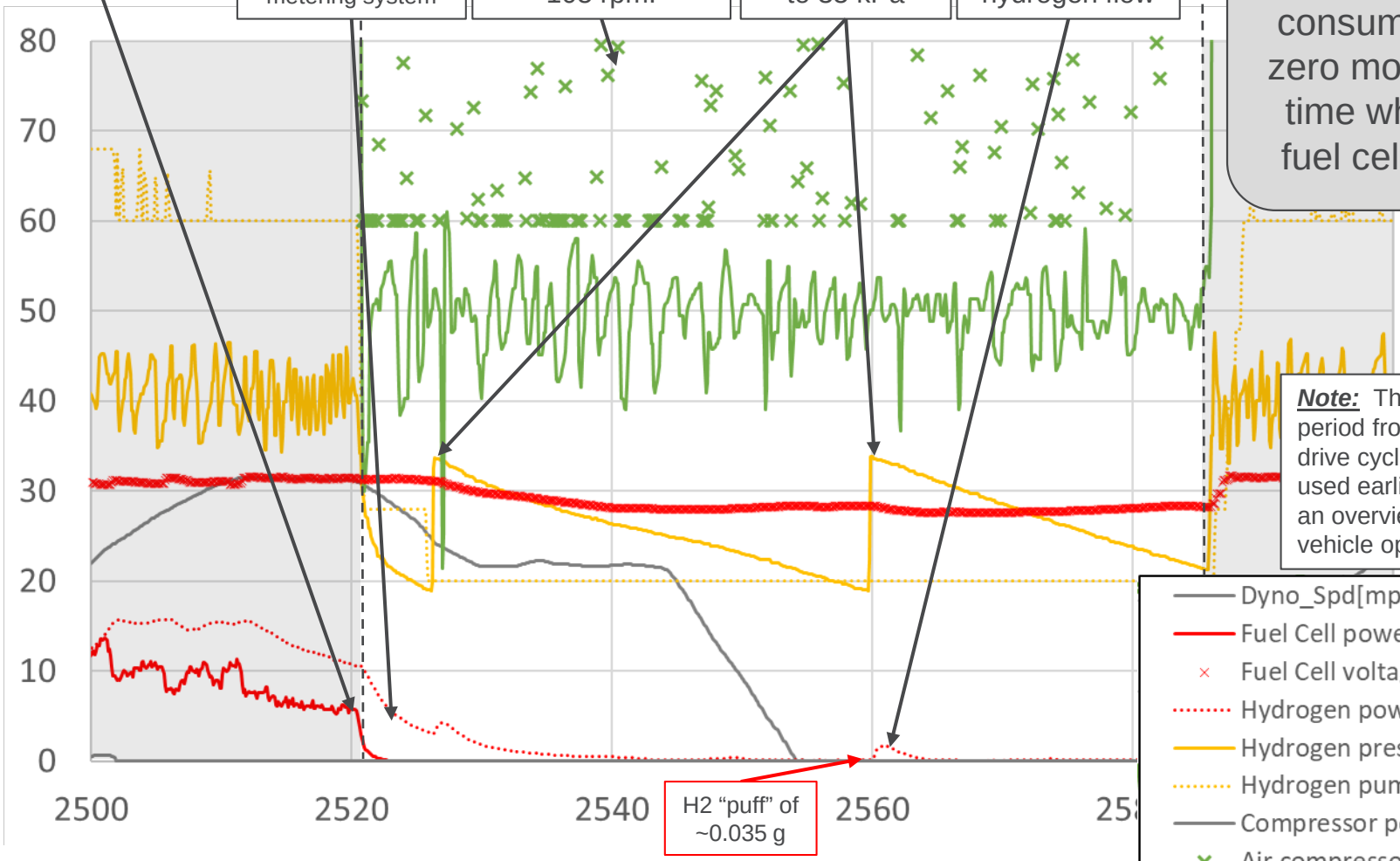
Slower hydrogen decay is due to mechanical filter through flow dynamics in the metering system

Air flow is around 50 NLpm and the compressor slows to an average of 105 rpm.

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'.



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

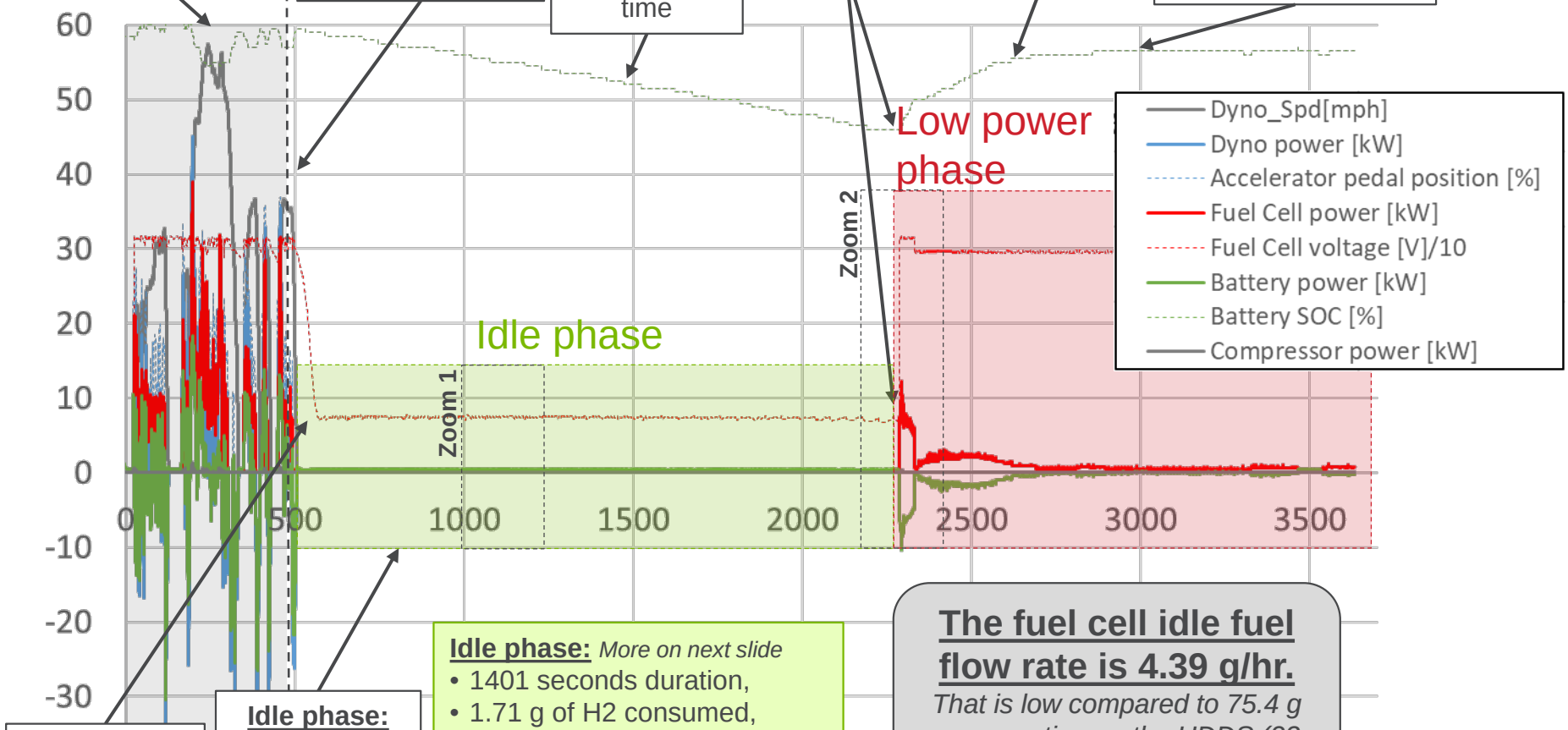
Vehicle stopped, transmission in park, ignition ON. Scenario: waiting in parking lot.

The battery SOC drops as accessory loads draw power over time

Low SOC triggers restart of FC system

FC system 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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MORE DETAILS ON SPECIAL 1 HOUR IDLE TEST

Hydrogen pressure bumps from 20 kPa to 35 kPa every ~ 40 seconds

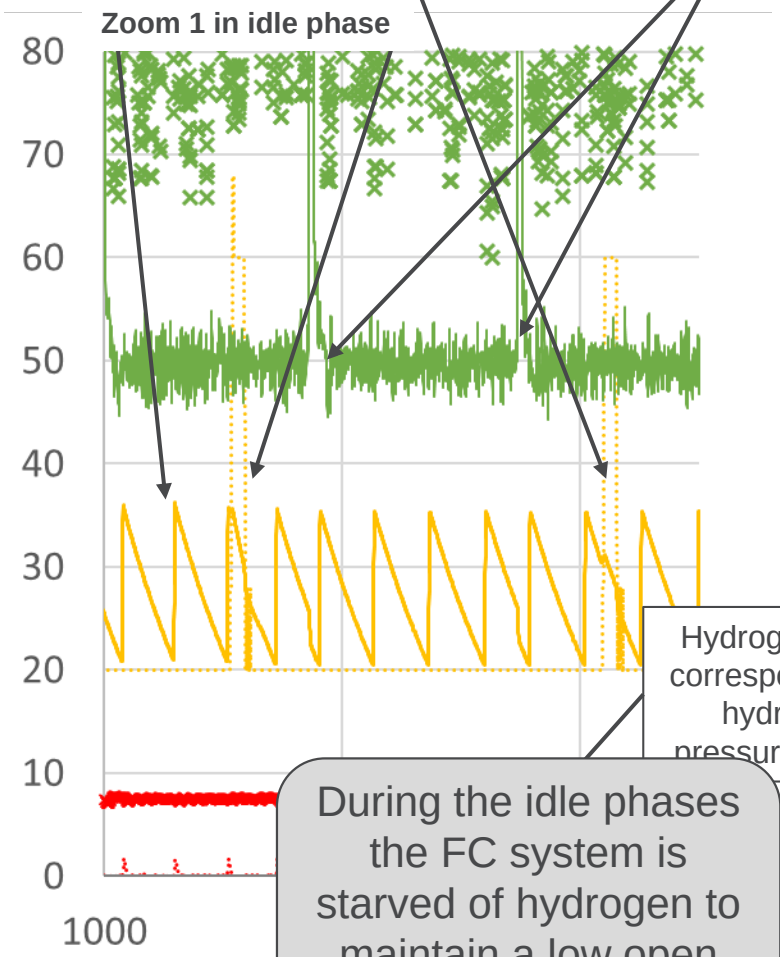
Hydrogen pumps step up from 20W to 60W for 10~12 second every 5 minutes

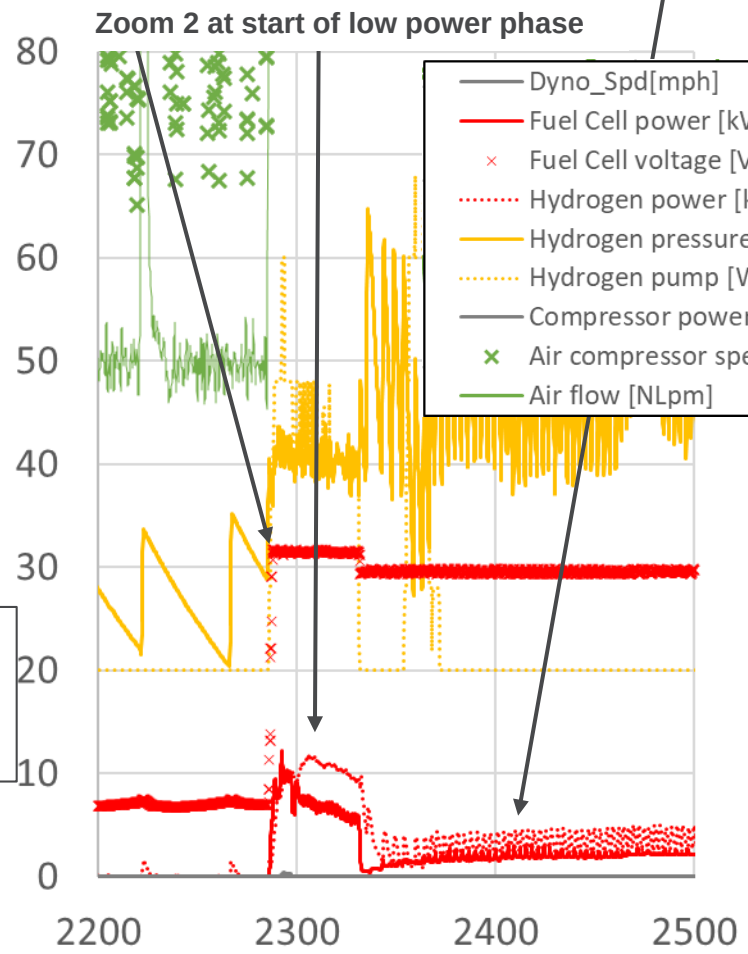
Air flow steps up from 50 to 200 NLpm for 4 second every 3 minutes

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.





Hydrogen puffs corresponding to hydrogen pressure bumps

During the idle phases the FC system is starved of hydrogen to maintain a low open circuit voltage.

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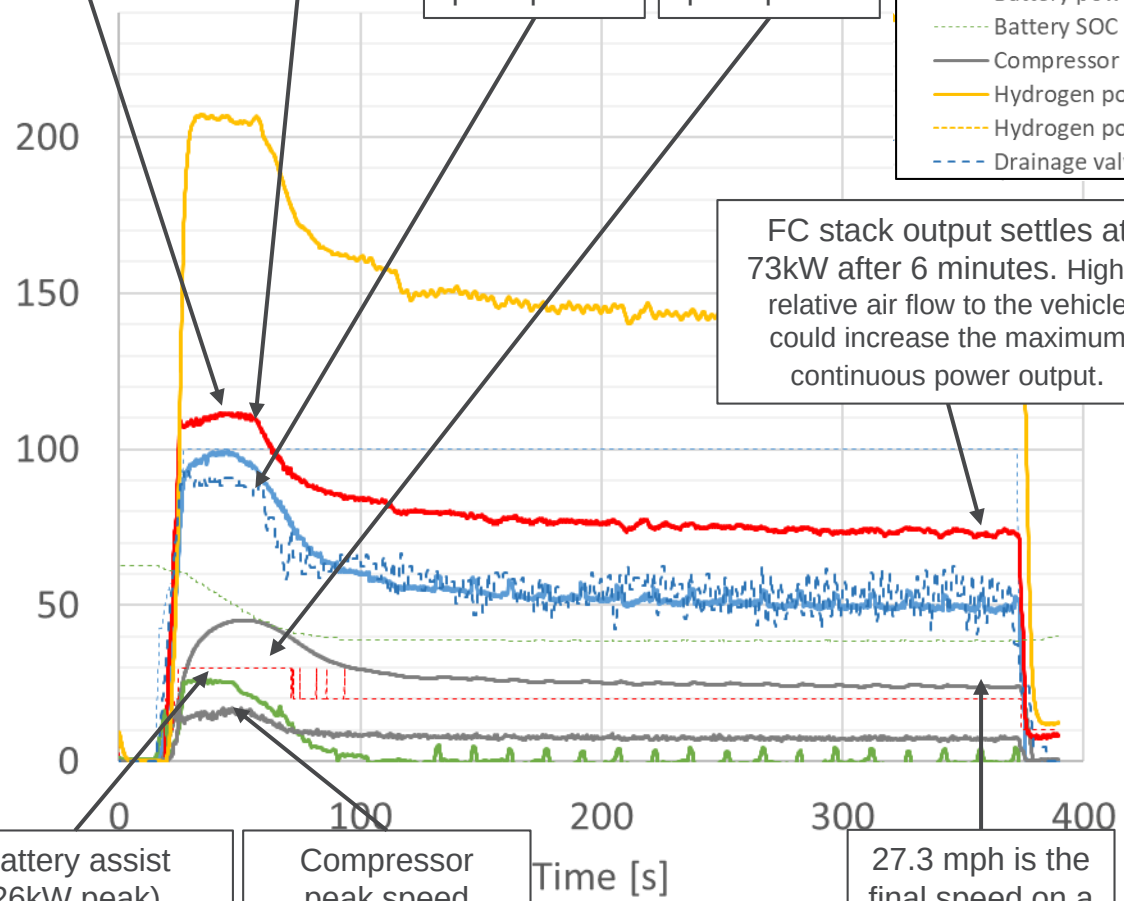
MAXIMUM POWER TESTING ON A 25% GRADE AT 72F

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.

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

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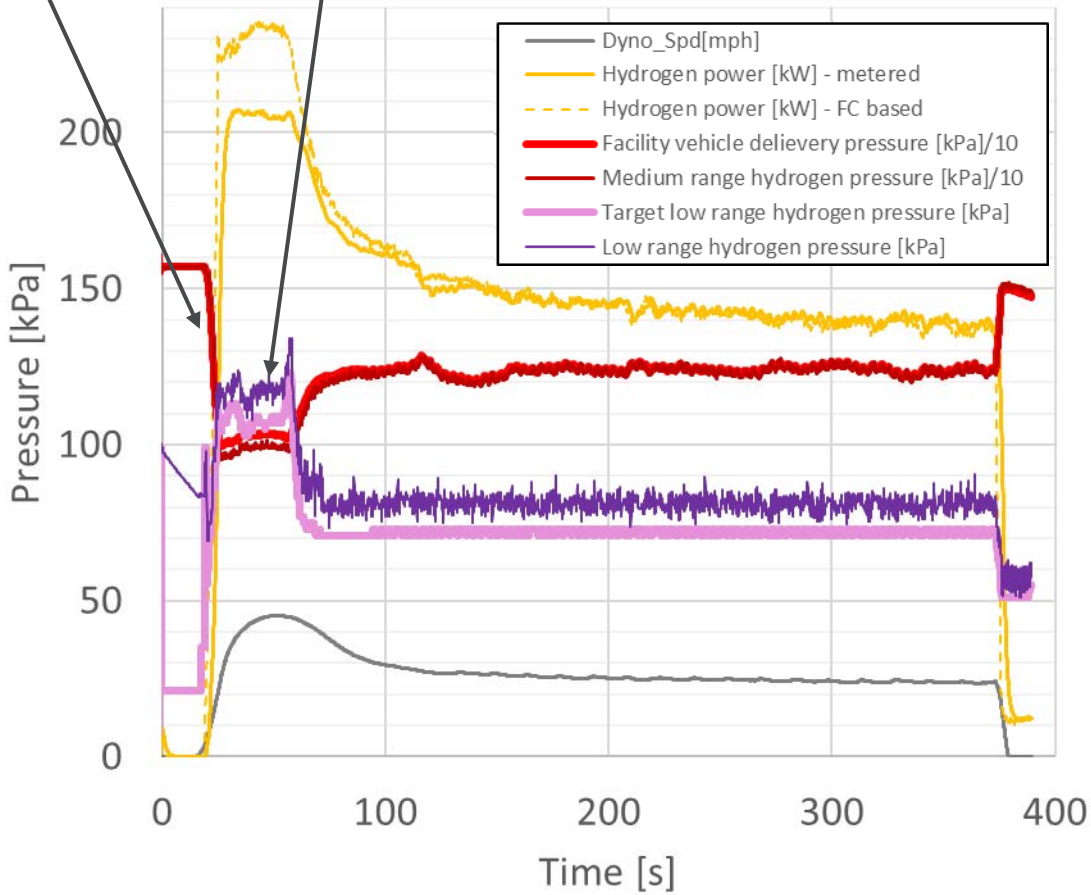
MAXIMUM POWER TESTING ON A 25% GRADE AT 72F – NO FUEL STARVATION

Pressure drop due to higher flows

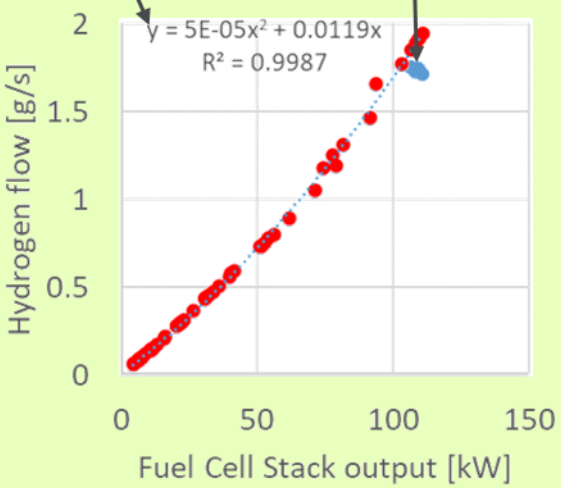
The actual low range pressure is above the low range target pressure



High Flow Metering Challenge

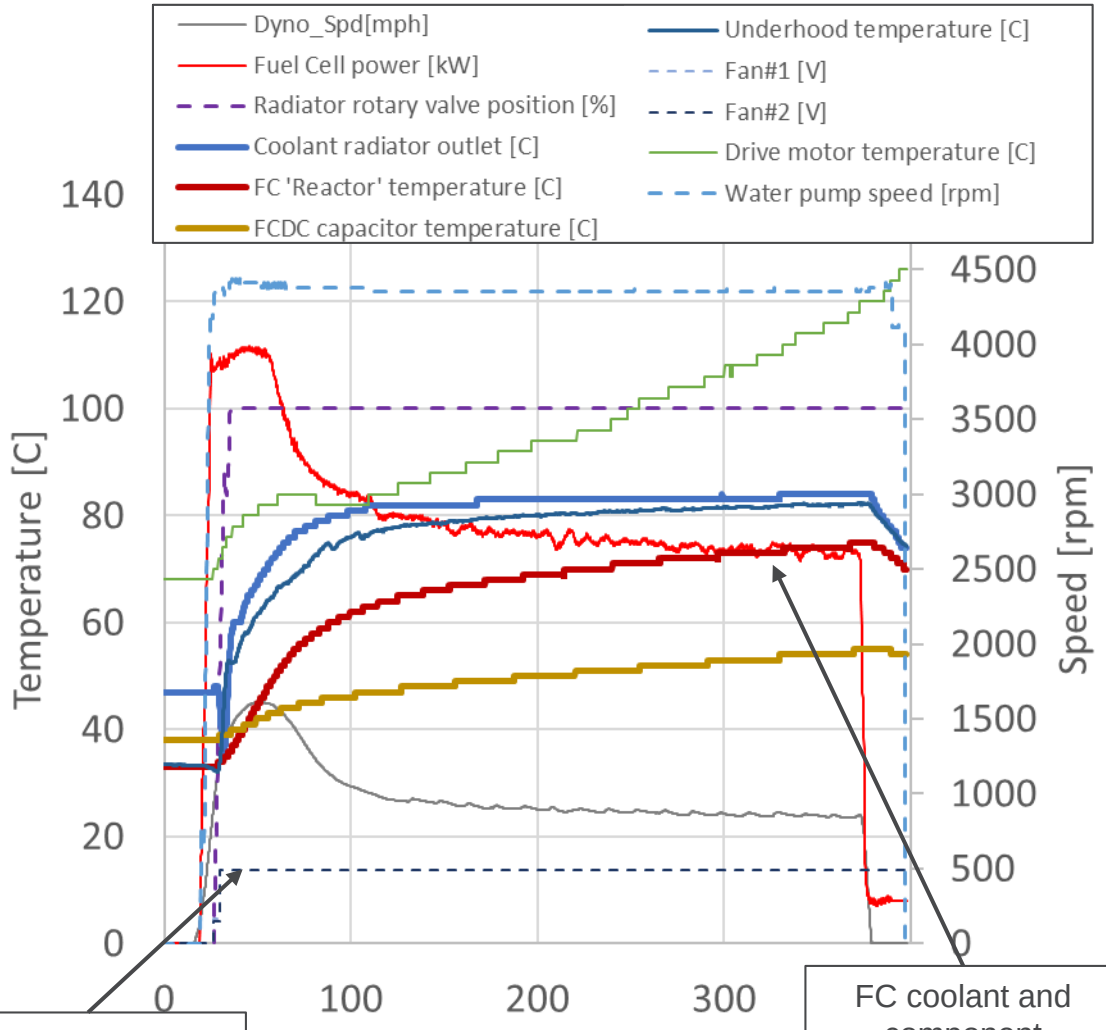
That fuel flow can be corrected based on the FC stack load.

The hydrogen metering maybe off at FC stack loads above 100kW



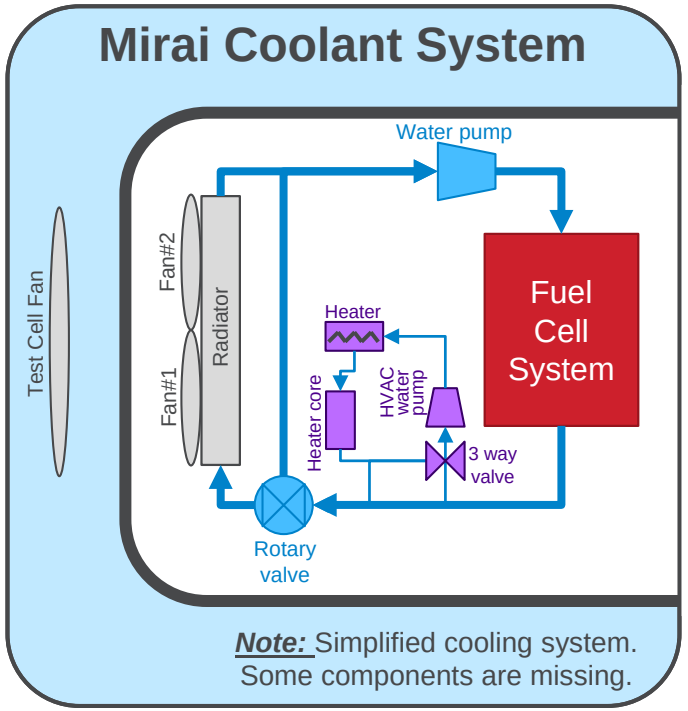
→ This is why two efficiency results were calculated for the FC stack and system efficiency analysis presented earlier.

MAXIMUM POWER TESTING ON A 25% GRADE AT 72F – THERMAL CONDITIONS



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

FC coolant and component temperate reach a steady state.



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

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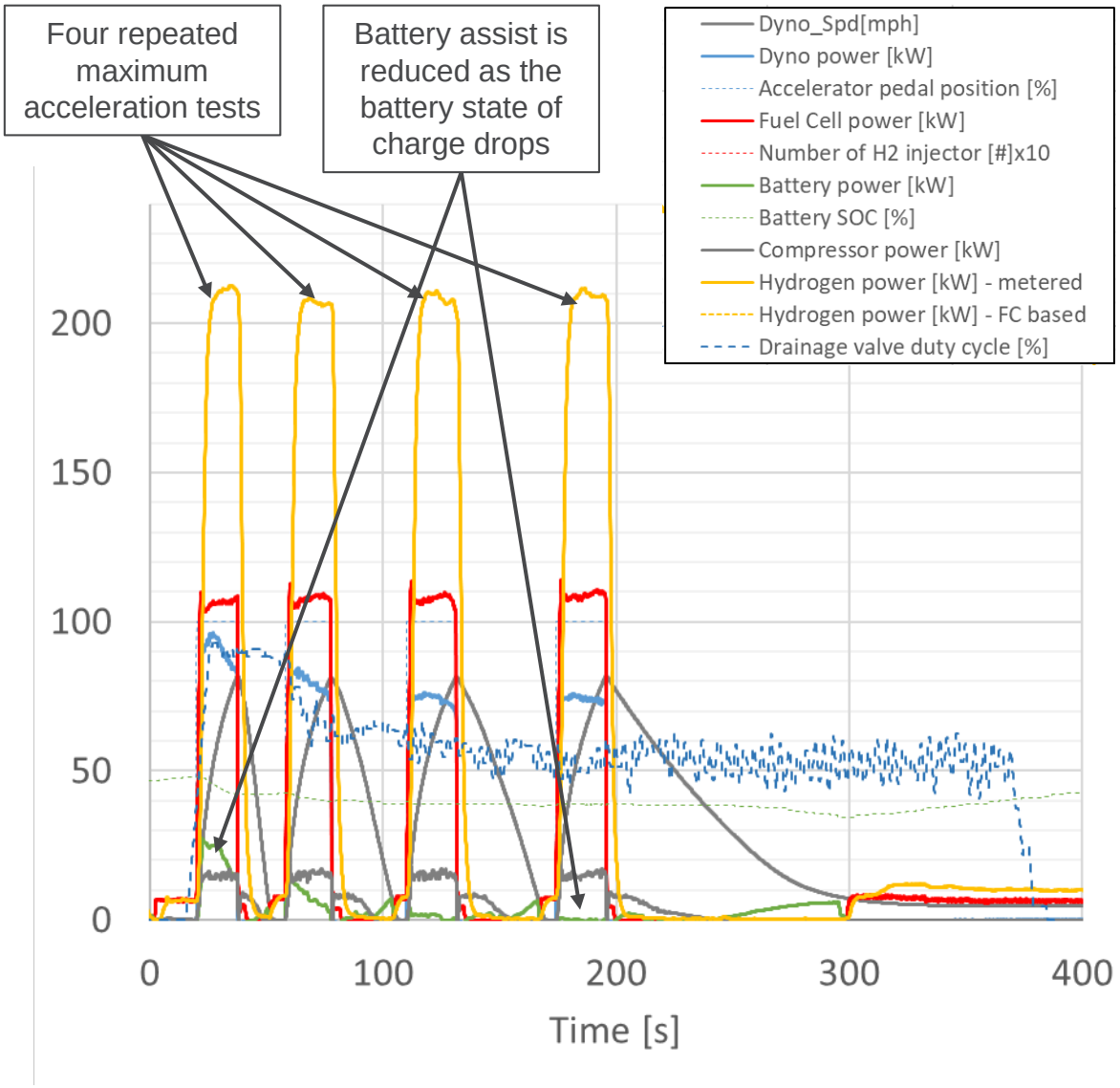
REPEATED MAXIMUM ACCELERATIONS TO 80 MPH AT 72F AMBIENT TEMPERATURE

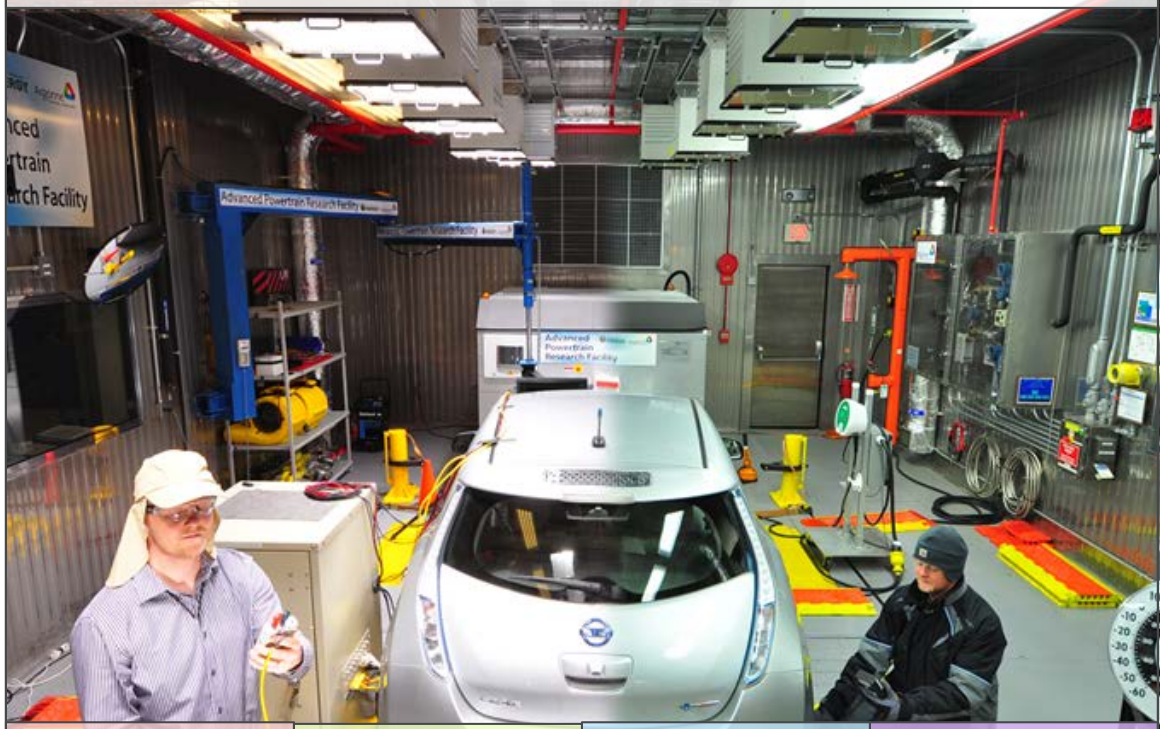


Run	0-80 mph [s]	Peak Stack [kW]	Average Stack [kW]
1	16.7	109.9	100.6
2	18.7	112.6	103.0
3	20.2	113.5	103.8
4	20.3	114.0	104.6

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

IMPACT OF TEMPERATURES: 0F, 20F, 72F AND 95F+850W/M^2

TESTING ACROSS A RANGE OF TEMPERATURES



Hot testing 95F + 850 W/m² (35C)	Standard testing 72F (22C)	Cold testing 20F (-7C)	Cold testing 0F (-18C)
Climate control 72F auto	Climate control OFF	Climate control 72F auto	Climate control 72F auto

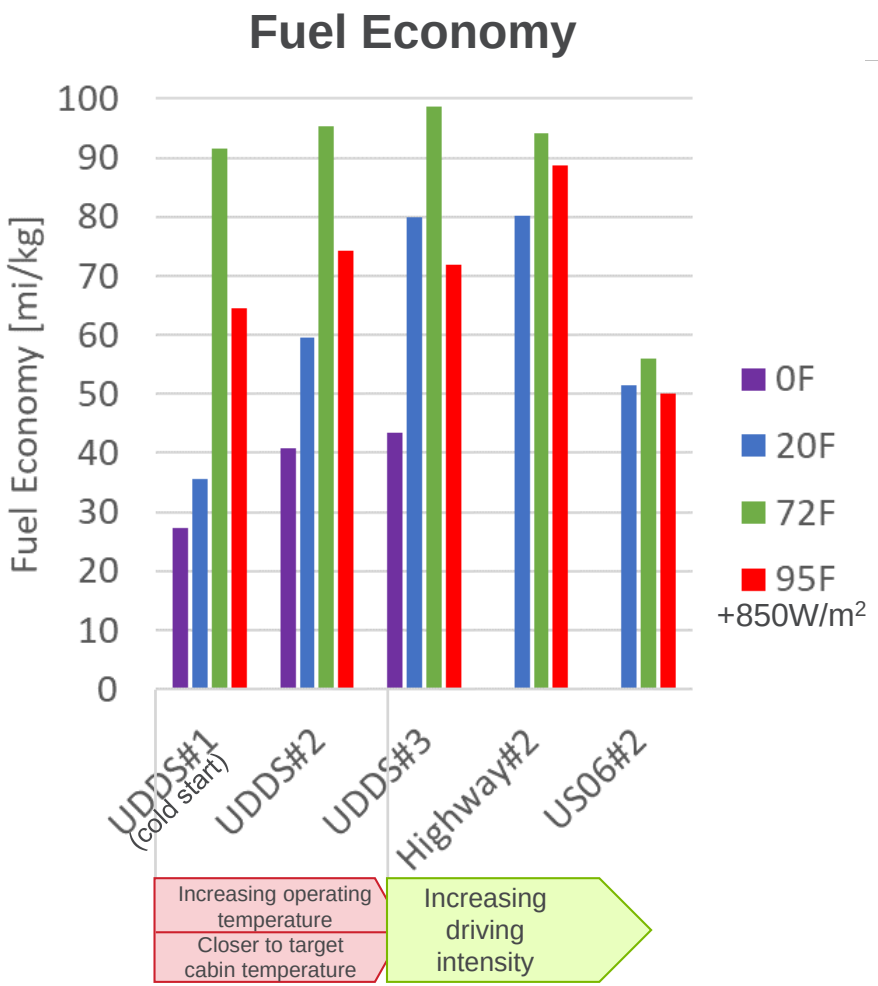
Thermal testing

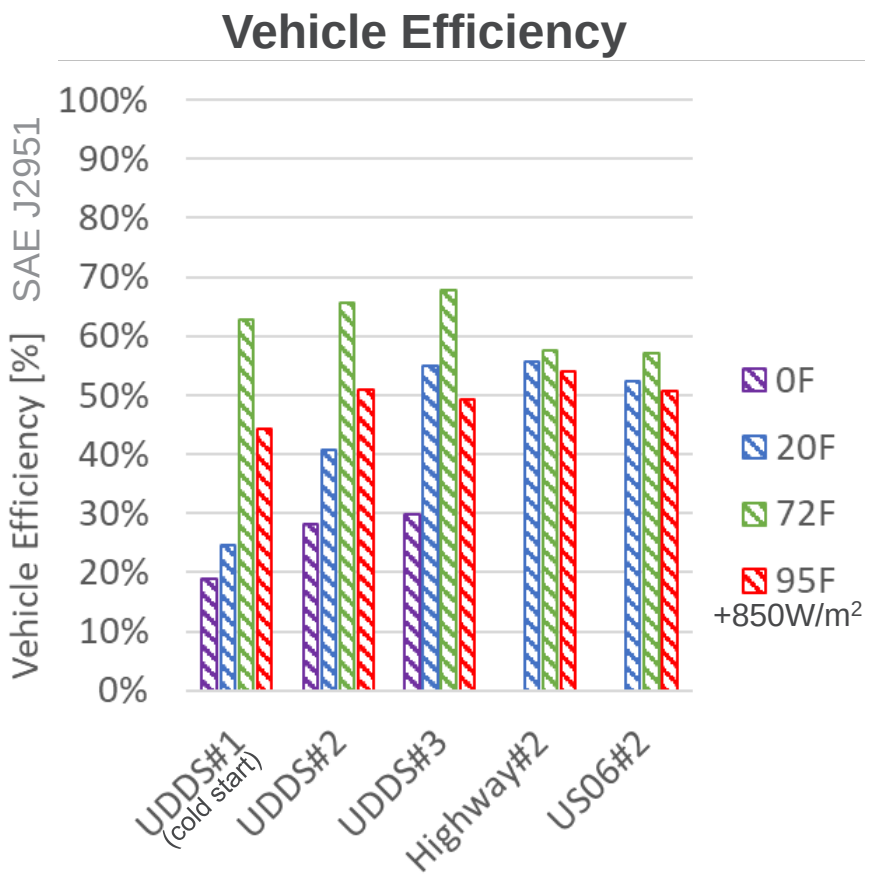
- The hood is closed in all cases
- The facility fan blows air dynamically across the front of the car at the same speed as the vehicle speed
- Cold start means that the vehicle was thermally ‘soaked’ at the target temperature for over 12 hours (typically 16 hours)

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)

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.

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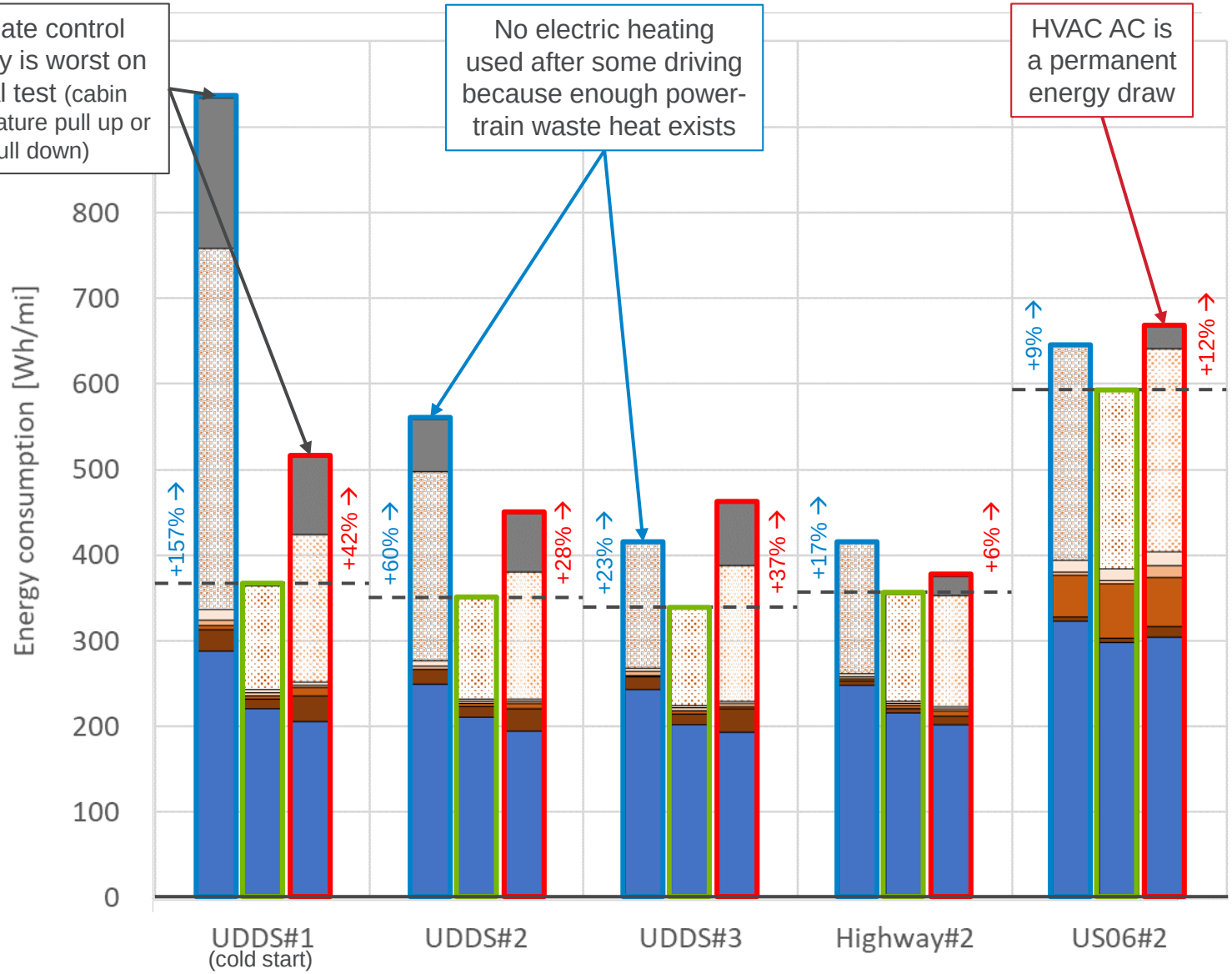
WHERE DID THE ENERGY GO?

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



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

Ambient test conditions:

- 20F
- 72F
- 95F+850W/m^2

Climate control:

- At 72F the climate control was off.
- At 20F and 95F the climate control was set to 72F auto.

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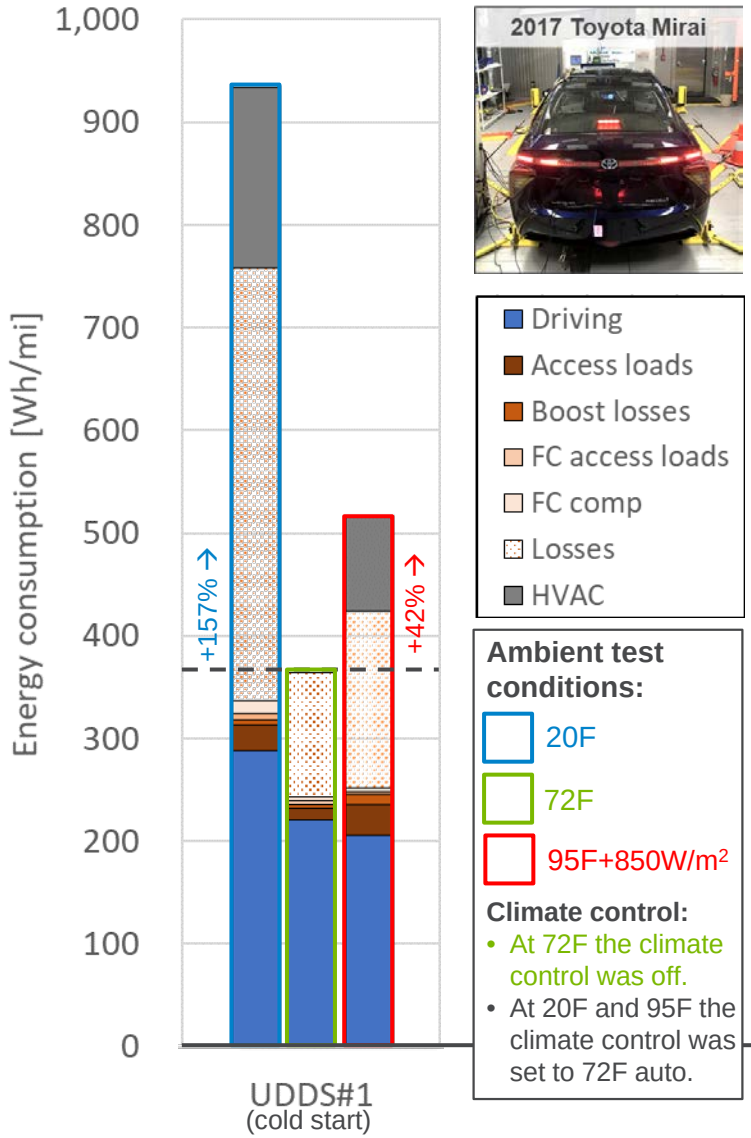
COMPARING A FUEL CELL VEHICLE TO A BATTERY ELECTRIC VEHICLE ACROSS TEMPERATURES



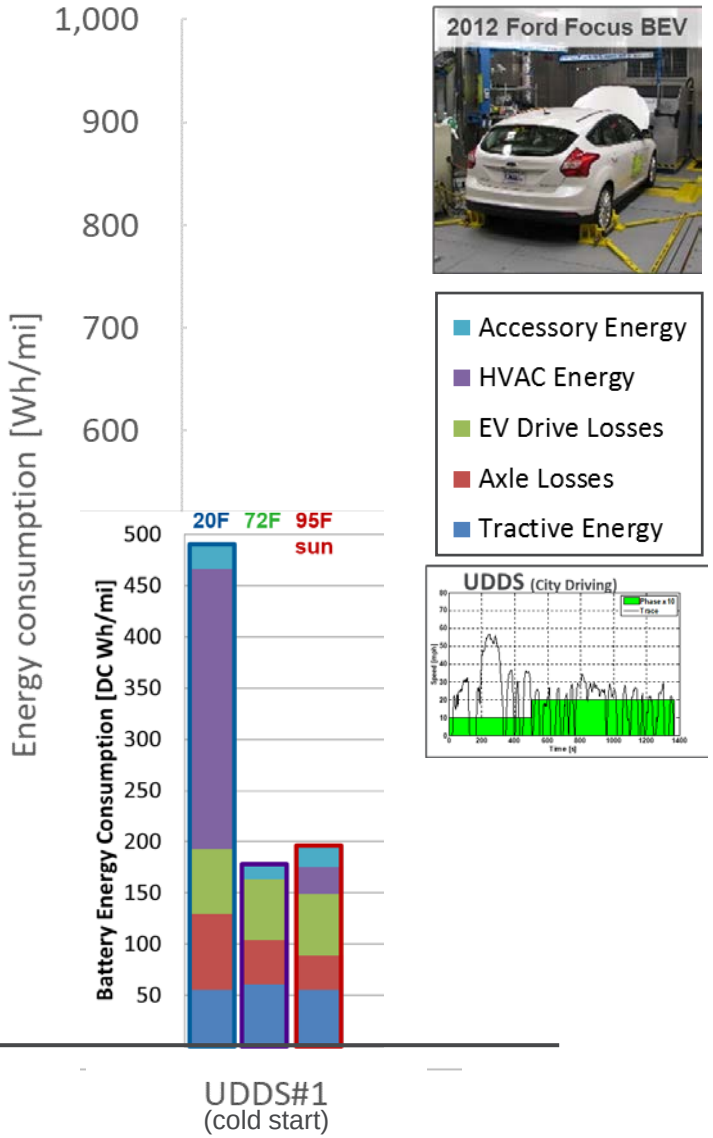
- Driving
- Access loads
- Boost losses
- FC access loads
- FC comp
- Losses
- HVAC

Ambient test conditions:

- 20F
- 72F
- 95F+850W/m^2

Climate control:

- At 72F the climate control was off.
- At 20F and 95F the climate control was set to 72F auto.



- Accessory Energy
- HVAC Energy
- EV Drive Losses
- Axle Losses
- Tractive Energy

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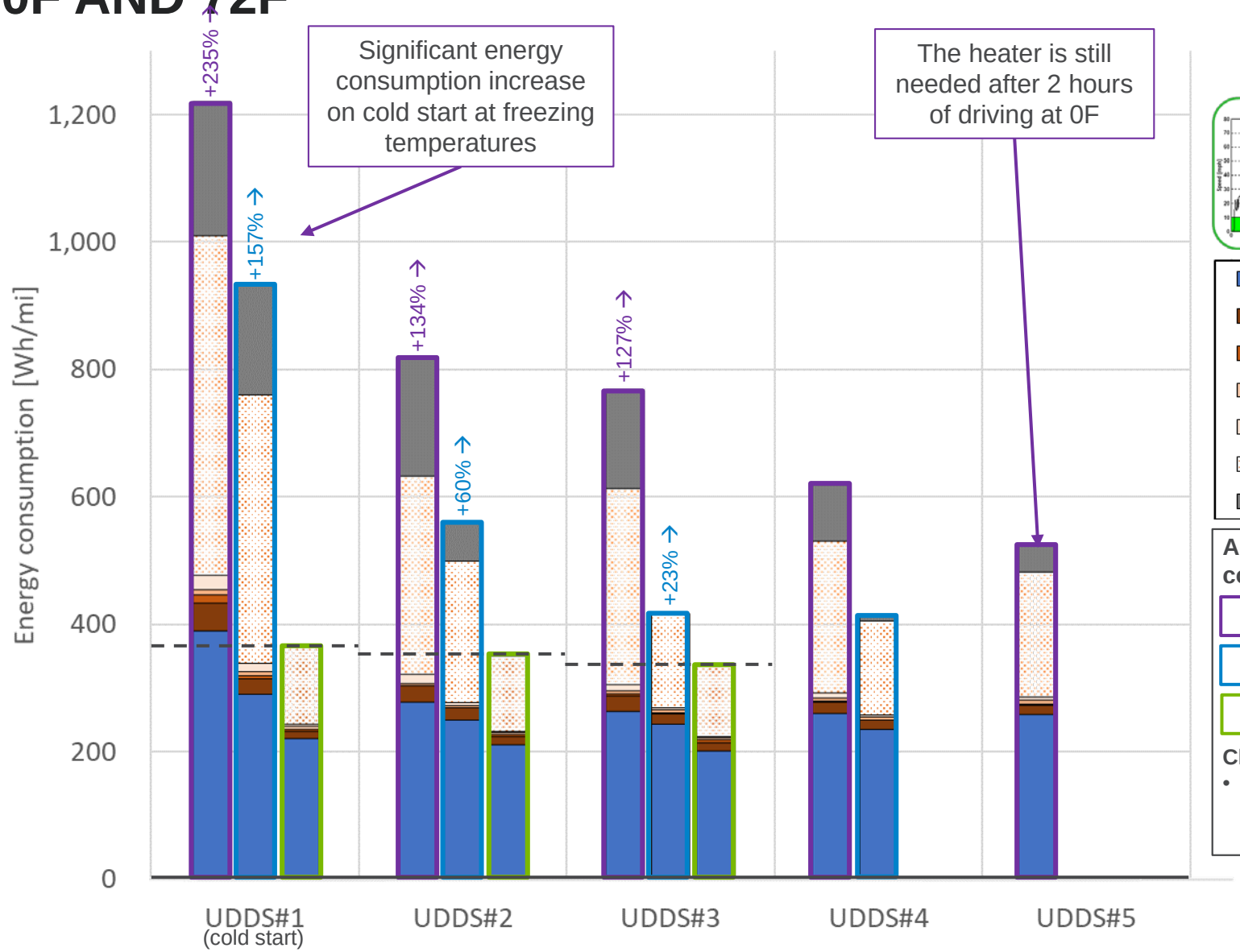
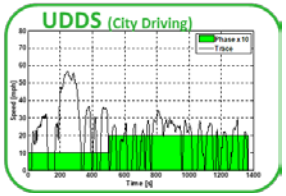
UDDS DRIVE CYCLES TEST SEQUENCE AT 0F, 20F AND 72F





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

Ambient test conditions:

- 0F
- 20F
- 72F

Climate control:

- the climate control was set to 72F auto in all cases

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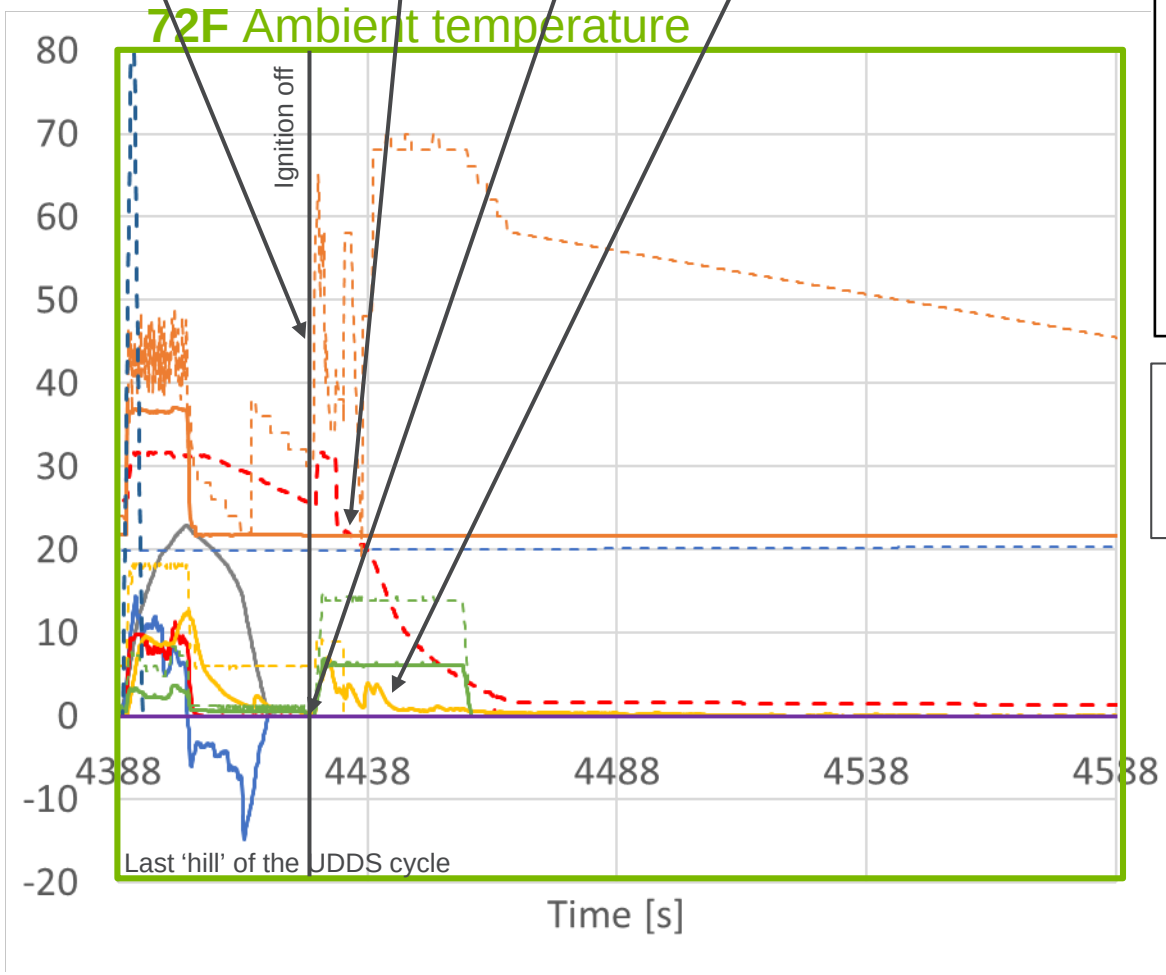
FUEL CELL SYSTEM SHUTDOWN AT 72F

Driver turns the car OFF after completing a UDDS drive cycle

FC voltage slowly decays

No FC stack power

A bit of hydrogen flow



- Dyno_Spd[mph]
- Dyno power [kW]
- Test Cell temperature [C]
- Fuel Cell power [kW]
- Fuel Cell voltage [V]/10
- Hydrogen power [kW]
- FC hydrogen pump speed [rpm]/100
- Hydrogen low range target pressure [kPa]
- Hydrogen low range pressure [kPa]
- FC mass air flow [NLpm]/100
- FC air compressor speed [rpm]/100
- Drainage valve duty cycle [%]
- HVAC power [kW]

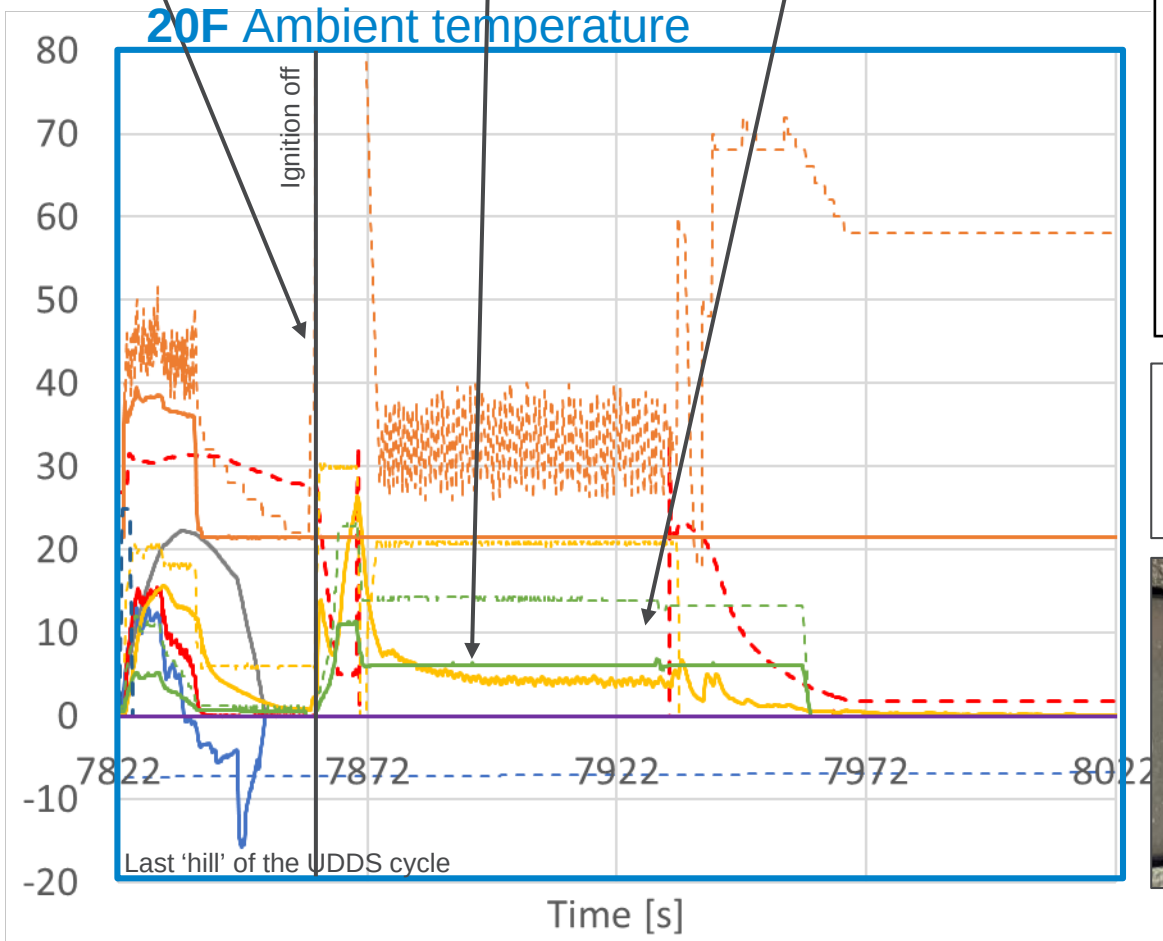
Purpose of the shut down: Leave the FC (esp PEM) in a 'good' state especially from a water management perspective.

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.



- Dyno_Spd[mph]
- Dyno power [kW]
- Test Cell temperature [C]
- Fuel Cell power [kW]
- Fuel Cell voltage [V]/10
- Hydrogen power [kW]
- FC hydrogen pump speed [rpm]/100
- Hydrogen low range target pressure [kPa]
- Hydrogen low range pressure [kPa]
- FC mass air flow [NLpm]/100
- FC air compressor speed [rpm]/100
- Drainage valve duty cycle [%]
- HVAC power [kW]

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.

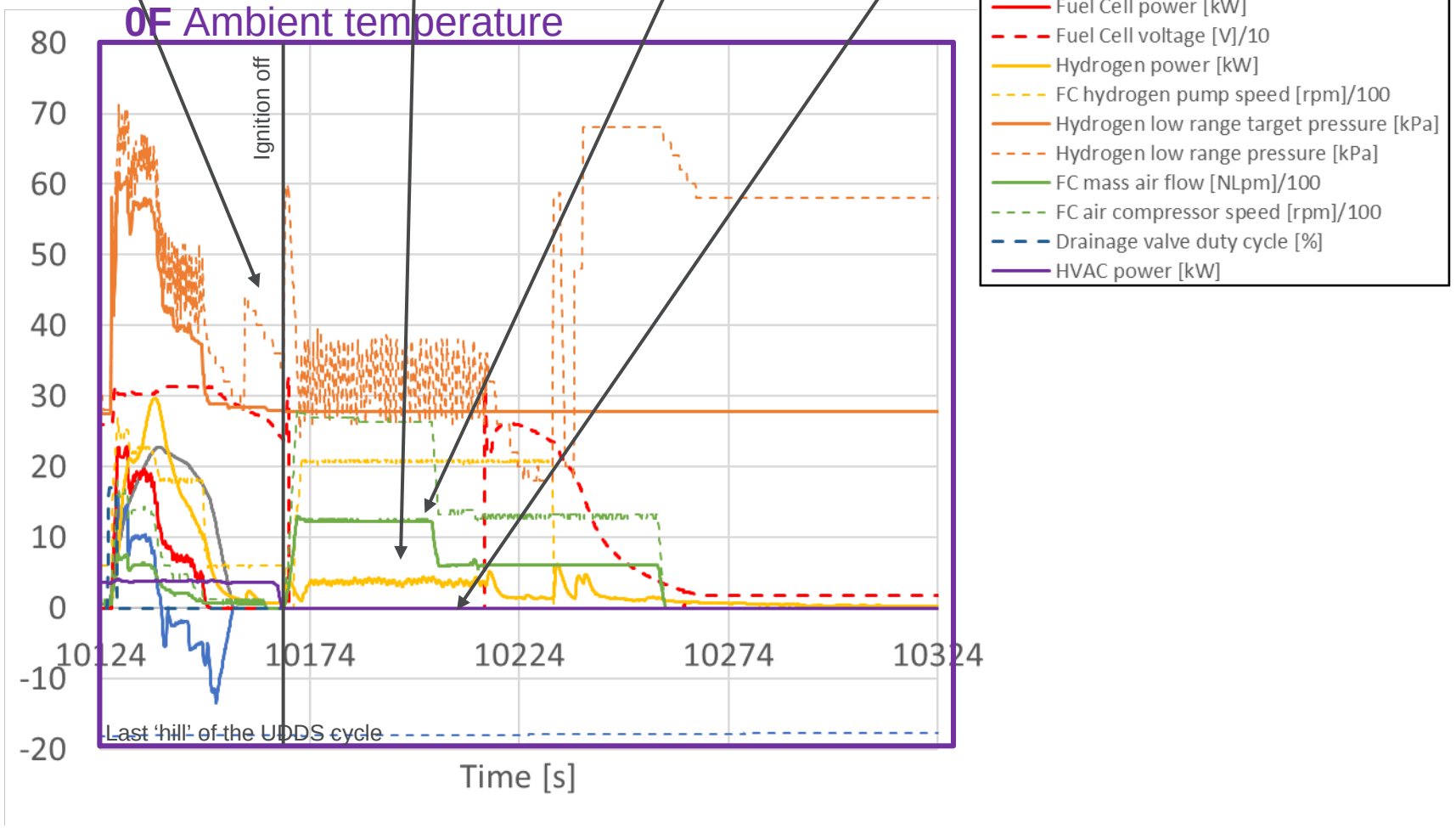
FUEL CELL SYSTEM SHUTDOWN AT 0F

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.



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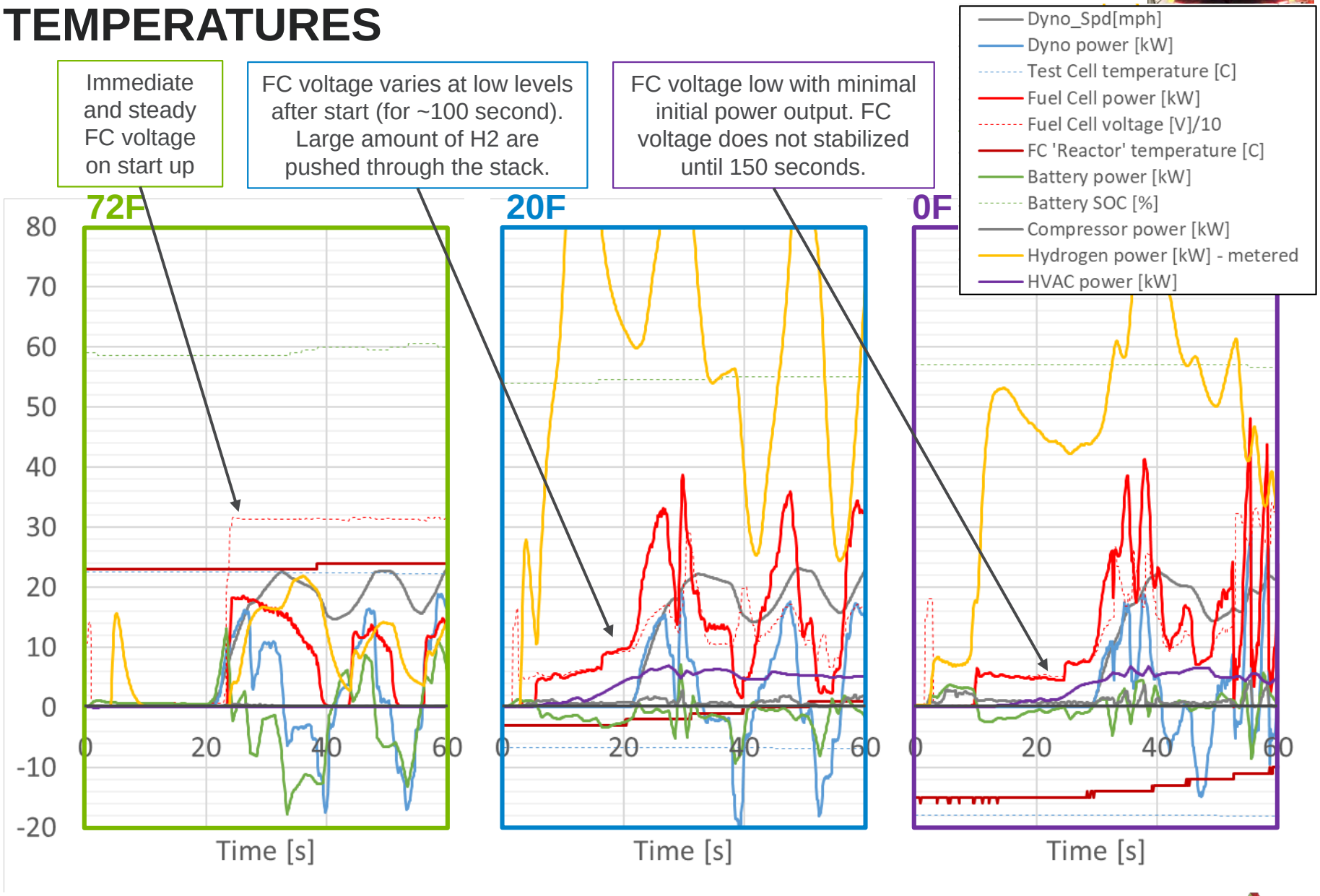
FC START UP ON COLD START IN FREEZING TEMPERATURES

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.



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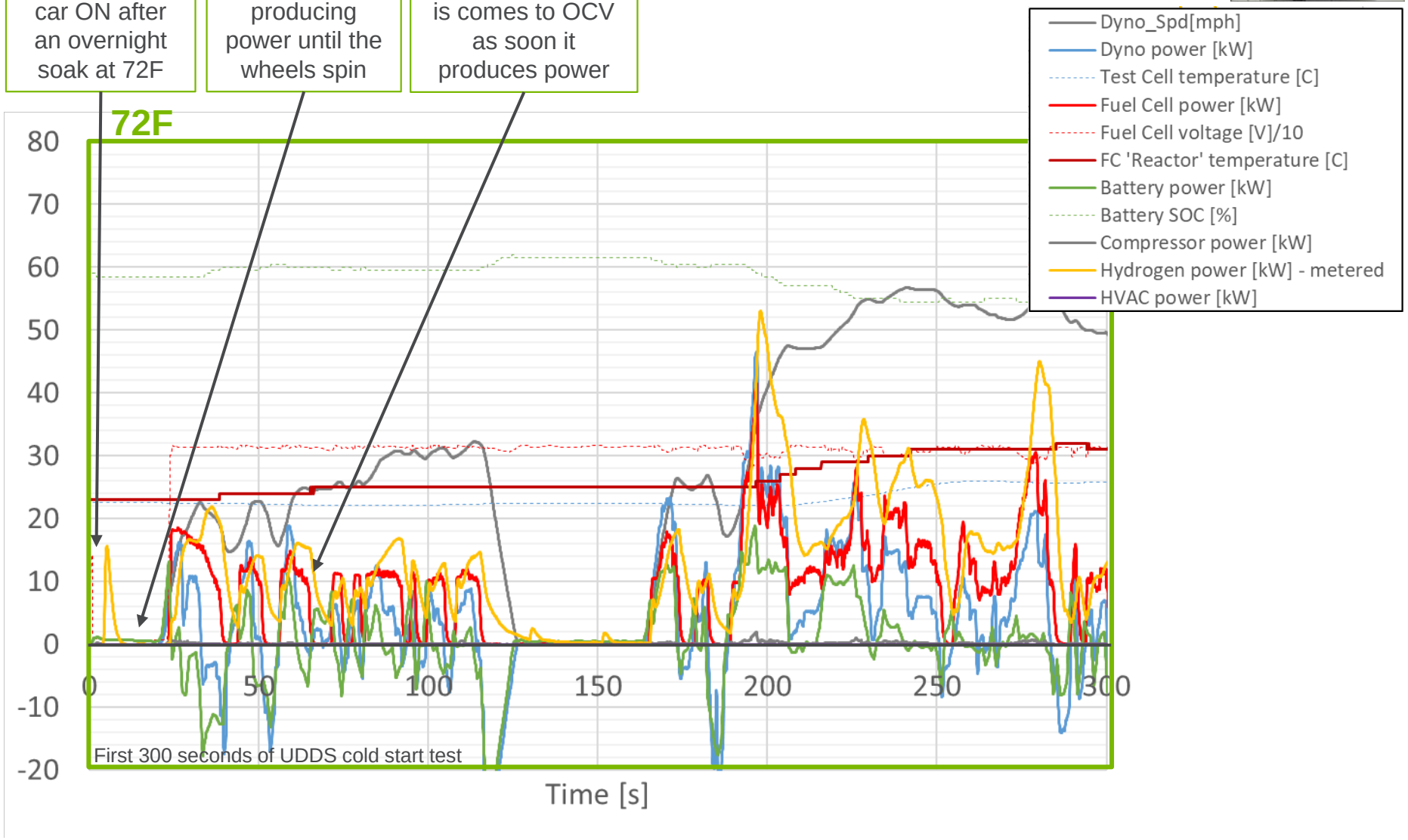
FUEL CELL START UP ON COLD START AT 72F

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



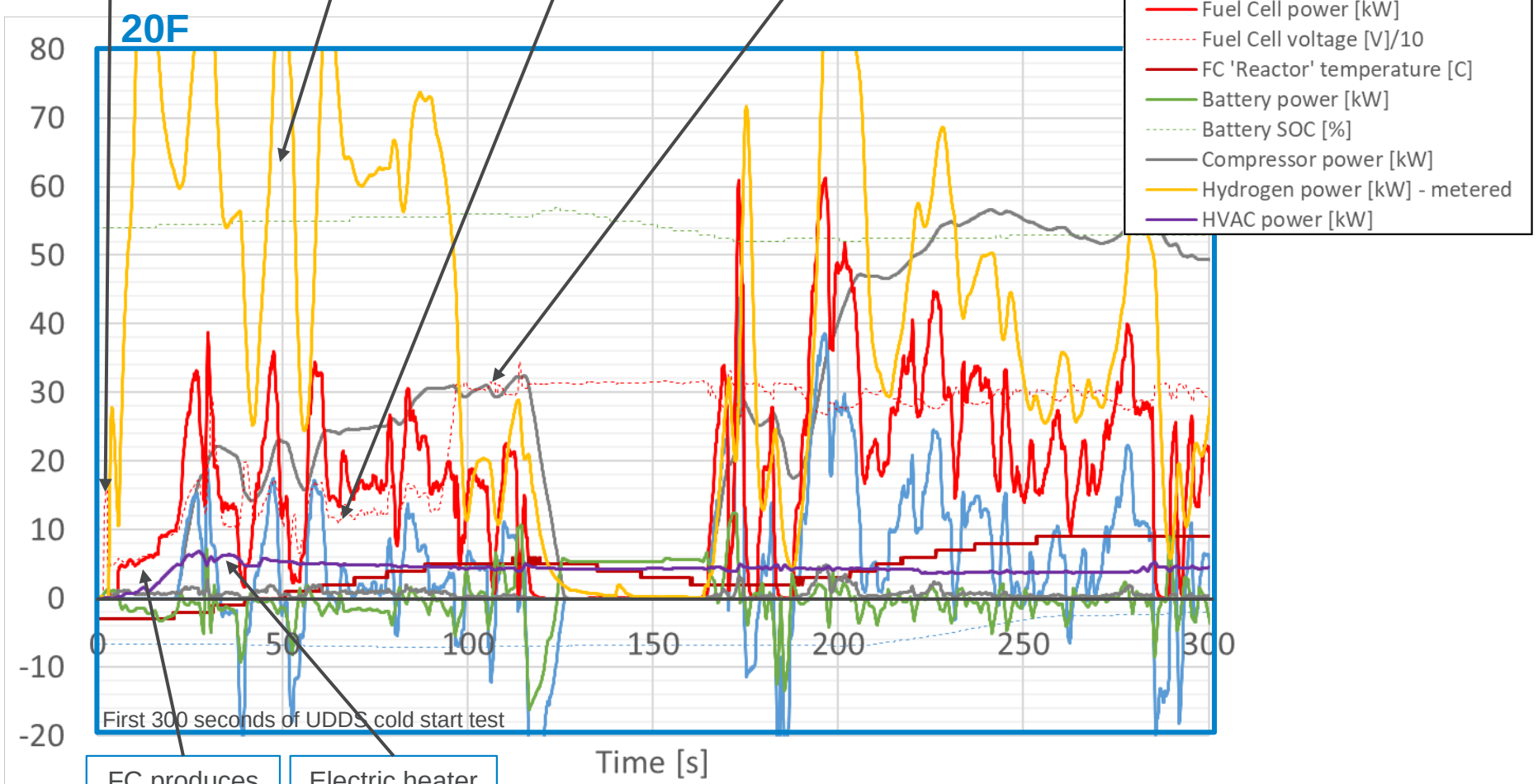
FUEL CELL START UP ON COLD START AT 20F

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



FC produces power before wheels spin

Electric heater power consumption

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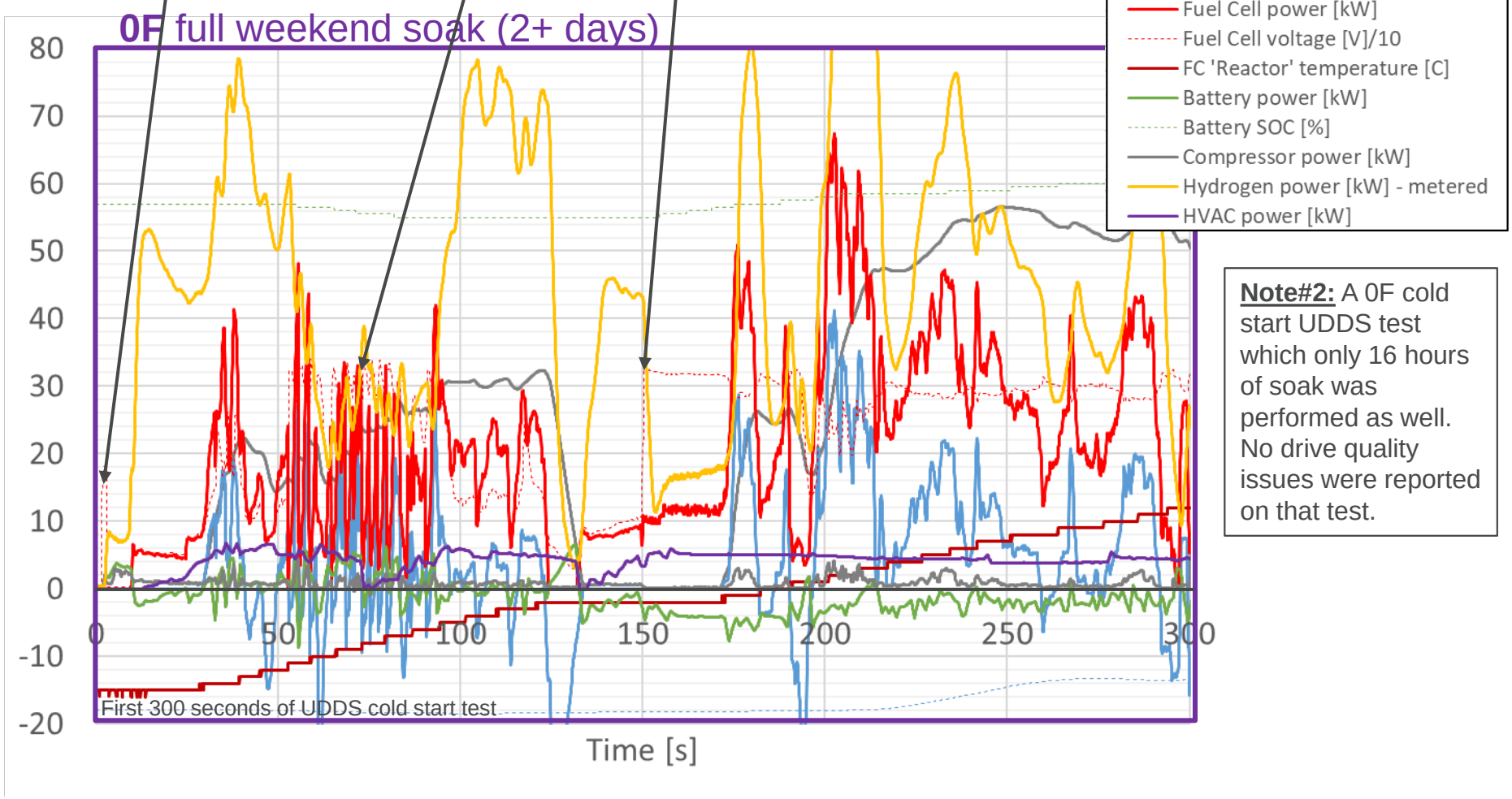
FUEL CELL START UP ON COLD START AT 0F

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.

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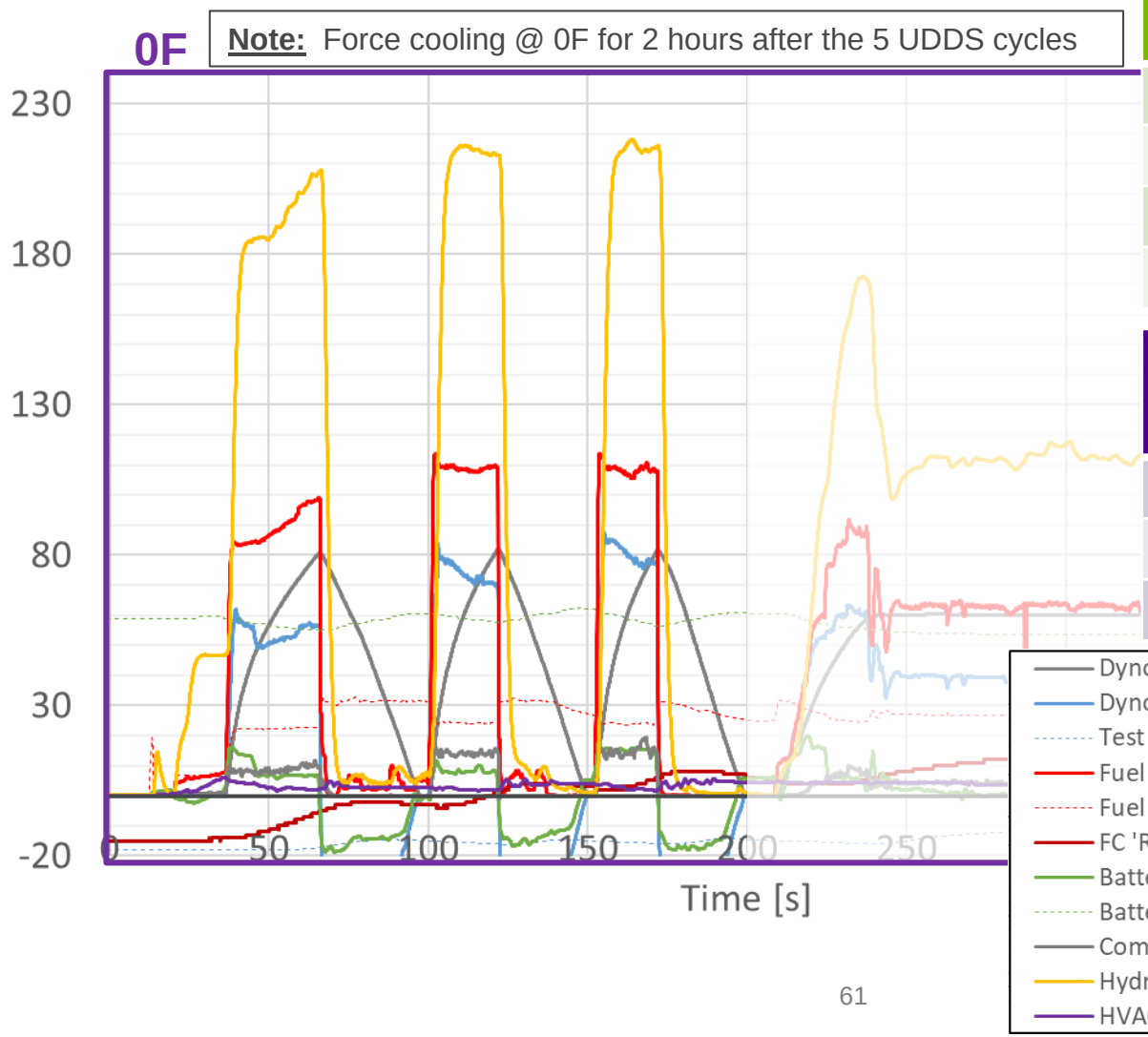
MAXIMUM ACCELERATION AT 0F

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



Run @72F	0-80 mph [s]	Peak Stack [kW]	Average Stack [kW]
1	16.7	109.9	100.6
2	18.7	112.6	103.0
3	20.2	113.5	103.8
4	20.3	114.0	104.6

Run @72F	0-80 mph [s]	Peak Stack [kW]	Average Stack [kW]
1	29	98.3	86.0
2	20.6	113.8	104.4
3	18.5	113.8	105.5

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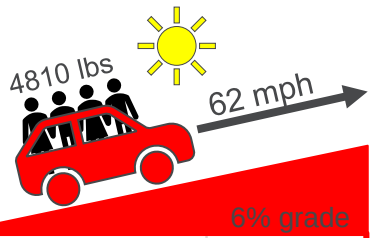
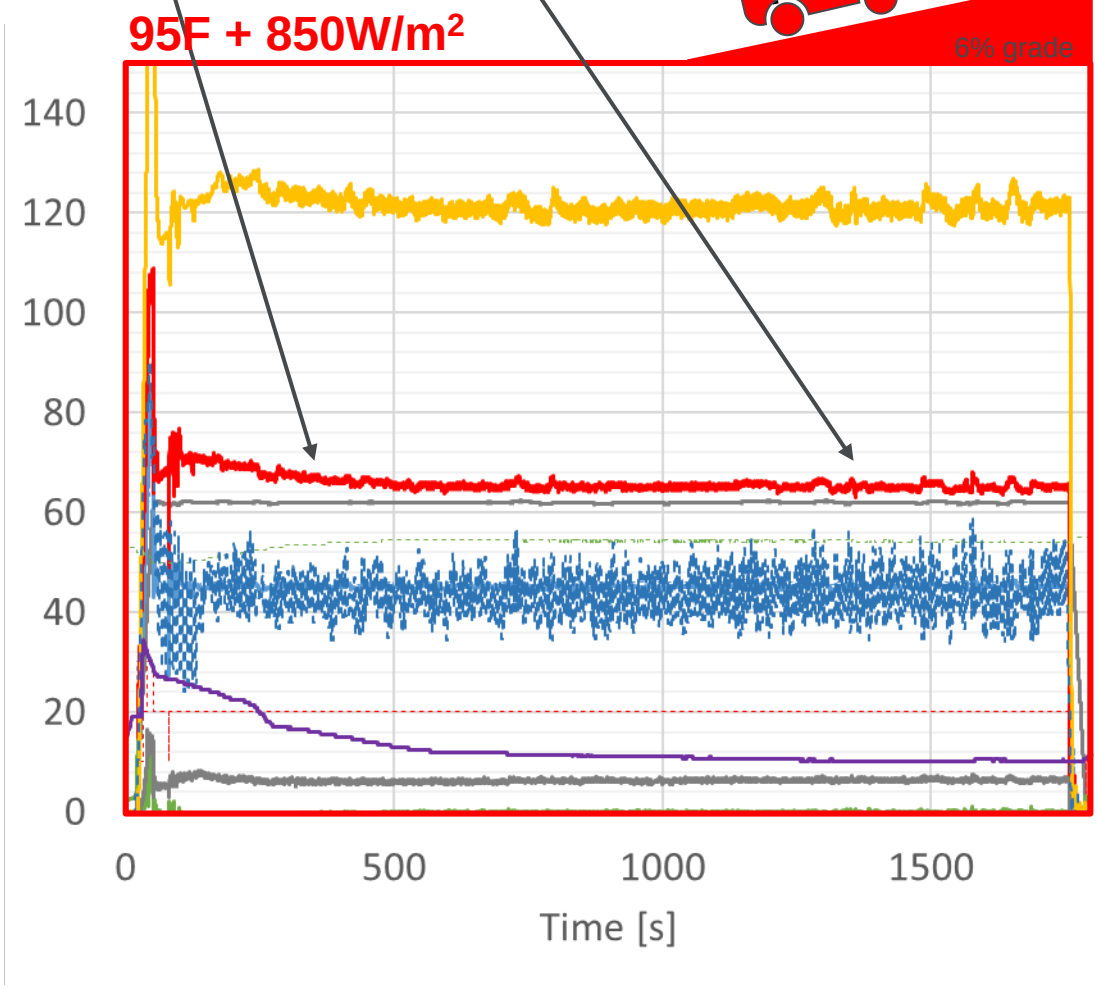
HILL CLIMB WITH SOLAR LOAD

The Mirai maintained the 62 mph speed target in these conditions

Continuous power of 63kW after 30 minutes





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.

- Dyno_Spd[mph]
- Dyno power [kW]
- Accelerator pedal position [%]
- Fuel Cell power [kW]
- Number of H2 injector [#]x10
- Battery power [kW]
- Battery SOC [%]
- Compressor power [kW]
- Hydrogen power [kW] - metered
- Drainage valve duty cycle [%]
- HVAC compressor [kW]x10

Hill Climb test

- 62 mph (100 km/h)
- 6% grade
- At 4810 lbs test weight (GVW)
- 95F ambient temperature
- 850 W/m^2 solar load
- Climate control set to 72F auto

→ Realistic worst case scenario

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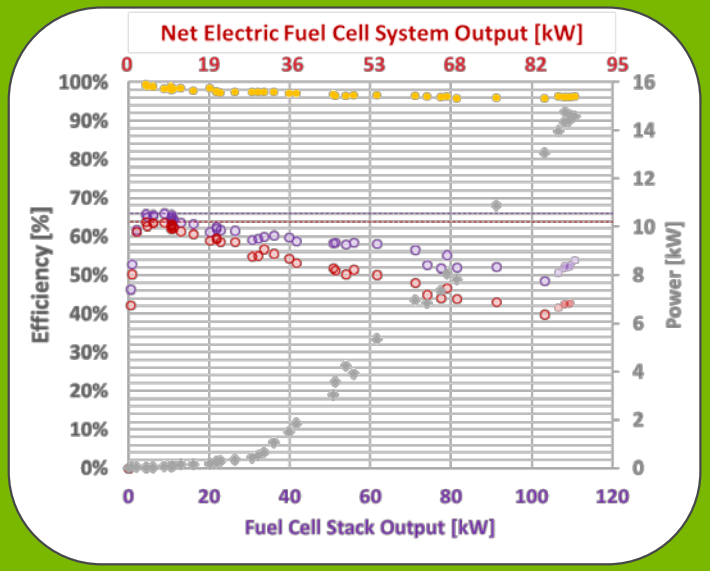
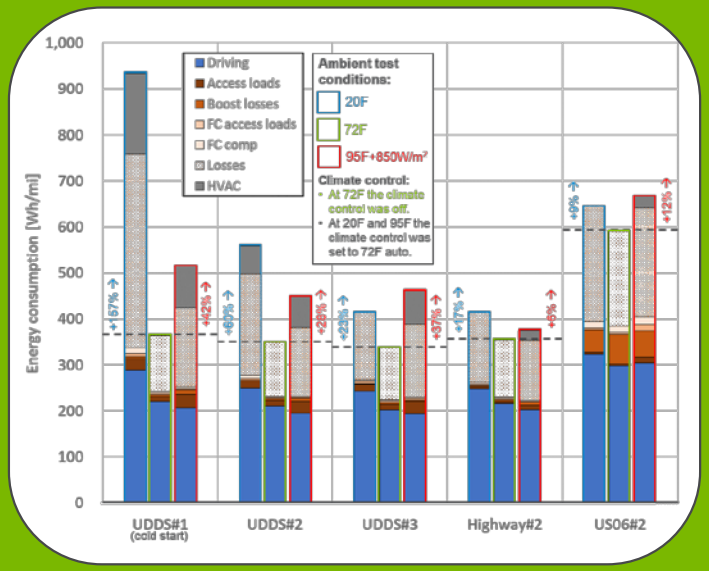
CONCLUSION AND TAKEAWAYS FROM TESTING A 2017 TOYOTA MIRAI FUEL CELL VEHICLE

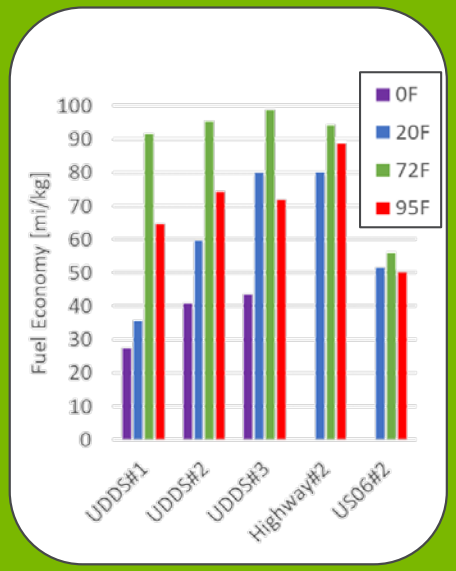
Fuel Cell Stack and System Efficiency Analysis



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.

Power output of the FC system conditioning to 0F is limited initially

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

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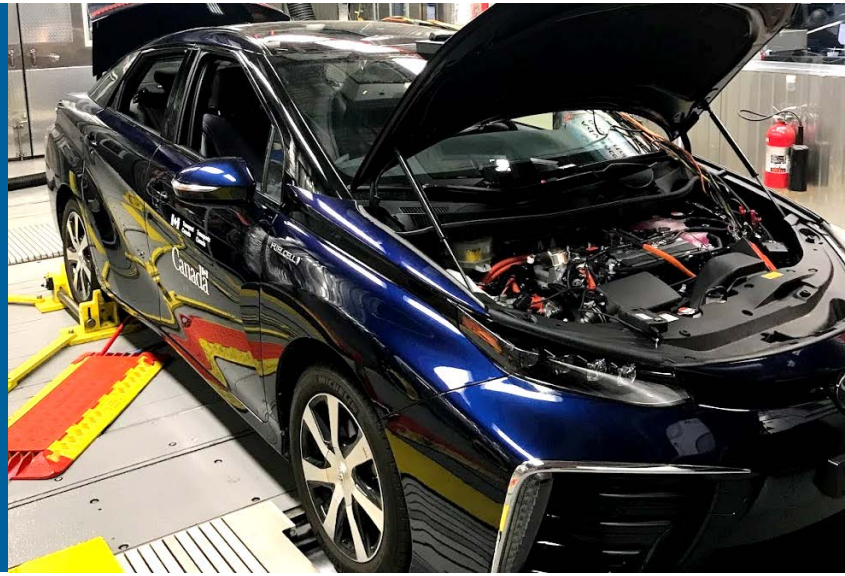
WWW.ANL.GOV/D3

TECHNOLOGY ASSESSMENT OF A FUEL CELL VEHICLE: 2017 TOYOTA MIRAI



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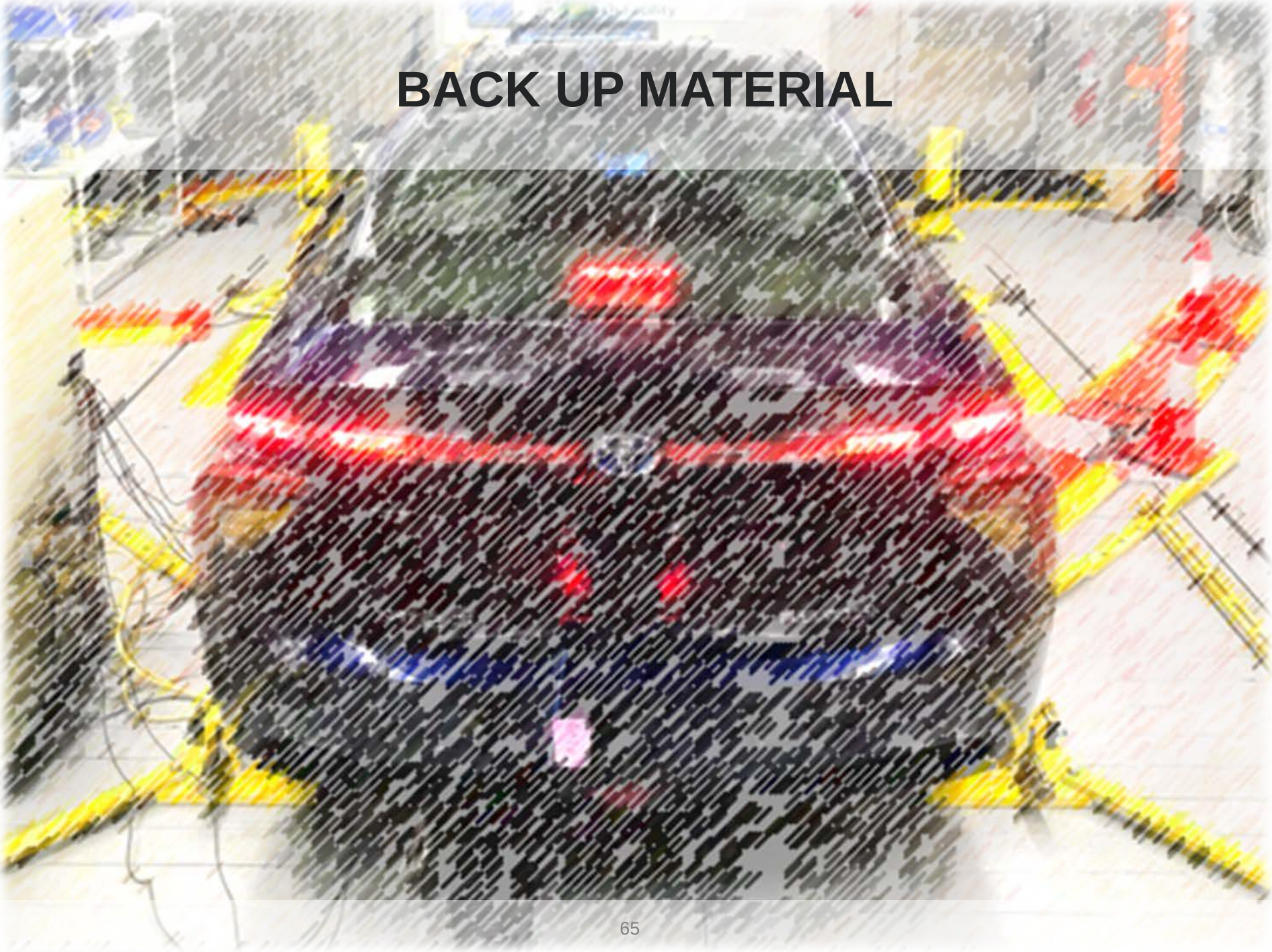
Transport Canada

AARON LOISELLE-LAPOINTE
Environment and Climate Change Canada

June 2018 (v10)
Argonne National Laboratory, IL

BACK UP MATERIAL



Advanced Powertrain Research Facility
4WD Chassis Dynamometer Thermal Test Cell

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U.S. DEPARTMENT OF ENERGY

"Research and Data Driven Lab"
"Independent Public Data"

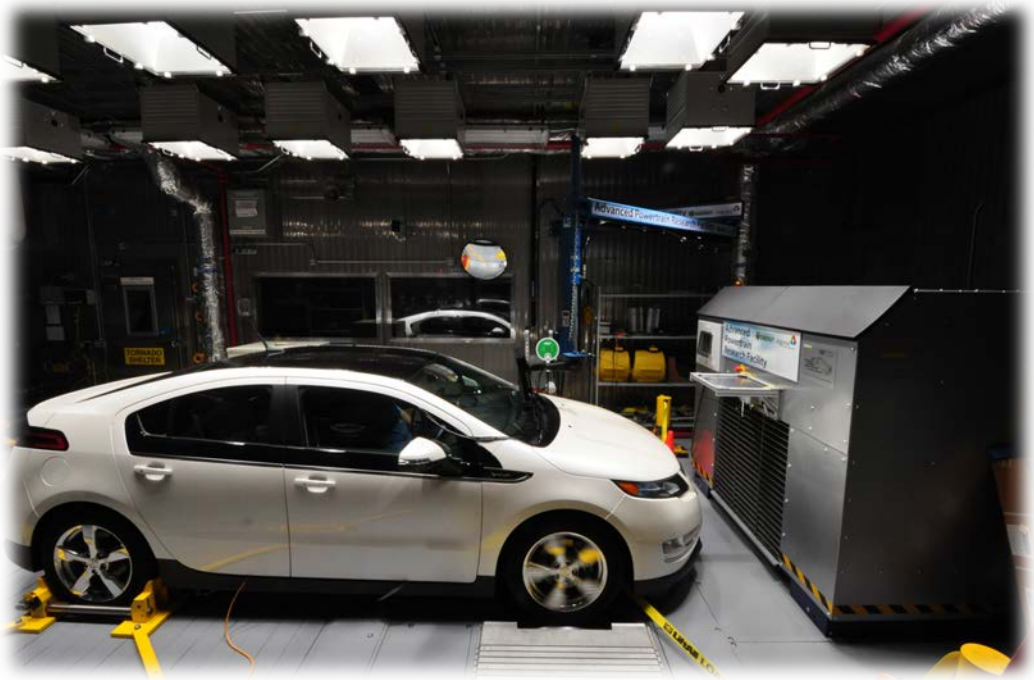
- **Test cell specifications**
  - ✓ 4WD chassis dynamometer
    - Variable wheel base (180inches max)
    - 250 hp/axle
    - 300 to 12,000 lb inertia emulation
  - ✓ Radiant sun energy emulation of 850W/m^2 (adjustable)
  - ✓ Variable speed cooling fan (0–62mph)
  - ✓ Gaseous fuel and hydrogen capable
  - ✓ 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

- **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

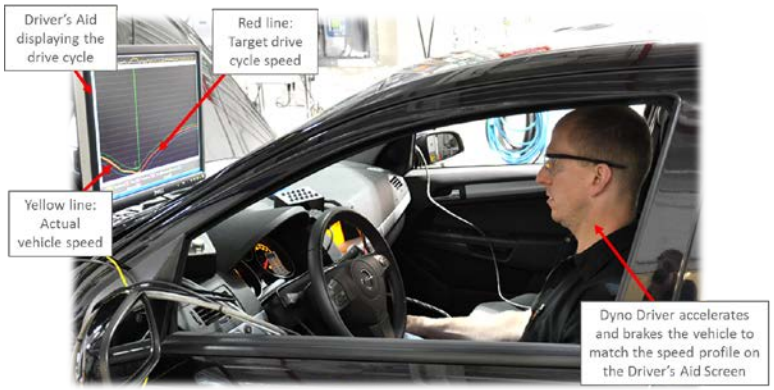
- **Special instrumentation**
  - ✓ High precision power analyzers (testing and charging)
  - ✓ CAN decoding and recording
  - ✓ OCR scan tool recording
  - ✓ Direct fuel flow metering
  - ✓ Infrared temperature camera
  - ✓ In cylinder pressure indicating systems
  - ✓ In-situ torque sensor measurement
  - ✓ 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

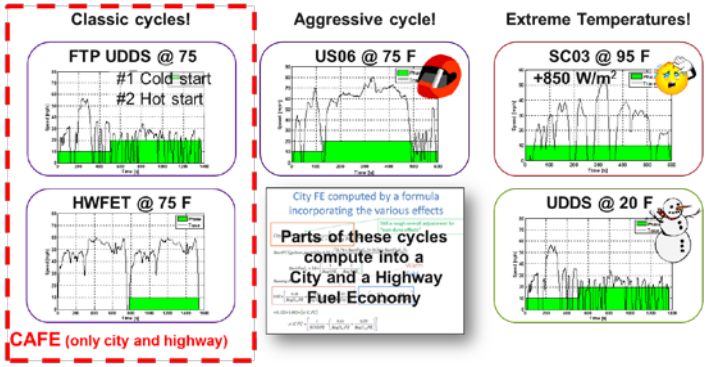
Chassis dynamometer test cell



A driver accelerates and brakes to follow a drive trace



A drive trace is a defined speed profile as a function of time



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

$$Power_{propulsion} = \left(m \times \frac{\partial(V)}{\partial t} + F_{roadload} \right) \times V$$

(At the wheel)

Inertia force: overcome change in momentum

Road load force: caused by wind resistance and other vehicle losses

$$F_{roadload} = A + B \times V + C \times V^2$$

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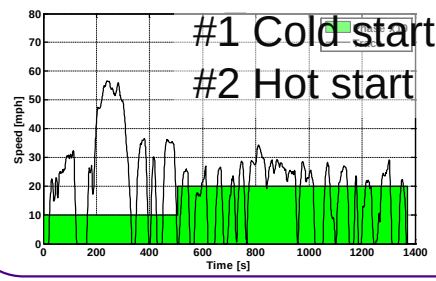
EPA'S 5 CYCLES TESTS FOR FUEL ECONOMY LABEL

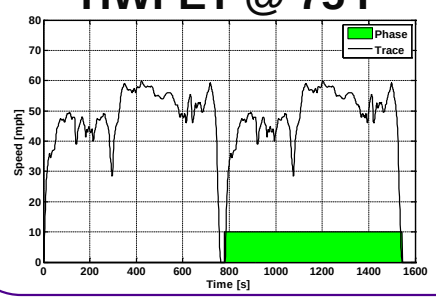
EPA implemented the new 5 Cycle Fuel Economy Label to close the gap to real world fuel economy the consumer can expect

Classic cycles!

FTP UDDS @ 75



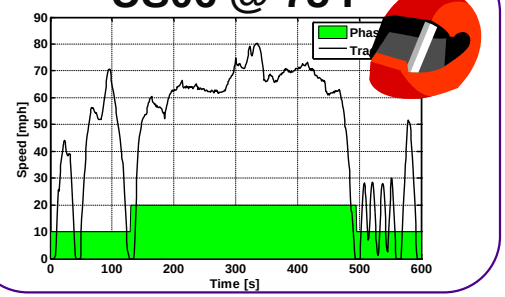
HWFET @ 75 F

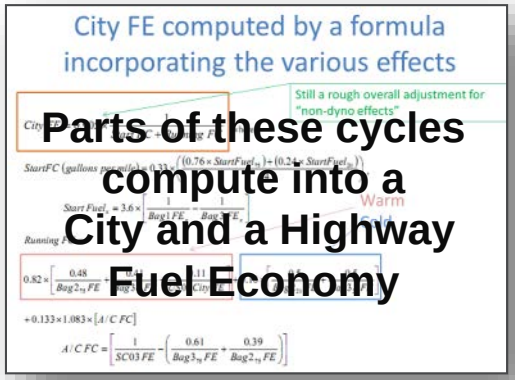


CAFE (only city and highway)

Aggressive cycle!

US06 @ 75 F

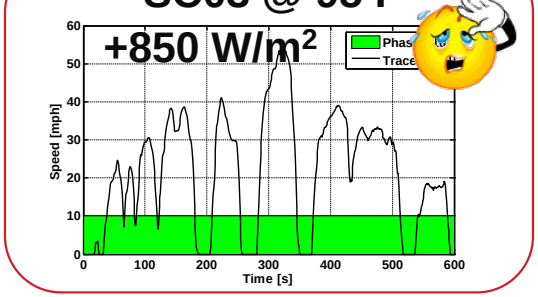




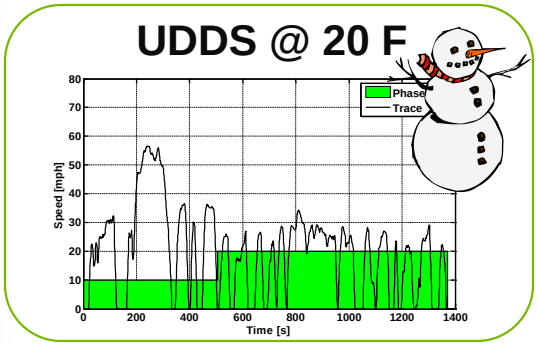
Parts of these cycles compute into a City and a Highway Fuel Economy

Extreme Temperatures!

SC03 @ 95 F



UDDS @ 20 F



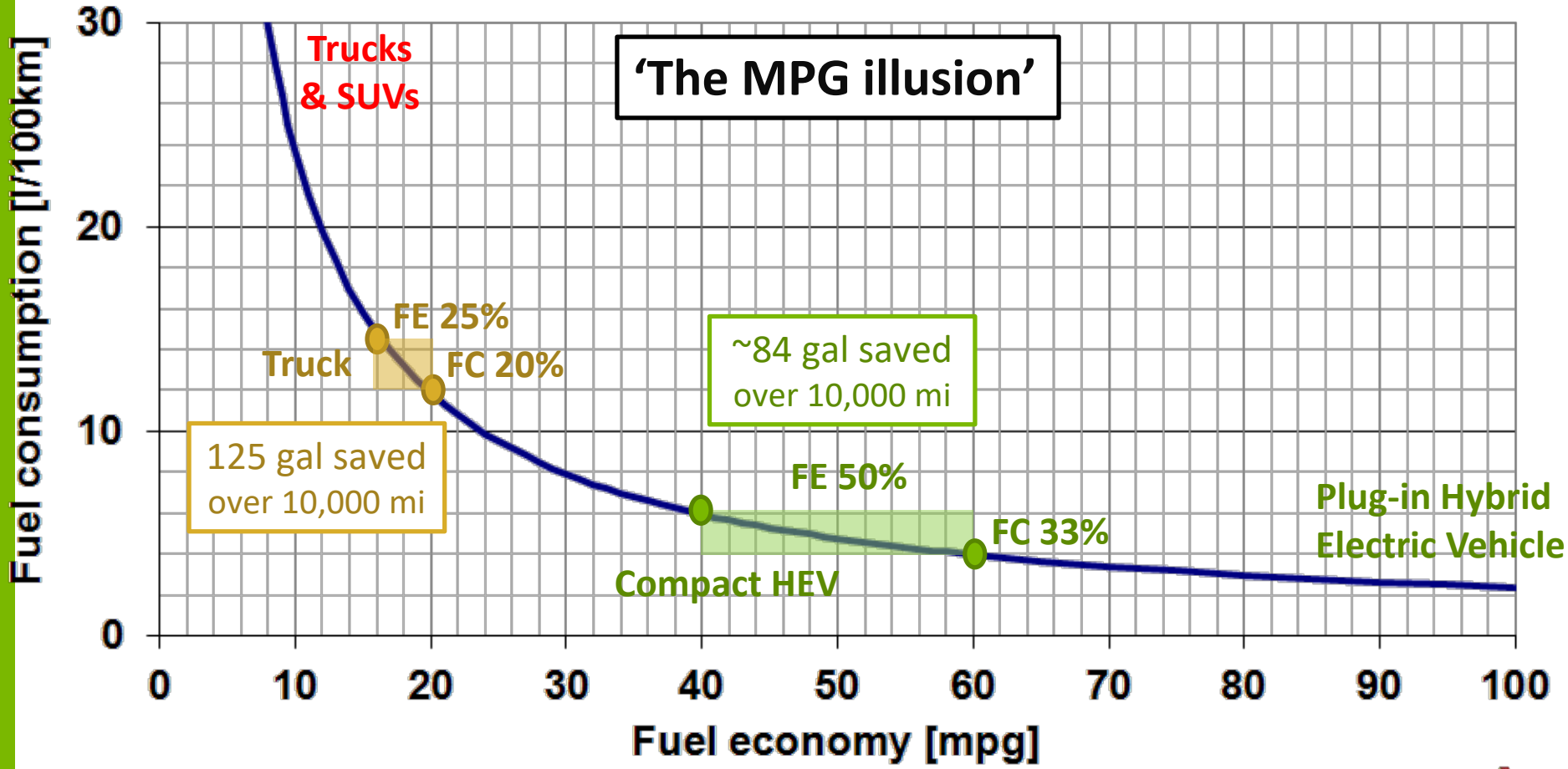
PSYCHOLOGY OF FUEL ECONOMY VS. FUEL CONSUMPTION

Fuel Economy = Distance / Fuel

If little fuel is used, FE *'explodes'* to a large number and becomes misleading

Fuel consumption= Fuel / Distance

FC is a better scale for very efficient vehicles!



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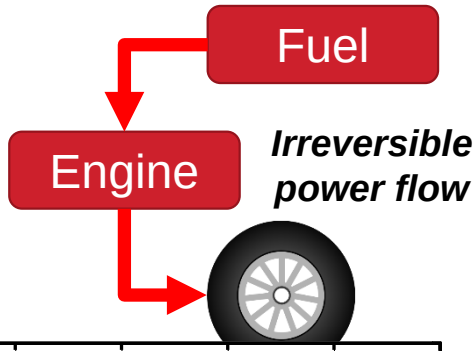
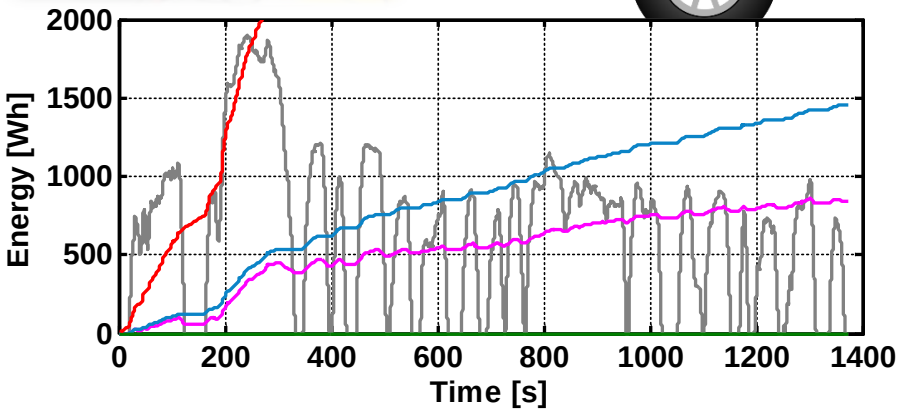
ELECTRIFICATION COMPLICATES EFFICIENCY CALCULATIONS

Conventional Vehicle

2012 Focus 2L

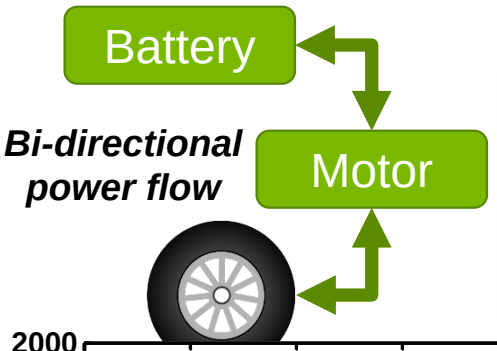


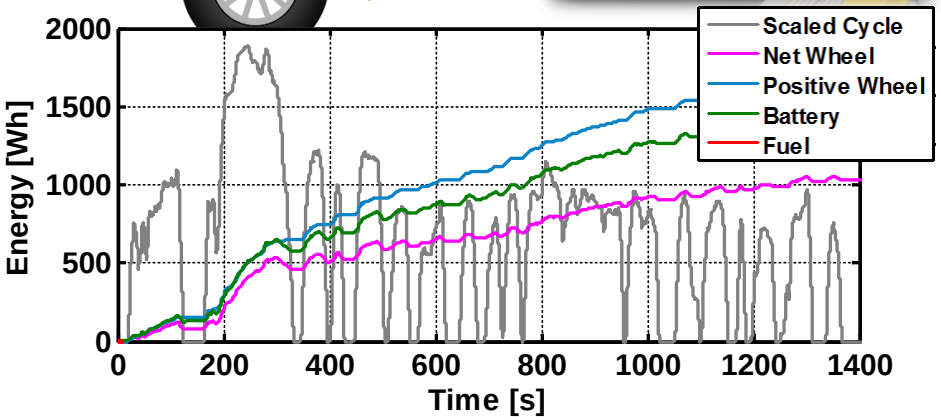


$$Efficiency = \frac{Energy_{out}}{Energy_{in}}$$

Electric Vehicle

2013 Focus BEV

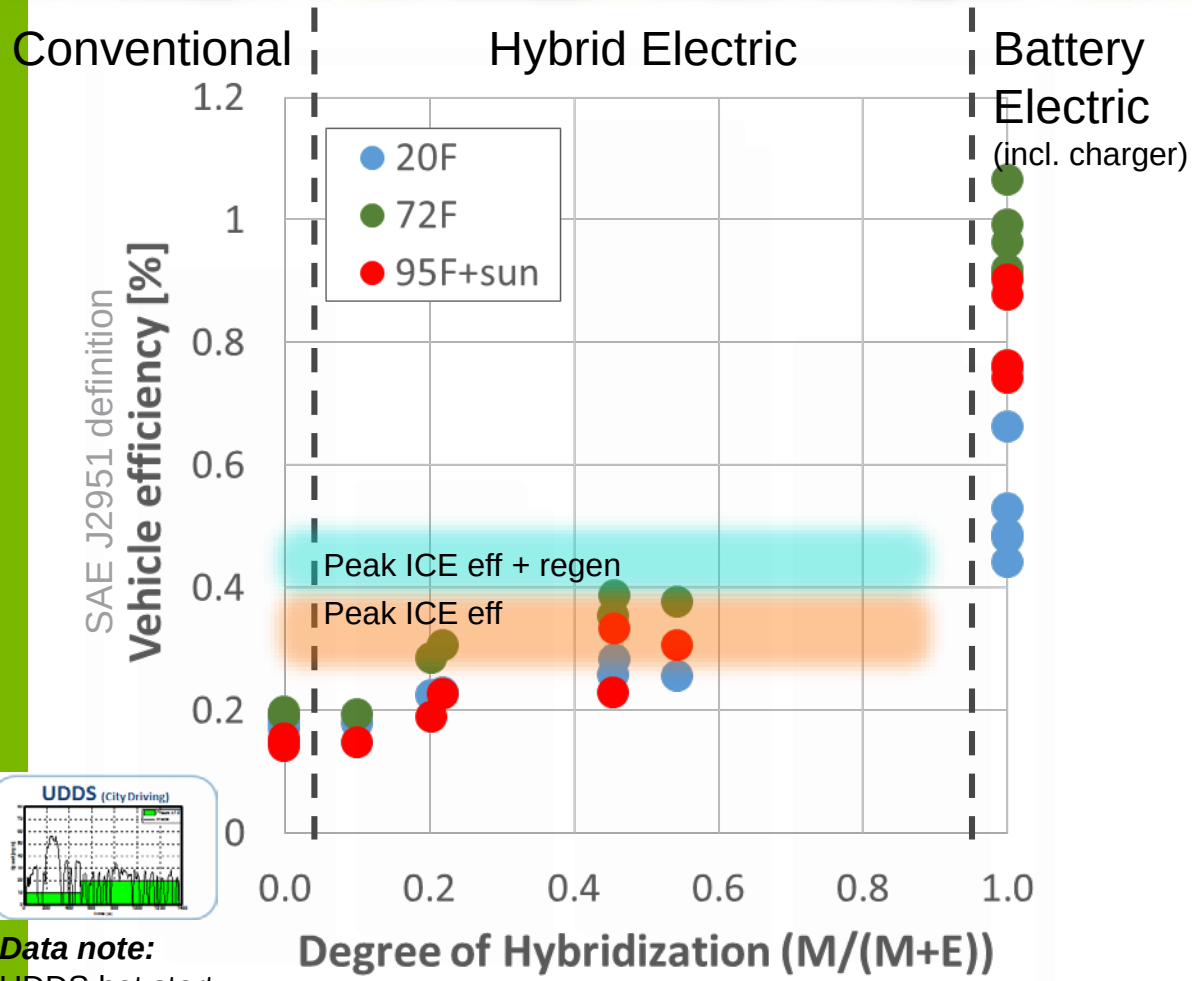




Regenerative braking reverses the power flow and charges the high voltage battery (In & Out reverse)

→ SAE J2951 defines "Cycle Energy" as the integration of ***positive*** power at the wheel over the cycle (regenerative braking = "free" energy)

HIGHER EFFICIENCY POWERTRAINS ARE MORE SENSITIVE



Data note:
UDDS hot start

Observations:

- Everything matters down to the accessory loads in electric vehicles.

Conventional	2012 Ford Focus
	2013 Jetta TDI
	2013 Chevy Cruze Diesel
Hybrid Electric	2013 Chevy Malibu Eco
	2013 VW Jetta HEV
	2013 Honda Civic 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

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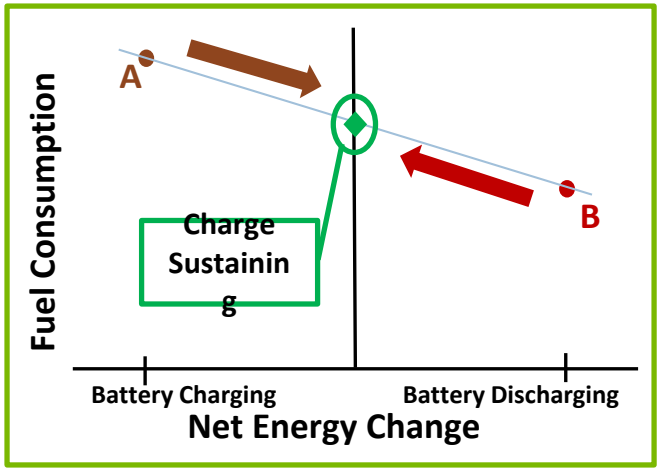
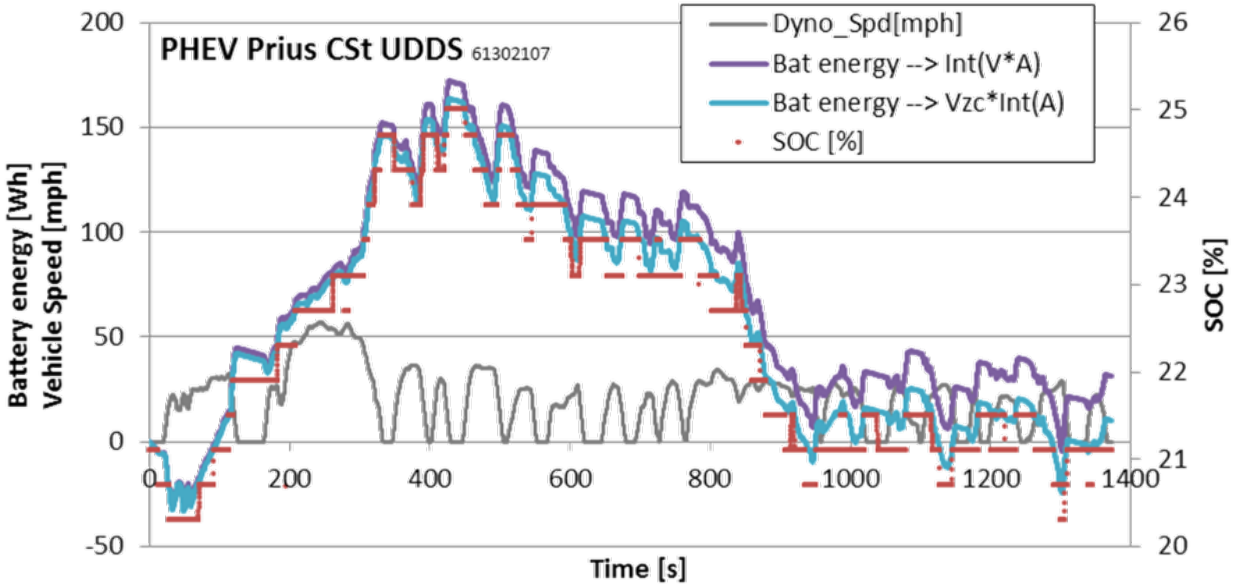
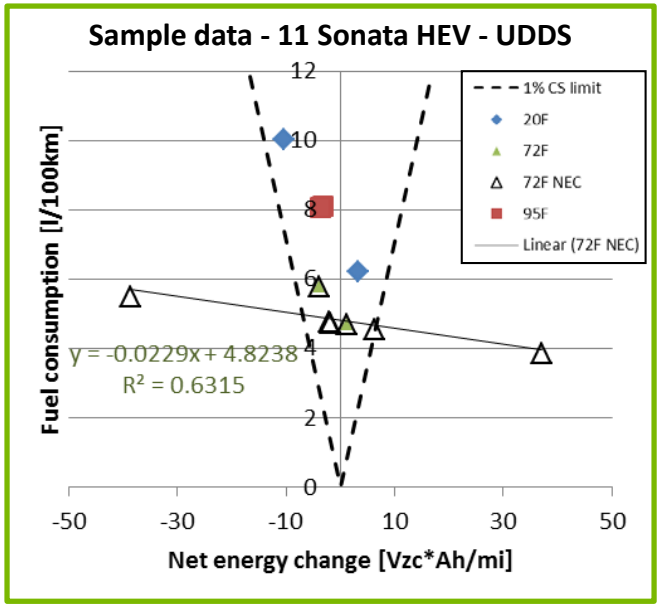
NET ENERGY CHANGE OF THE BATTERY DETERMINES IF A HEV IS CHARGE SUSTAINING OVER THE TEST CYCLE

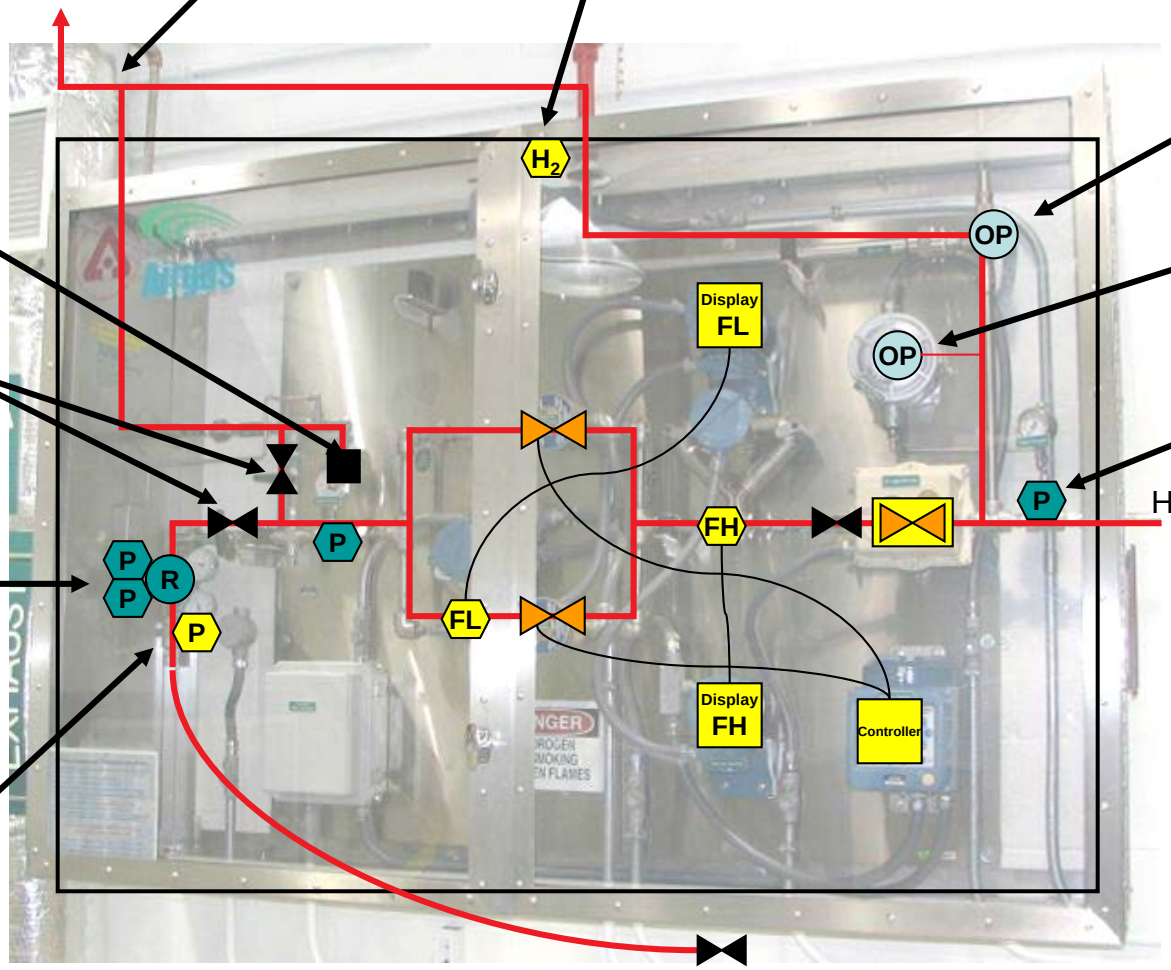
- Net energy change (NEC) = net battery energy delta over the test cycle
- A test is considered charge sustaining when the NEC of battery is less then 1% of fuel energy used over the test cycle
- If an HEV discharges it's battery over a test cycle, the fuel consumption will be increased.



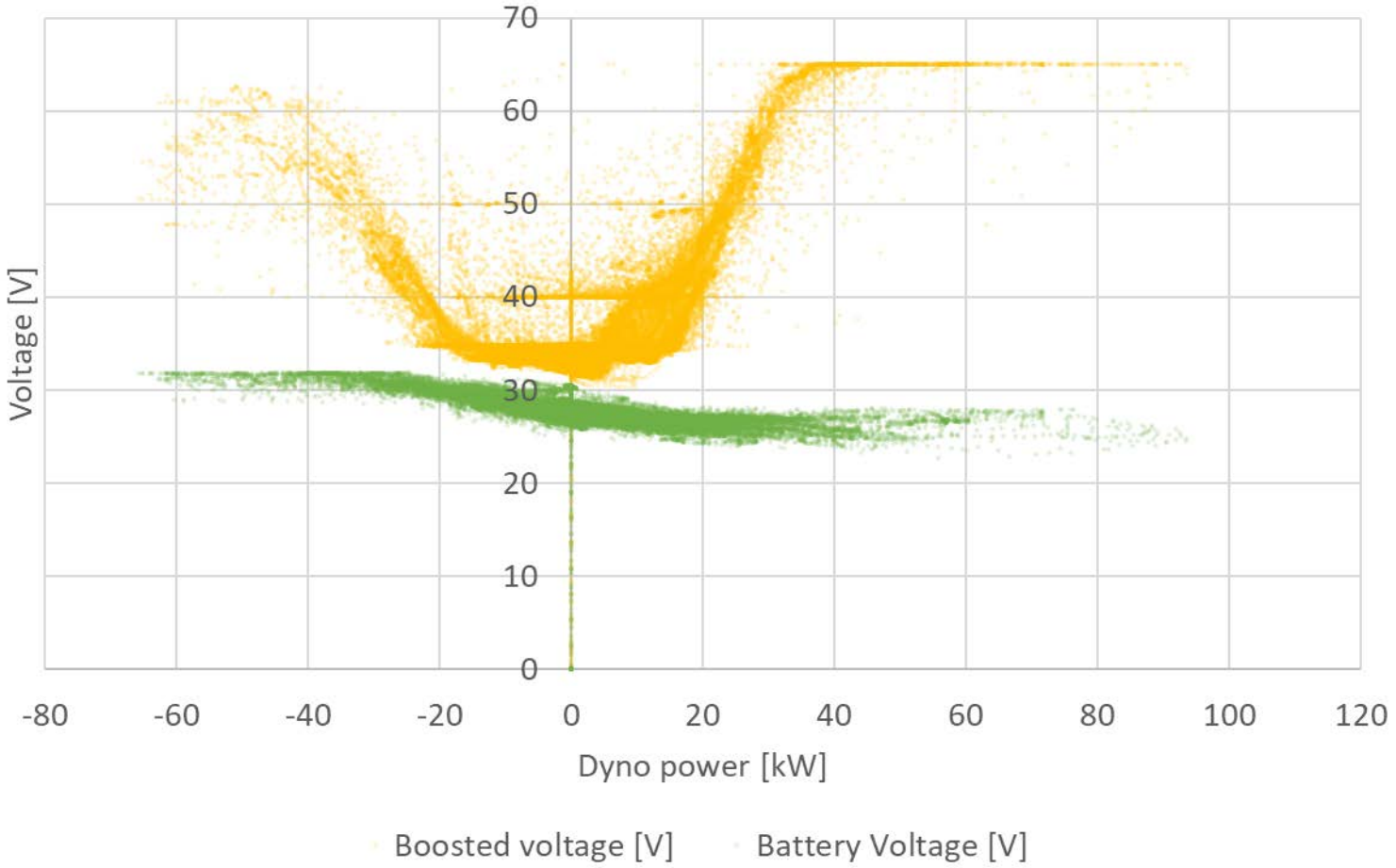




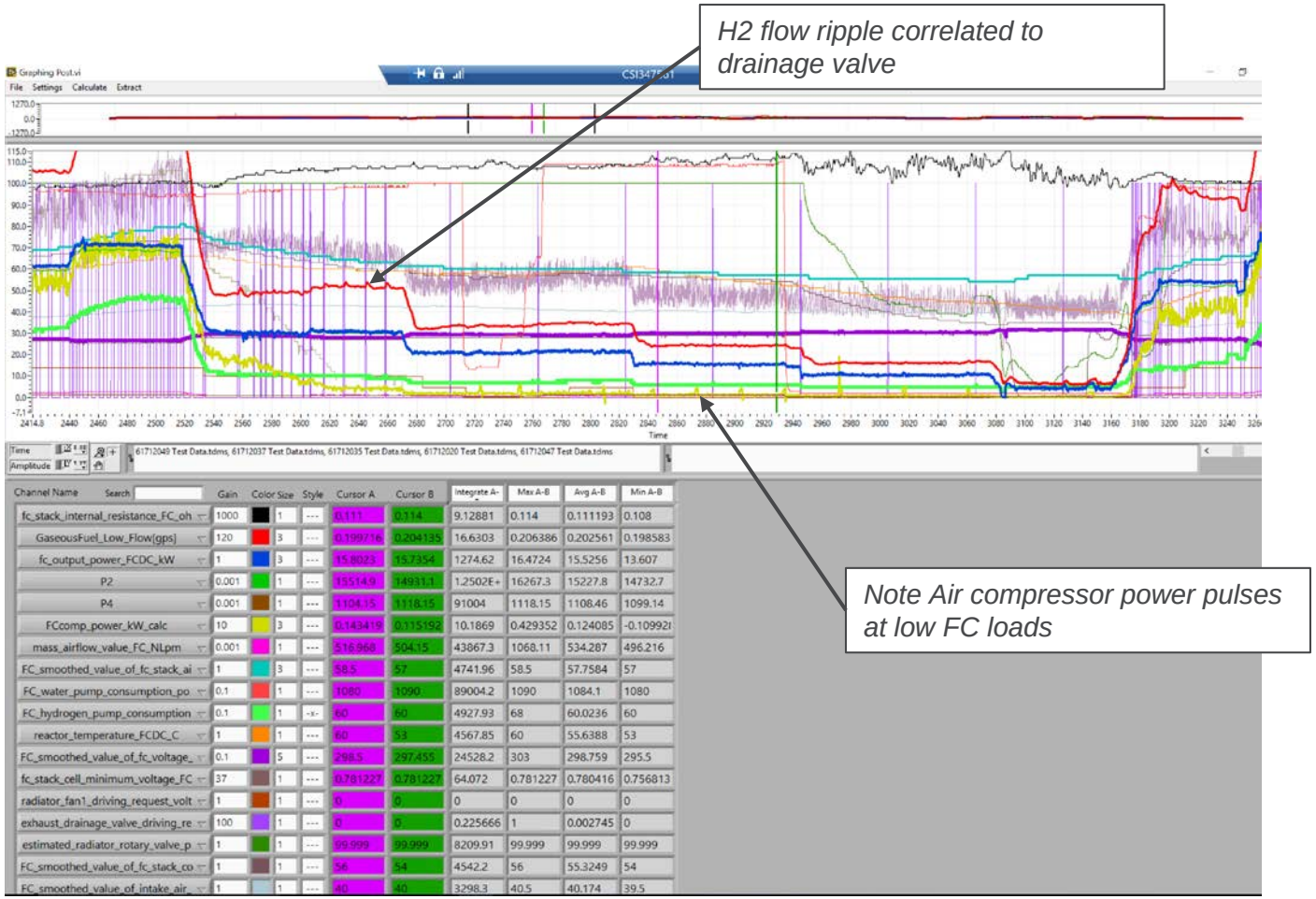
SAFETY AND METERING PANEL



BOOST CONVERTER OPERATION



RIPPLE AND PULSES IN STEADY OPERATION



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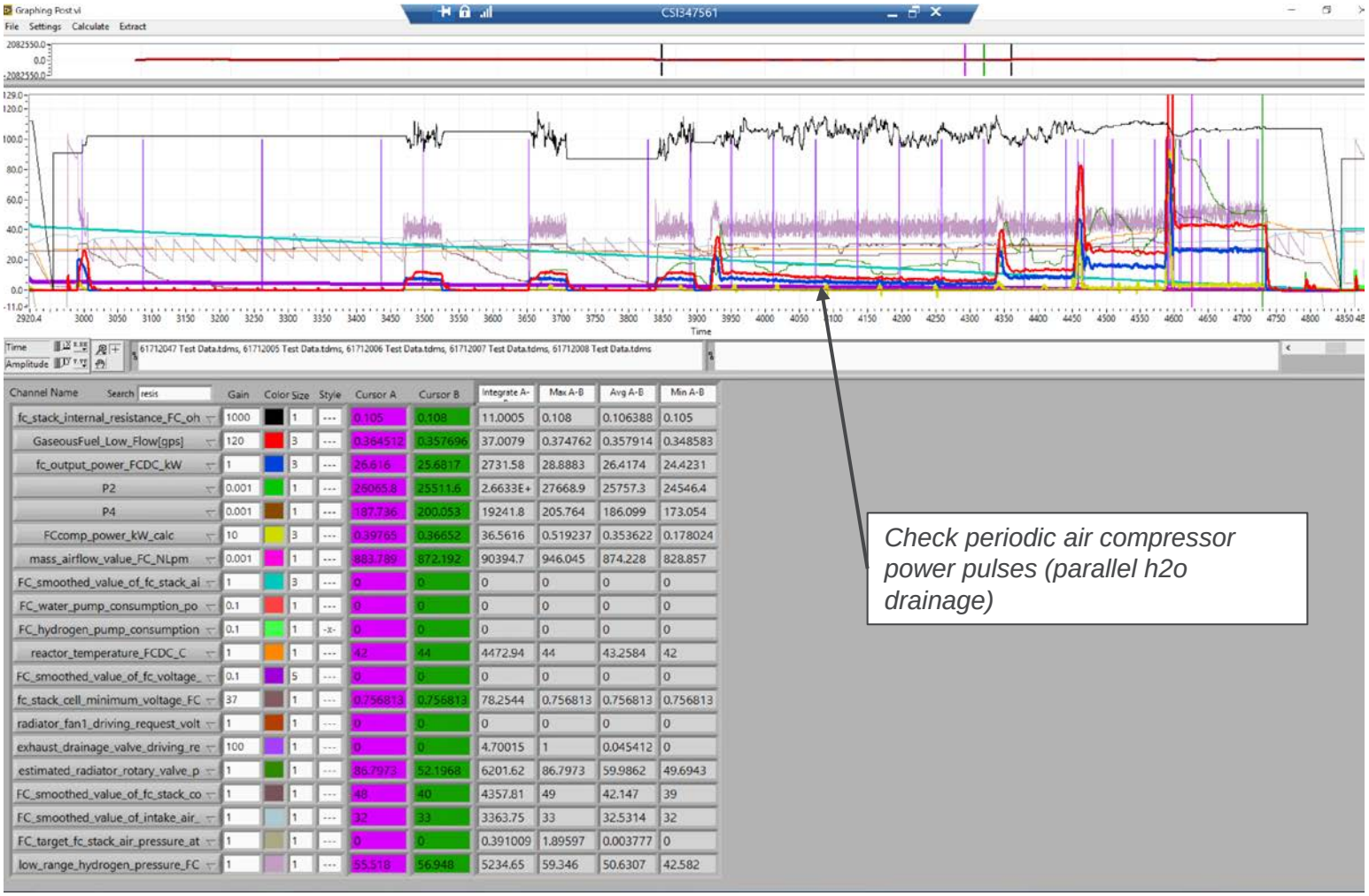
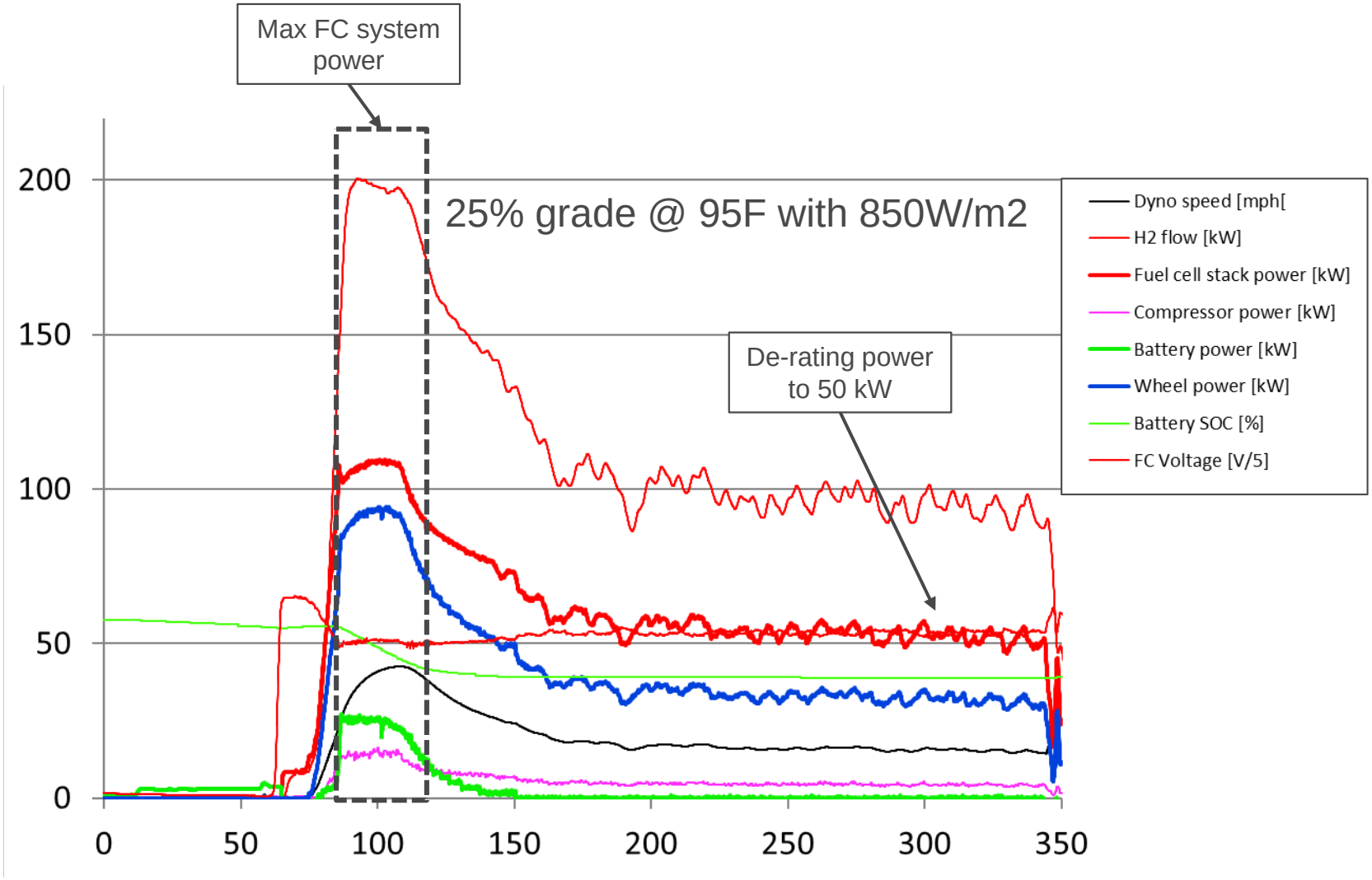
61712006 SSS @ 72F 15, 30, 45, 60, 75 MPH



Check periodic air compressor power pulses (parallel h2o drainage)

25% GRADE @ 95F WITH 850 W/M^2



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