Advanced Powertrain Research Facility
AVTA Nissan Leaf testing and analysis

Note: This presentation summarizes the major finding which have been presented at several different occasions in the past.

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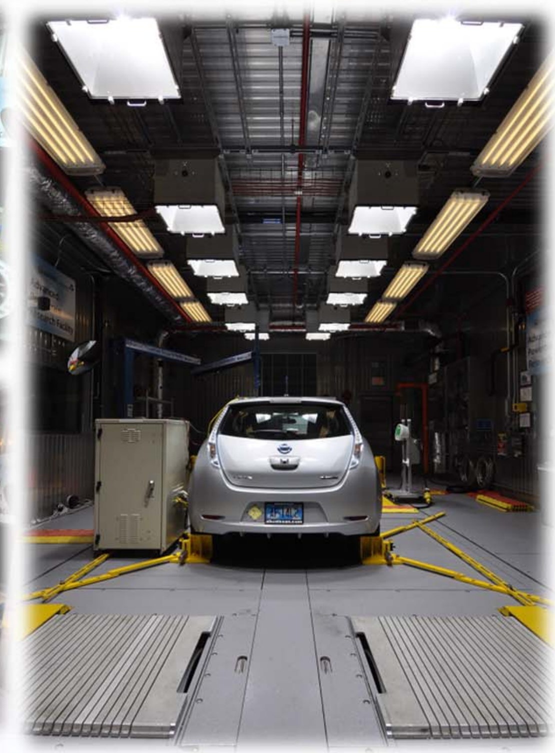
Sponsored by Lee Slezak

Overview

- Vehicle information
- Instrumentation and test plan
- General test results
  - SAE J1634 Short cut test method
  - Energy Consumption and range
  - Two Leafs, two different results
  - Battery performance, depletion and charging
  - Accessory load summary
- Thermal testing
  - 72F results
  - 20F results
  - 95F with solar load results
- Conclusions



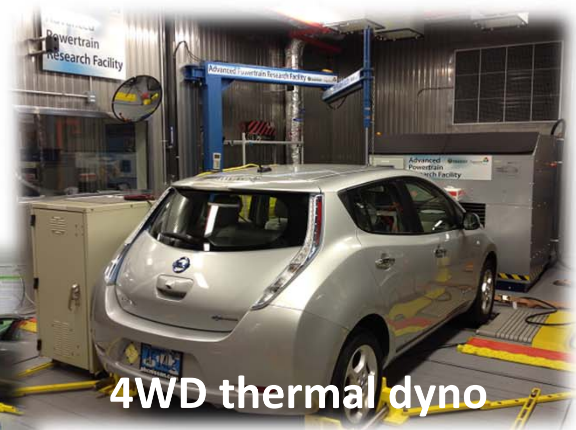


Nissan Leaf - Battery Electric Vehicle Benchmark Goals

- AVTA Test Vehicle
- Level 1 Benchmark
- BEV with Lithium Ion battery
- Energy consumption at different temperatures
- Mass impact study (not part of this presentation)

Baseline dyno testing



AVTA INL Argonne NATIONAL LABORATORY

Nissan Leaf	
Vehicle architecture	Battery Electric Vehicle
Test weight	3750 lb
Power plant	Traction PM motor • 80kW AC synchronous electric motor*
Battery	Lithium Ion battery • 24 kWh lithium-ion battery Charging* • 3.3 kW onboard charger (J1772 connector)* • 120V portable trickle charging cable*
Performance (0- 62 mph)	10 seconds* 90 mph*
Fuel economy	range – 100 miles/charge based upon US EPA LA4 City cycle[1]

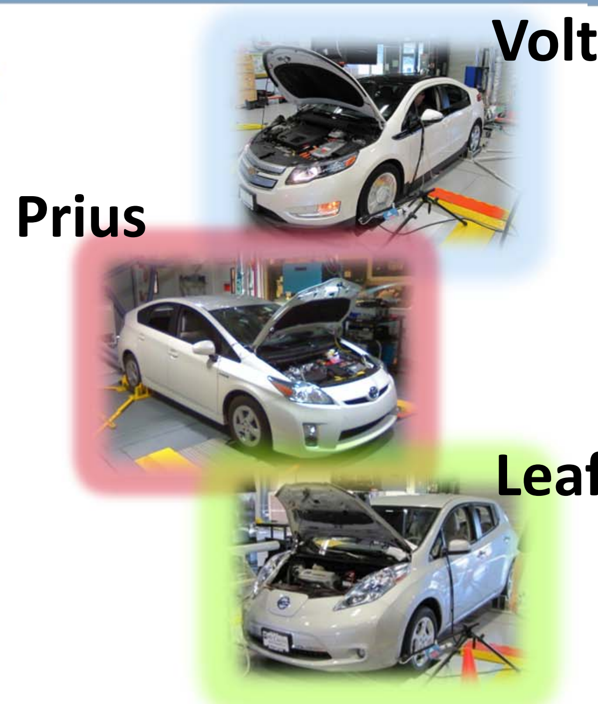
* Manufacturer data www.nissanusa.com

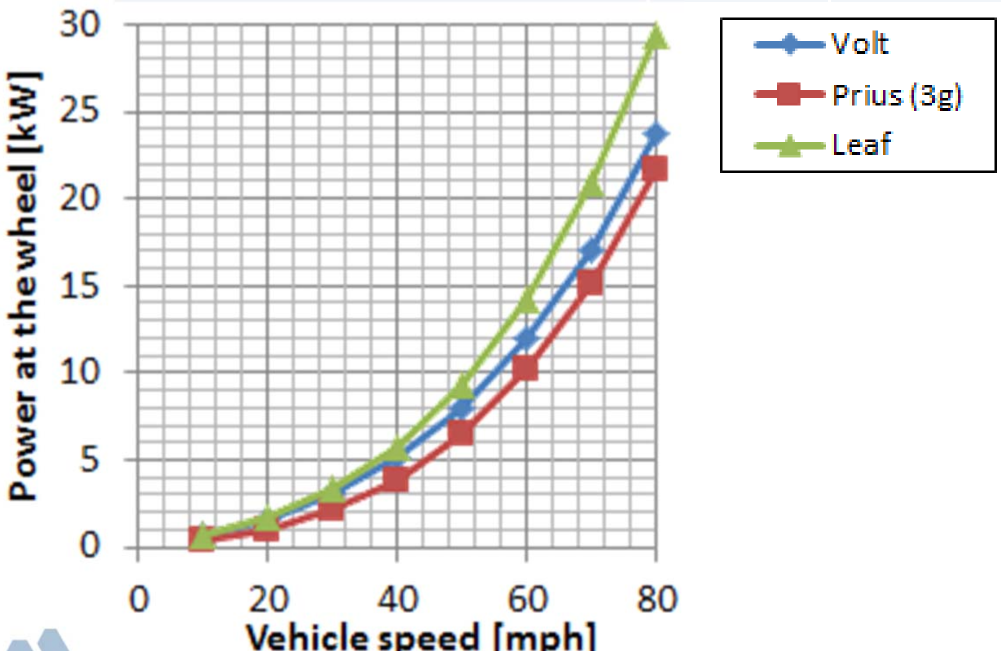
Fleet testing

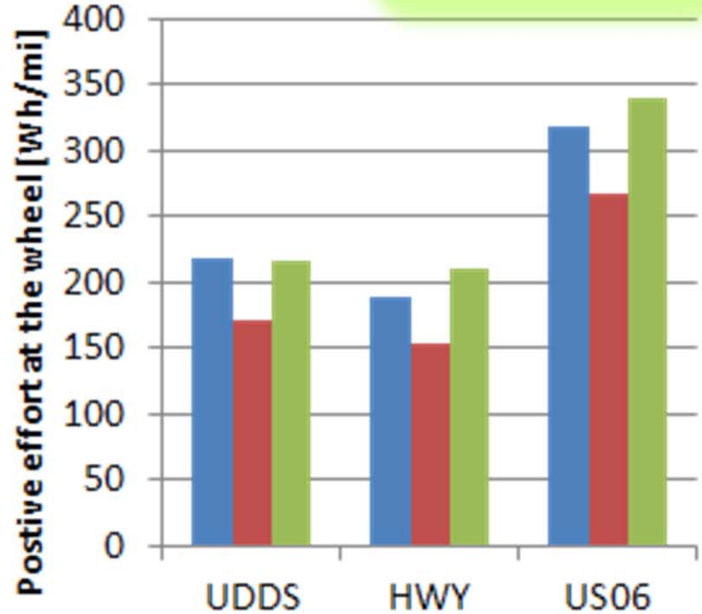
With potential end of life testing

Comparison with Other Competitors

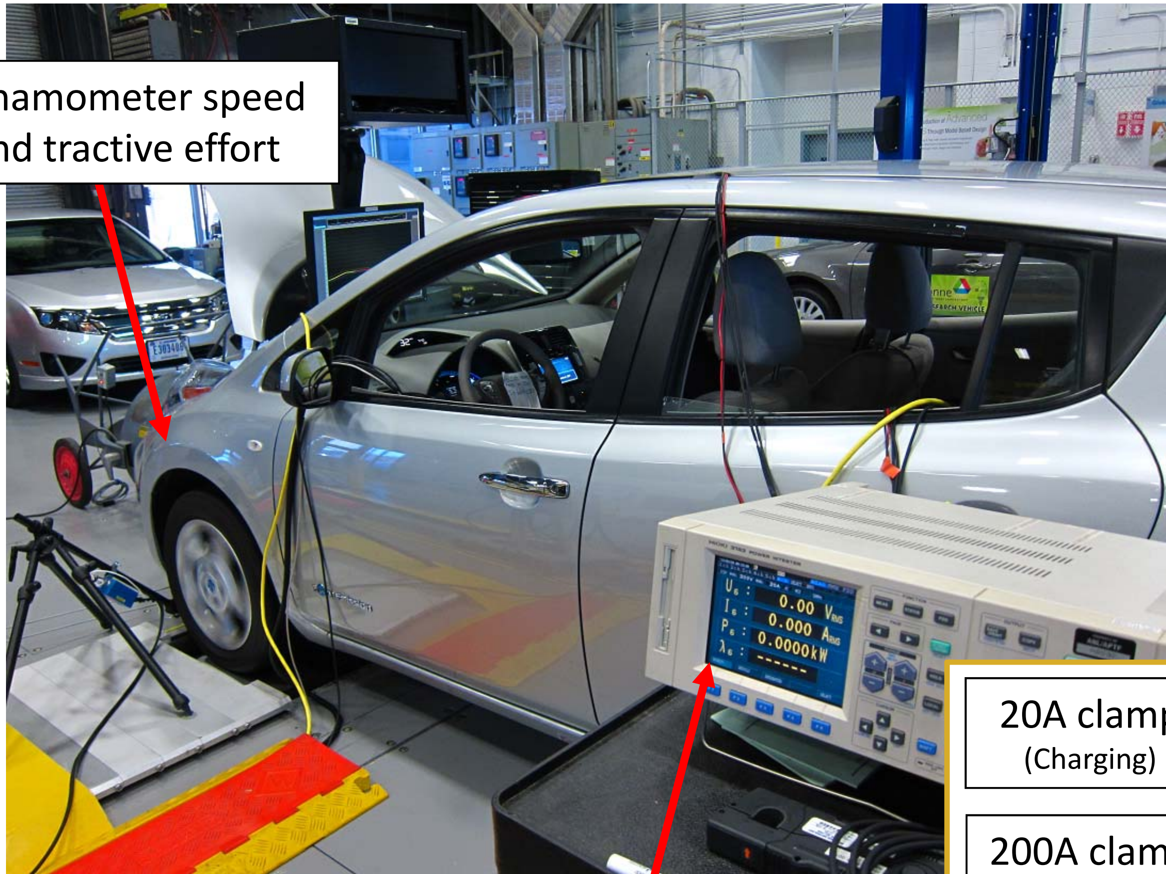
	Volt	Prius (3rd gen)	Leaf
Type	PHEV	HEV	BEV
ETW [lb]	4116	3375	3750
CS FE hot UDDS [mpg]	44.2	64	N/A
CD EC hot UDDS [DC Wh/mi]	226	N/A	199
Performance 0-60 mph [s]	9.2	9.8	10.0
Price [$]	39,145	23,500	35,200





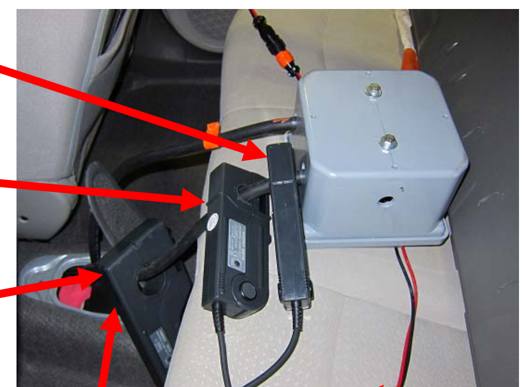


Level 1 Instrumentation - Power and Energy



Select CAN
1. Accel pedal position
2. Motor speed
3. Battery V, I

Note: The instrumentation was non-invasive and limited as the vehicle is going into the AVTA fleet test with INL

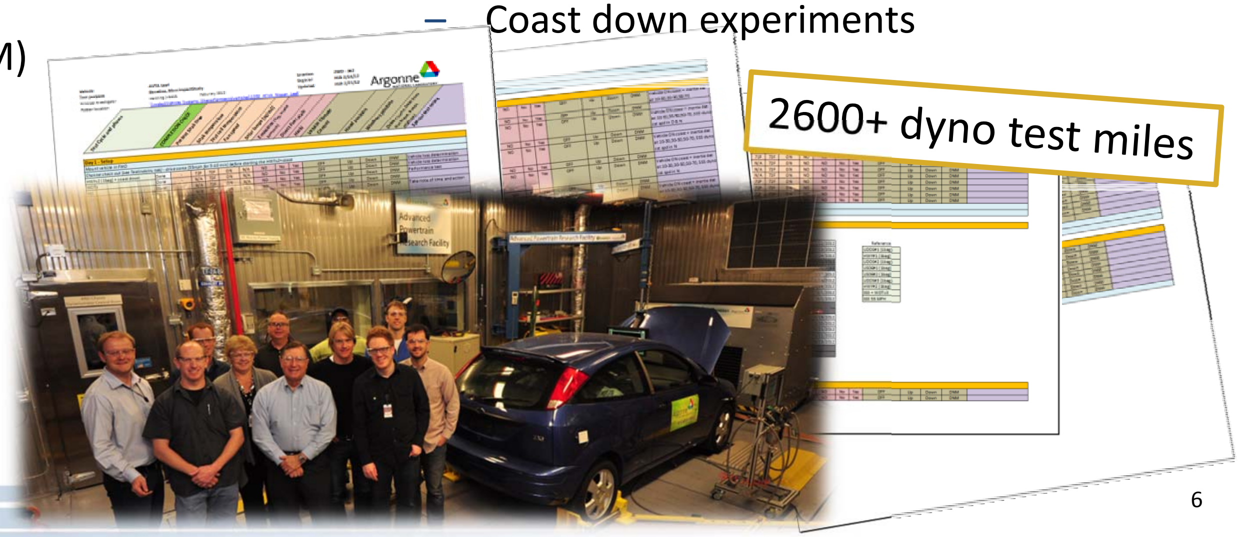


Extensive test plan for the Nissan Leaf

- Standard level 1 tests:
  - UDDS
  - HWY
  - US06
  - SC03

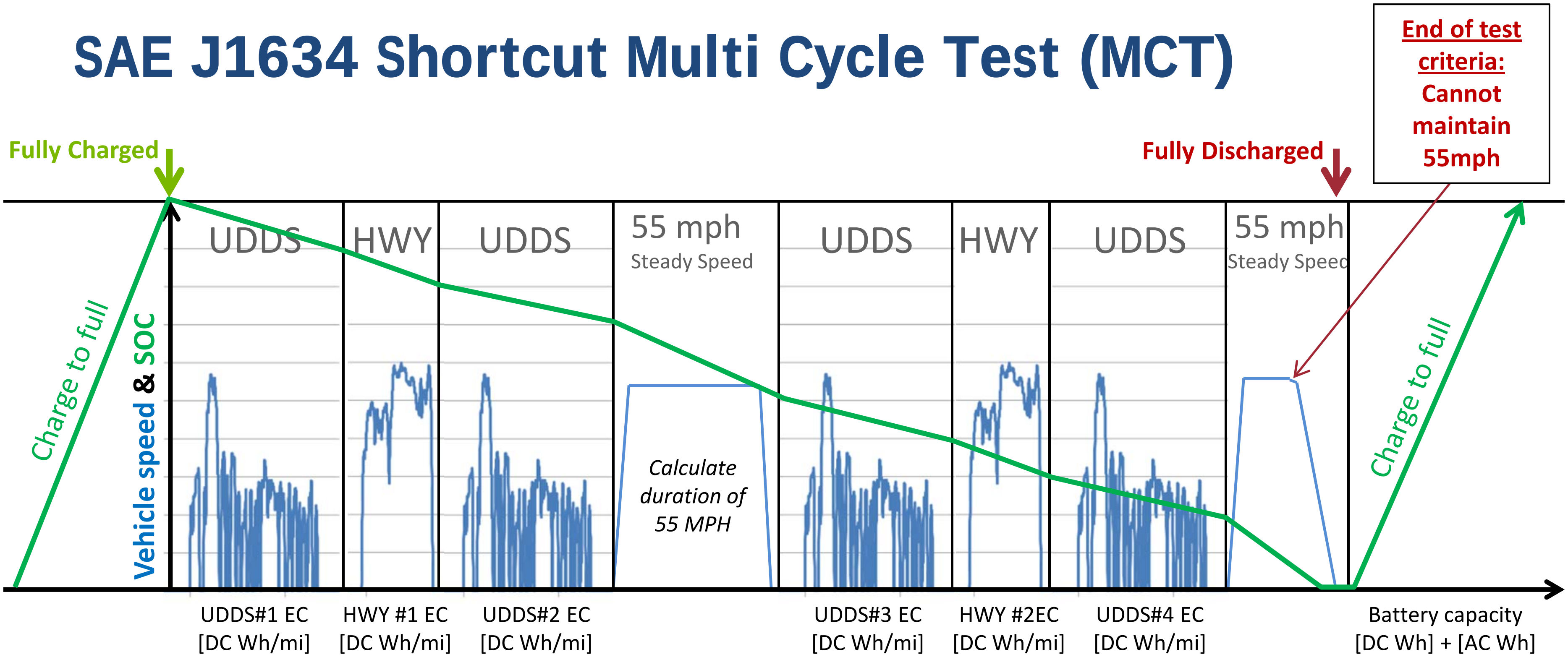
  → Energy consumption and range
- Additionally
  - LA92
  - NEDC
  - JC08
  - World cycle
  - Real World cycle (UofM)
- Mass impact study
  - Separate study not discussed today

- Thermal testing at 20F and 95F with solar load
- Performance and component tests
  - Steady state speed and WOTs at different SOCs
  - Air conditioning pull down tests
  - Heater pull up tests
  - Charging
    - Level 2 at 72F, 20F and 95F
    - Level 2 over weekend at 72F
    - Large number of charge events
  - Coast down experiments



Thanks to the great APRF staff (Special thanks to Mr. Stauber who drove most of the 2600 miles for repeatability)

SAE J1634 Shortcut Multi Cycle Test (MCT)



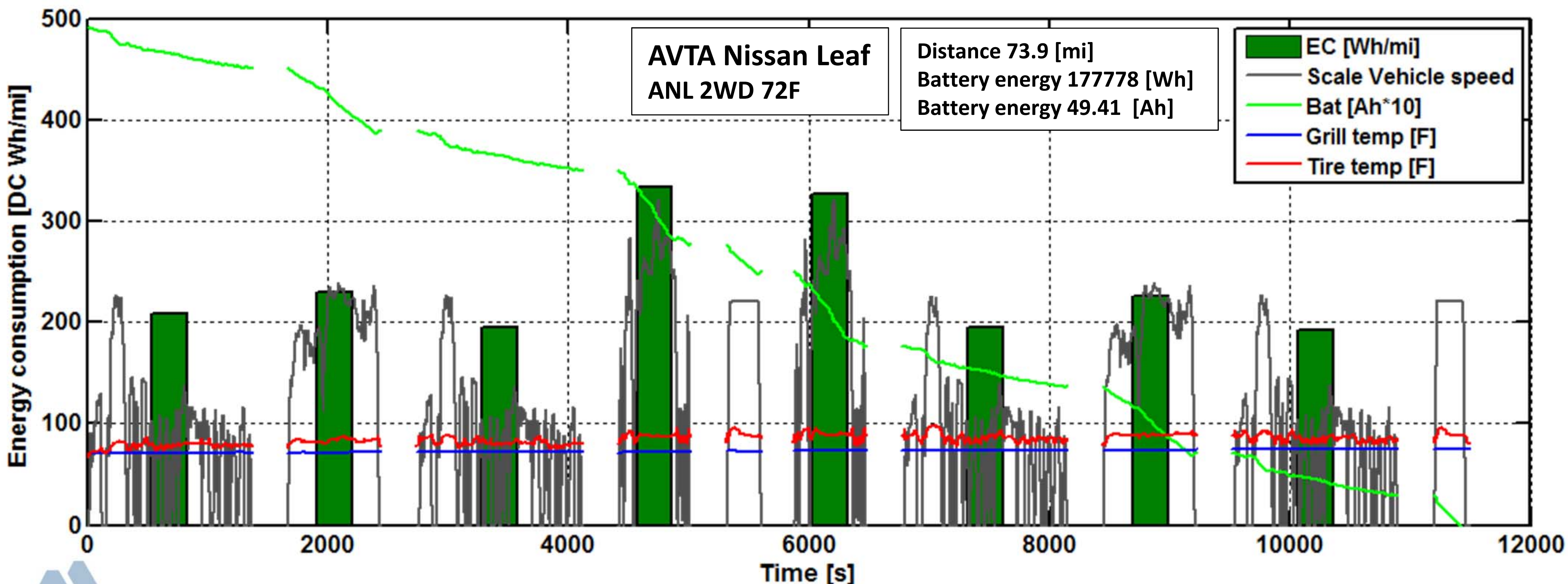
- **Goal:** determine AC energy consumption and range of a BEV on multiple cycles in one test day, instead of several full charge test days.
- Based on past APRF BEV data, the MCT does*:
  - Match **Efficiency**
  - Extrapolate **Range**
  - Includes "First Cycle Effect"
  - Fixes ambiguous end-of-range
  - Spreads cycles to different SOCs

*See M Duoba's work on SAE J1634

AVTA Nissan Leaf Test Results on modified J1634 MCT with US06

Calculated Cycle Results	UDDS	HWY	US06
Energy consumption [DC Wh/mi]	194	228	334
Energy consumption [AC Wh/mi]	233	274	395
Range [mi]	92	78	54

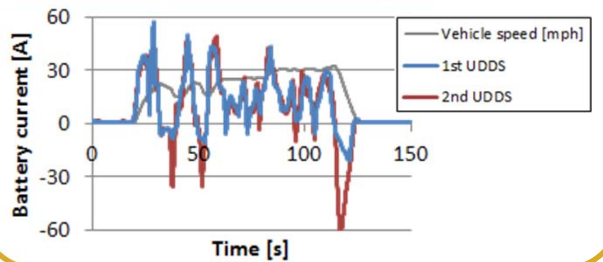
Measured Charging results	UDDS
Grid Charge Energy [AC Wh]	21352
DC Charge Energy [DC Wh]	18234
DC Charge Energy [DC Ah]	49.20



60% to 80% Powertrain Efficiency on Drive Cycles

A full battery limits regen:

Cycle	Dyno neg.	Battery neg.
UDDS#1	-0.772 kWh	-0.473 kWh
UDDS#2	-0.777 kWh	-0.534 kWh



General conclusion:

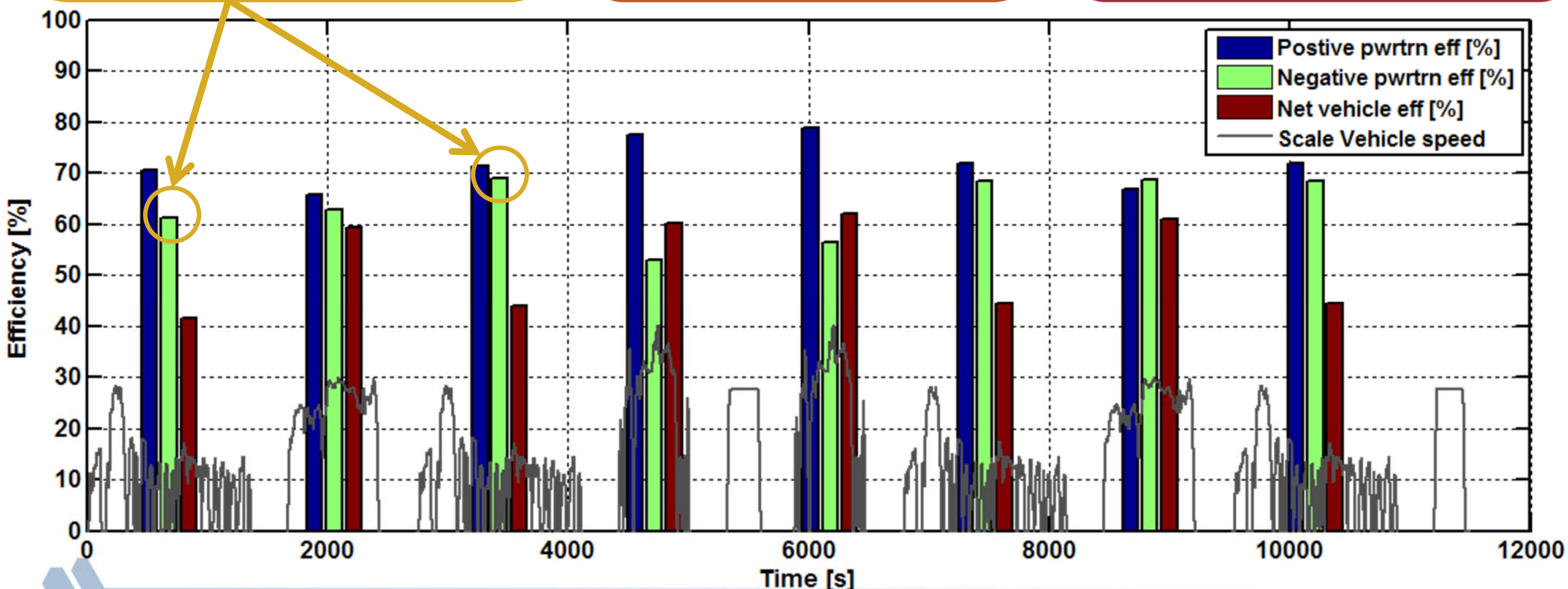
- Higher loads yield higher powertrain efficiencies
- The accessory loads (DCDC) lower the vehicle efficiency on low load cycles

Calculation definition

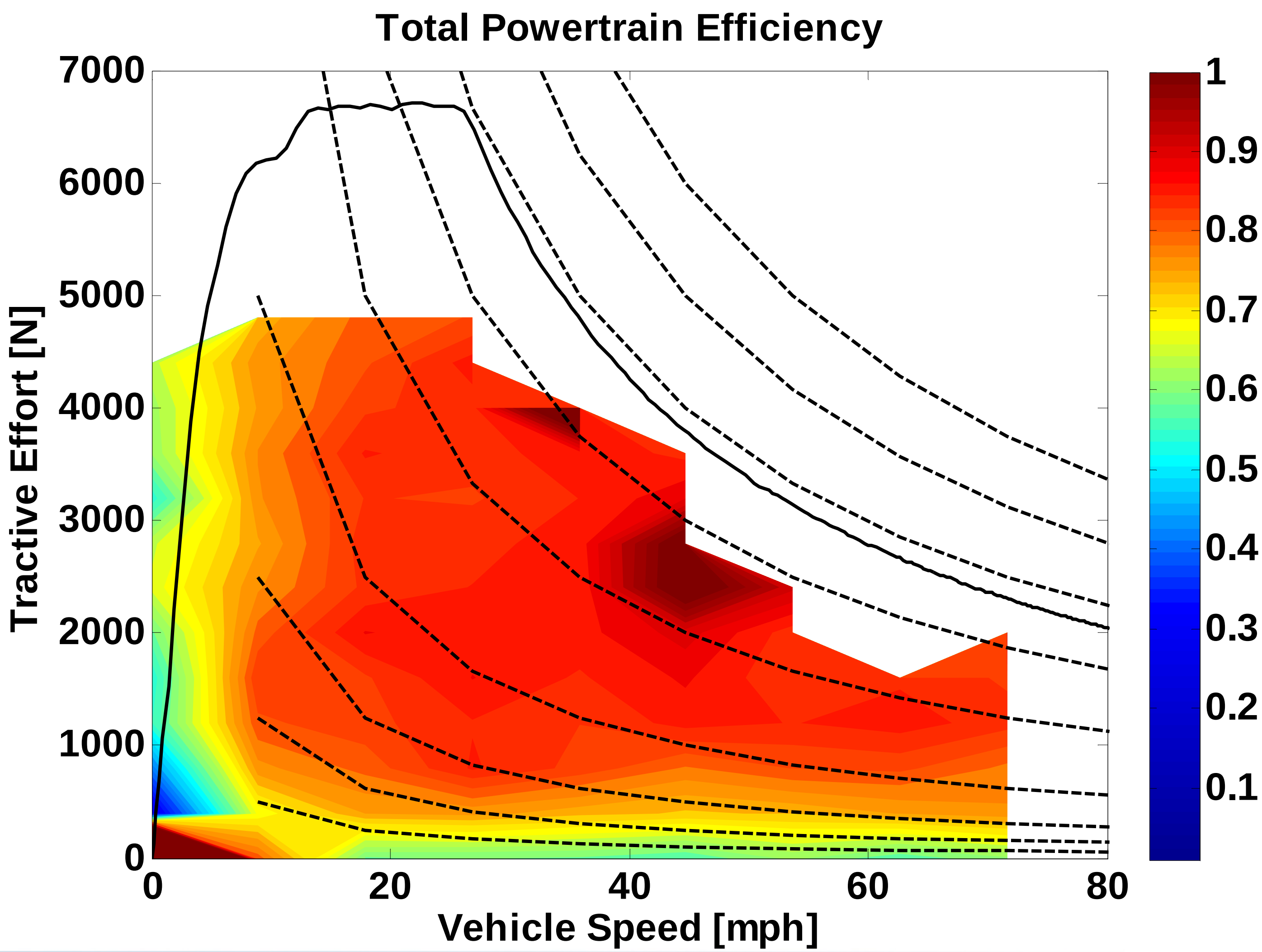
$$PowertrainEfficiency_{positive} = \frac{\int (BatteryPower_{positive} - DCDCPower)dt}{\int (DynoTractiveEffort_{positive})dt}$$

$$PowertrainEfficiency_{negative} = \frac{\int (DynoTractiveEffort_{negative})dt}{\int (BatteryPower_{negative} + DCDCPower)dt}$$

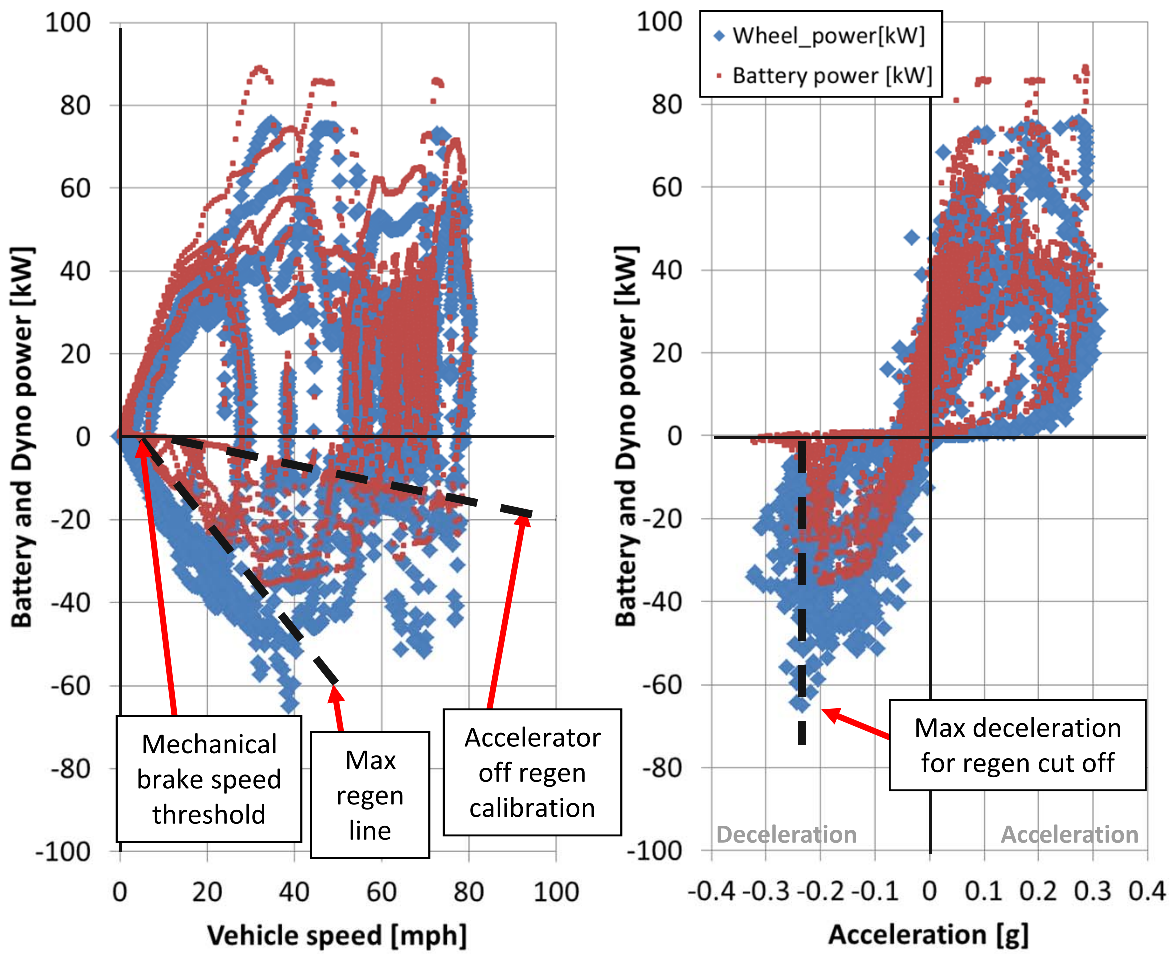
$$VehicleEfficiency_{net} = \frac{\int (BatteryPower)dt}{\int (DynoTractiveEffort)dt}$$



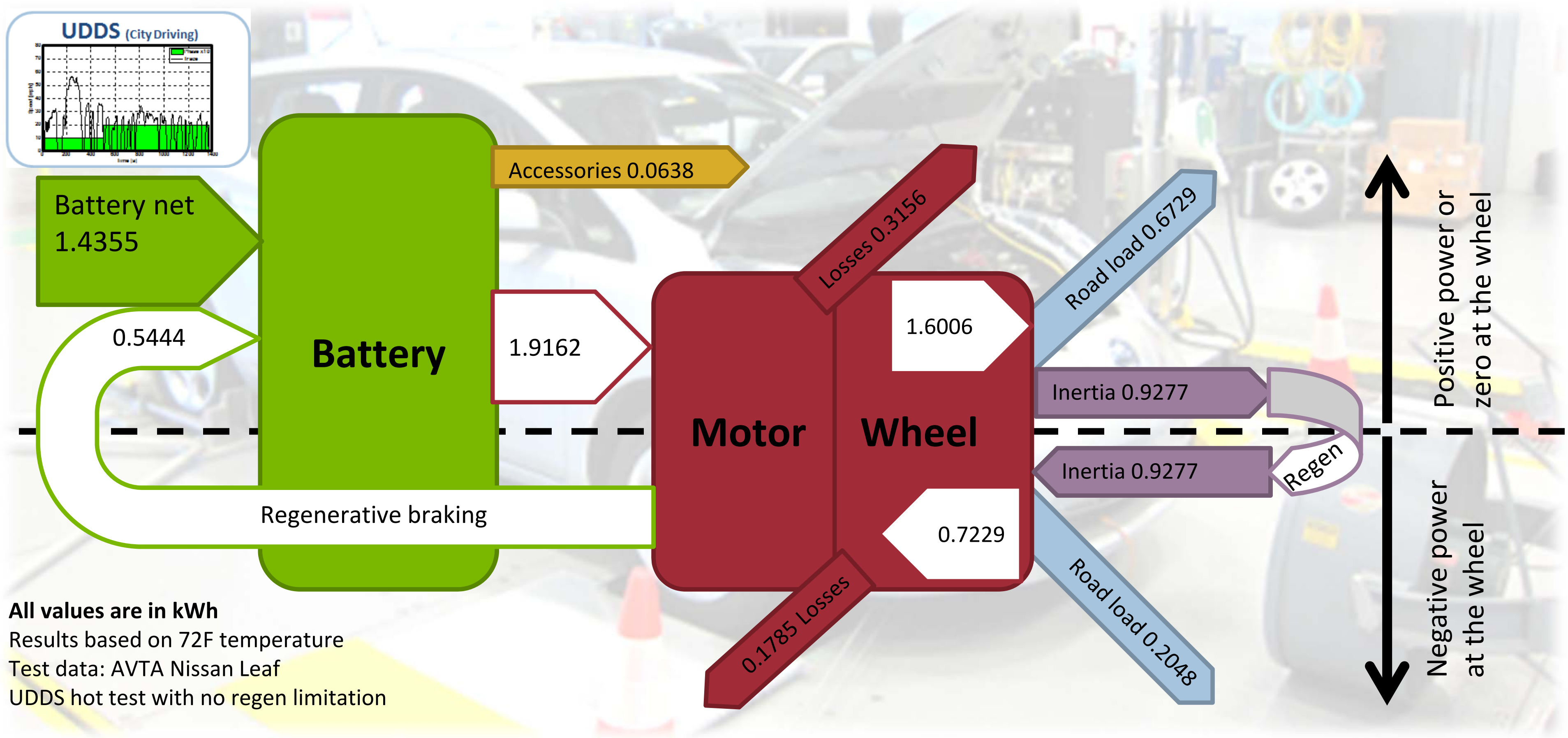
Powertrain efficiency using composite of UDDS, HWFET, US06 tests = Tractive power/Batt power



US06 Shows the Regenerative Braking Envelop



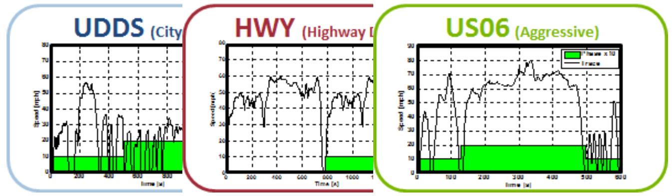
Energy Distribution for the Nissan Leaf



All values are in kWh
Results based on 72F temperature
Test data: AVTA Nissan Leaf
UDDS hot test with no regen limitation

Energy flow in a Battery Electric Vehicle

Battery energy
(Net DC battery energy used to completed the drive cycle)
100%



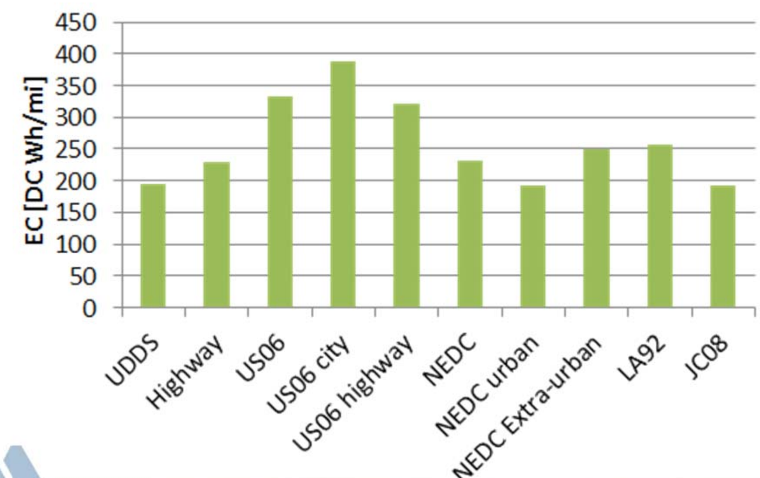
Note: Results based on 72F temperature
Hot tests with no regen limitation

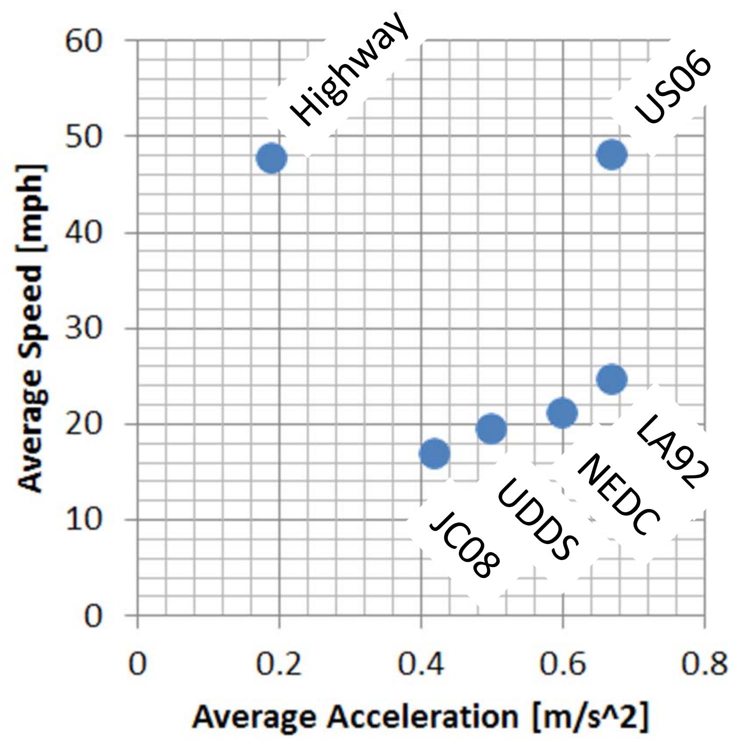
	City	High-way	US06
	Energy portion [%] with respect to Net DC battery energy		
Accessory loads (Dyno test accessory loads – low compared to on road)	4.4%	1.8%	1.2%
Inertia energy to Wheel (Positive power integrated)	64.3%	15.0%	40.0%
Inertia energy to Battery (Regenerative breaking recovered)	-37.9%	-6.7%	-16.1%
Road load energy to Wheel (Aerodynamic drag and rolling resistance)	46.9%	72.8%	60.5%
Powertrain losses	22.0%	17.1%	14.4%

AVTA Leaf Energy Consumption on different test cycles

Drive Cycle	Energy Consumption [DC Wh/mi]
UDDS	194.4
Highway	228.0
US06	333.0
US06 city	387.7
US06 highway	322.0
NEDC	230.4
NEDC urban	192.1
NEDC Extra-urban	249.2
LA92	257.1
JC08	191.3

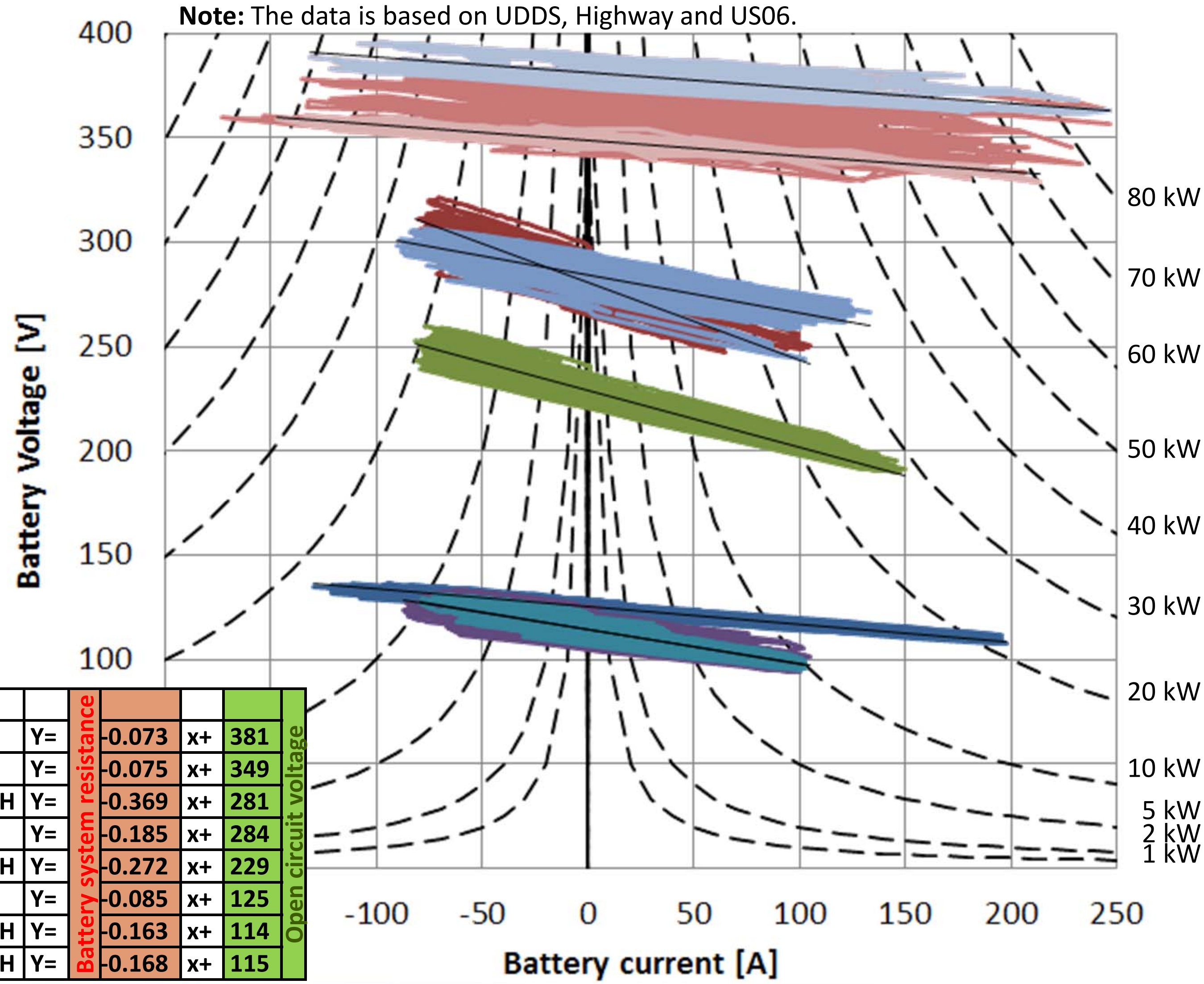
Test Note: these results are for single hot start tests on 2WD in 72F





In-Situ Battery Performance Data before Leaf

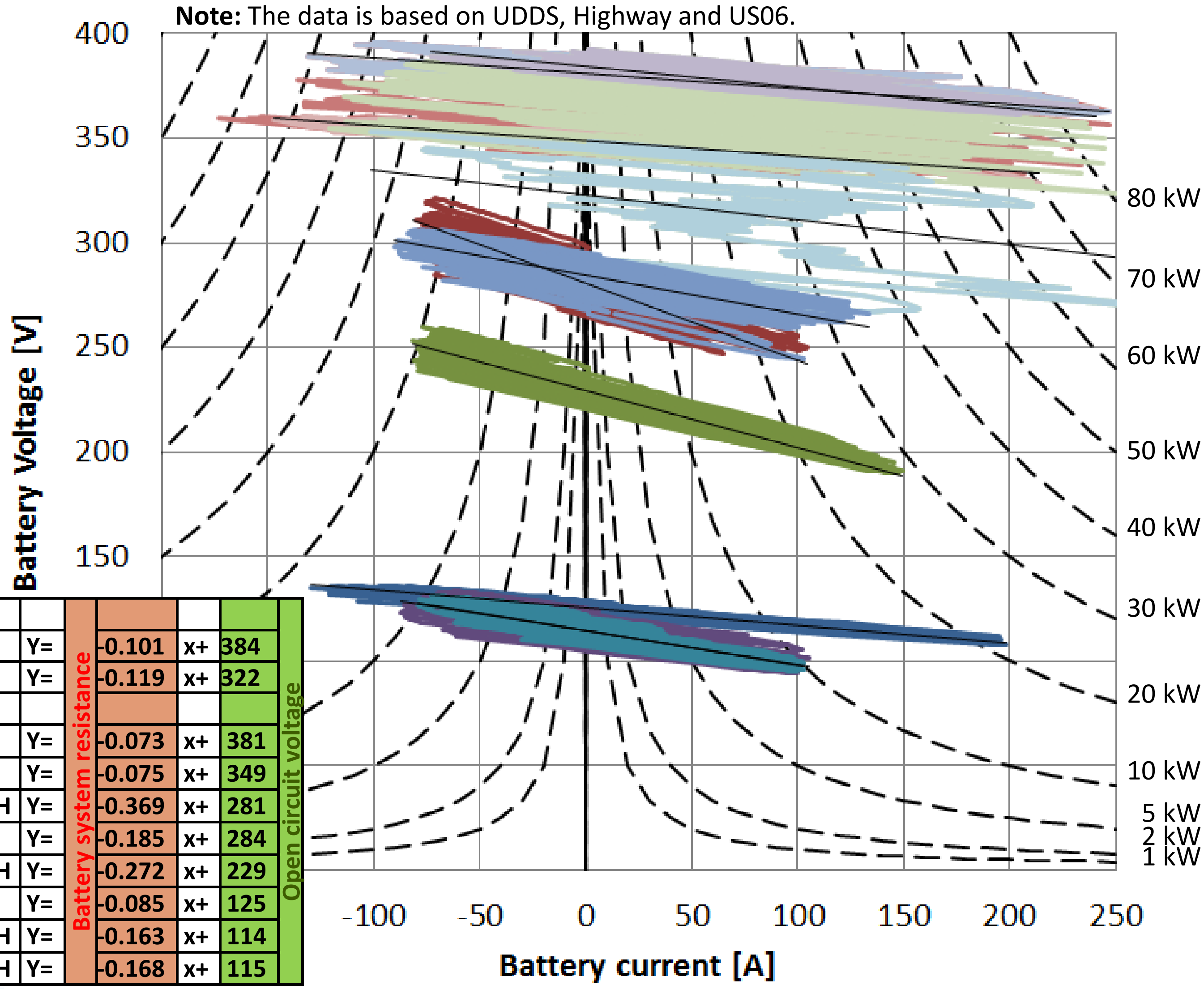
- Quick review of past battery data



				Battery system resistance		Open circuit voltage
Volt	Li					
Volt SOC high	Li	Y=	-0.073	x+	381	
Volt SOC low	Li	Y=	-0.075	x+	349	
Fusion HEV	NiMH	Y=	-0.369	x+	281	
Sonata HEV	Li	Y=	-0.185	x+	284	
Prius (3rd gen)	NiMH	Y=	-0.272	x+	229	
S400h	Li	Y=	-0.085	x+	125	
Insight	NiMH	Y=	-0.163	x+	114	
CRZ	NiMH	Y=	-0.168	x+	115	

In-Situ Battery Performance Data with Leaf

- Lithium Ion has low system resistance
- The Leaf as a BEV discharges the battery which results in a large voltage swing
- The end of battery depletion shows in a sudden Voltage drop



				Battery system resistance		Open circuit voltage
Leaf	Li					
Leaf SOC high	Li	Y=	-0.101	x+	384	
Leaf SOC low	Li	Y=	-0.119	x+	322	
Volt	Li					
Volt SOC high	Li	Y=	-0.073	x+	381	
Volt SOC low	Li	Y=	-0.075	x+	349	
Fusion HEV	NiMH	Y=	-0.369	x+	281	
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Insight	NiMH	Y=	-0.163	x+	114	
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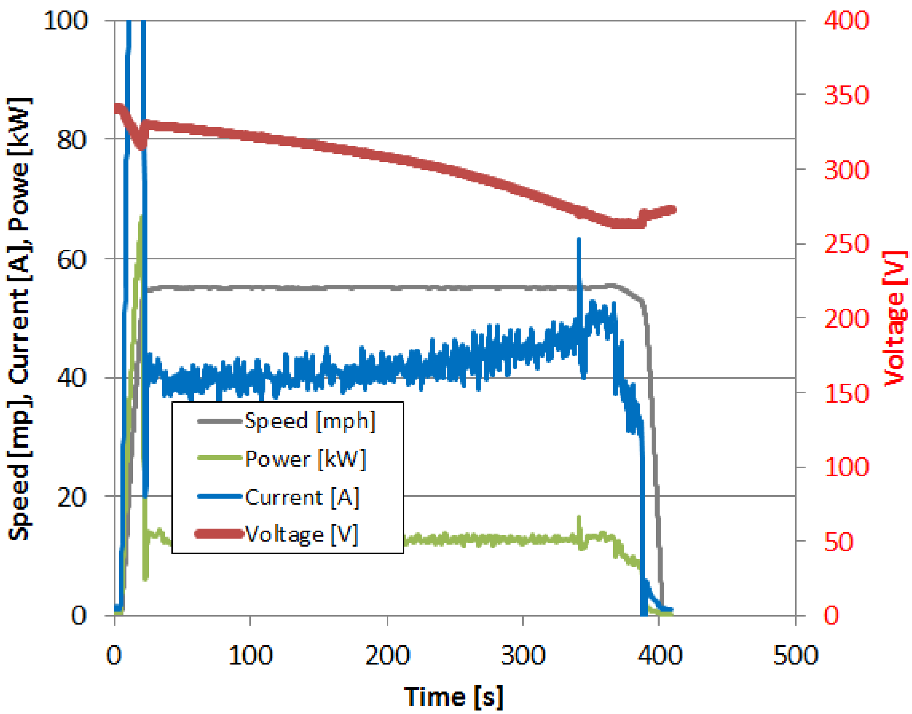
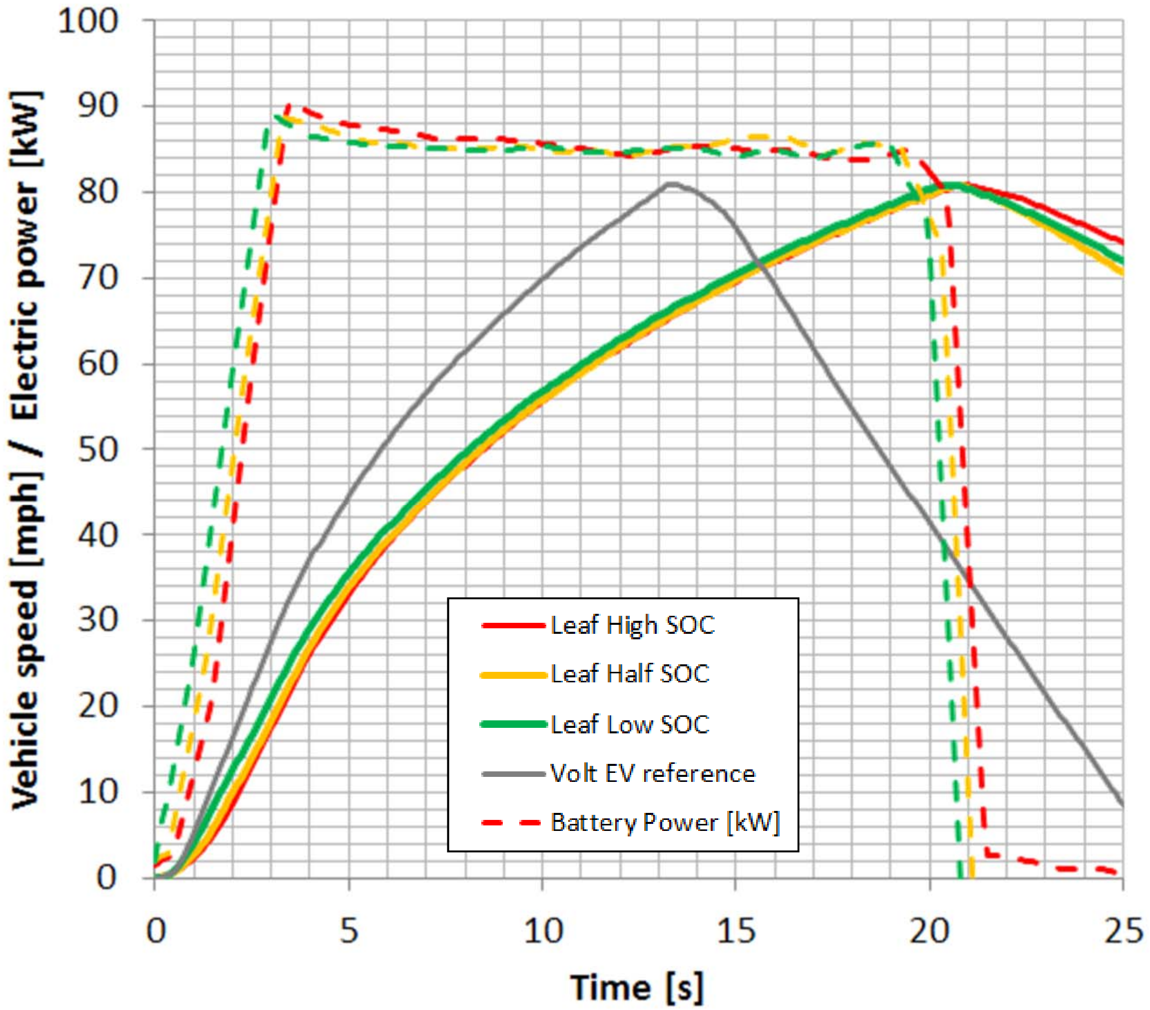
Drastic Voltage Drop at Battery Depletion

- When the vehicle reaches the end of the battery's capacity, the battery system voltage drops dramatically
- Two different Leafs, two different voltage cut-offs which could contribute to the battery capacity difference



No Performance Degradation at Different Battery States

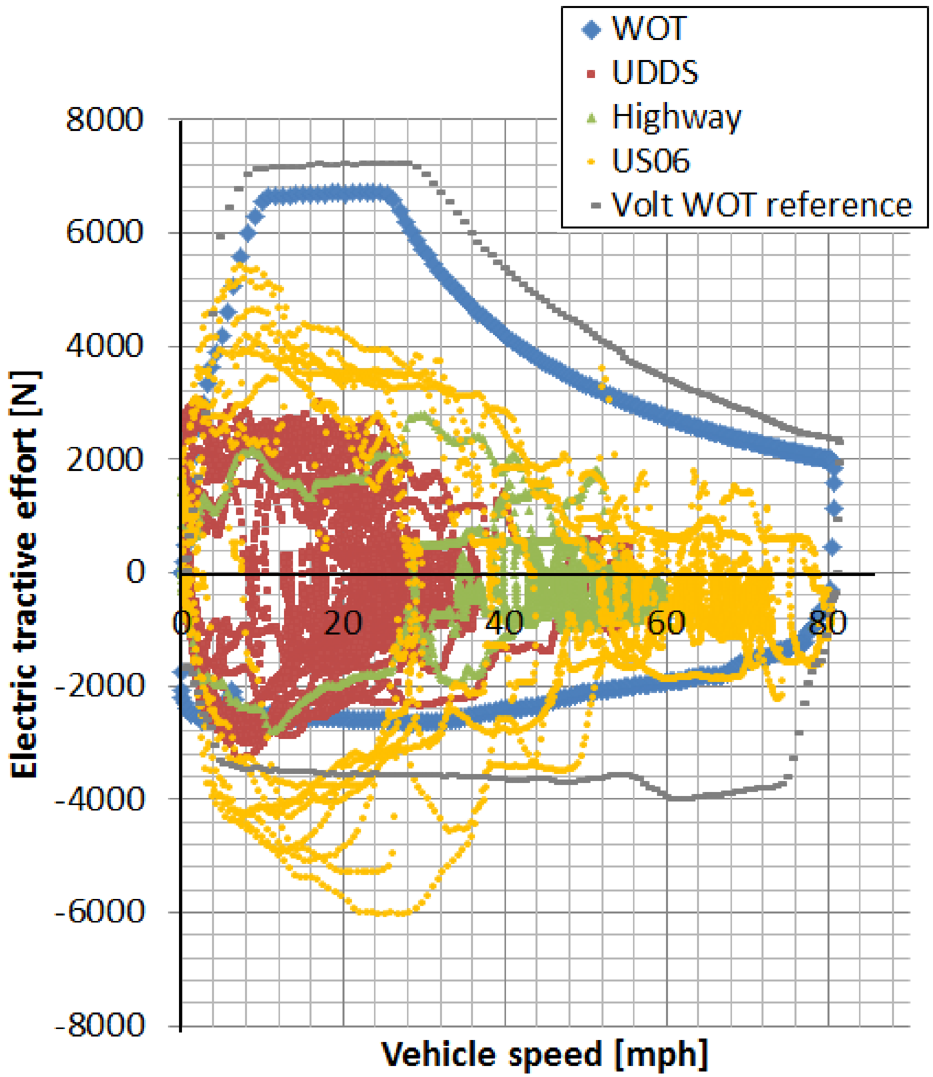


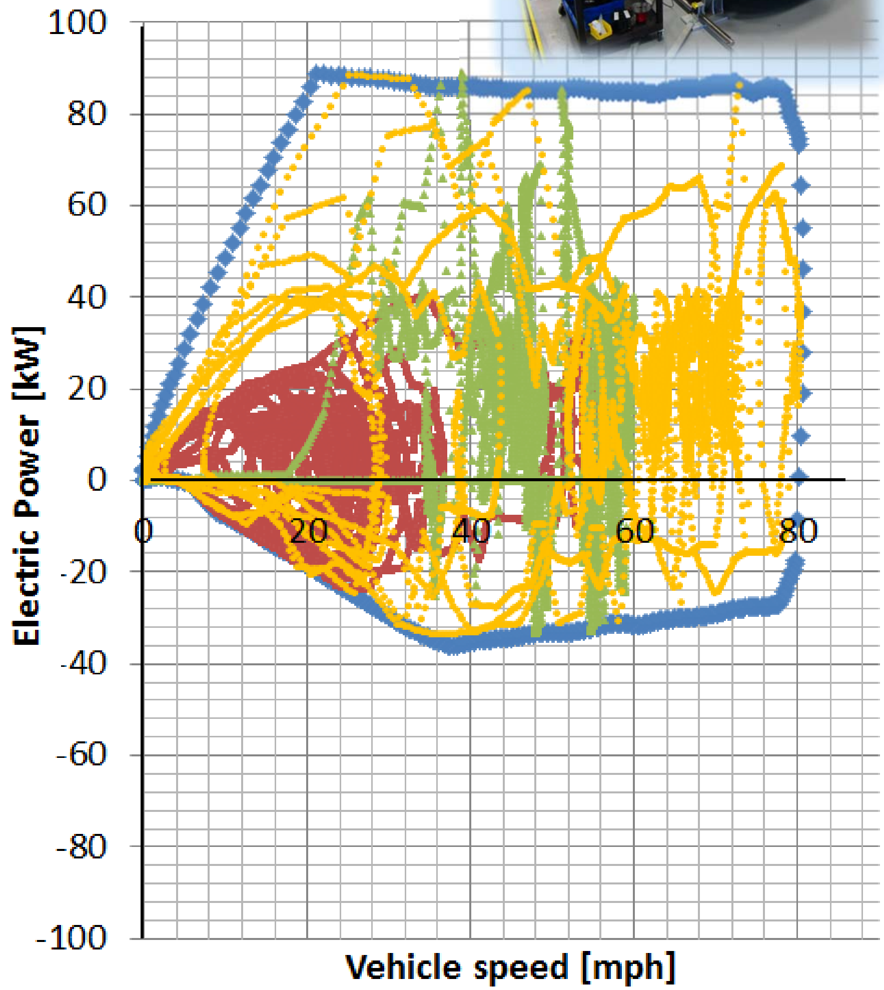
Note: Initial tip in was modulated because of tire slip on steel dyno roller

AVTA Leaf

Tractive Performance Envelop

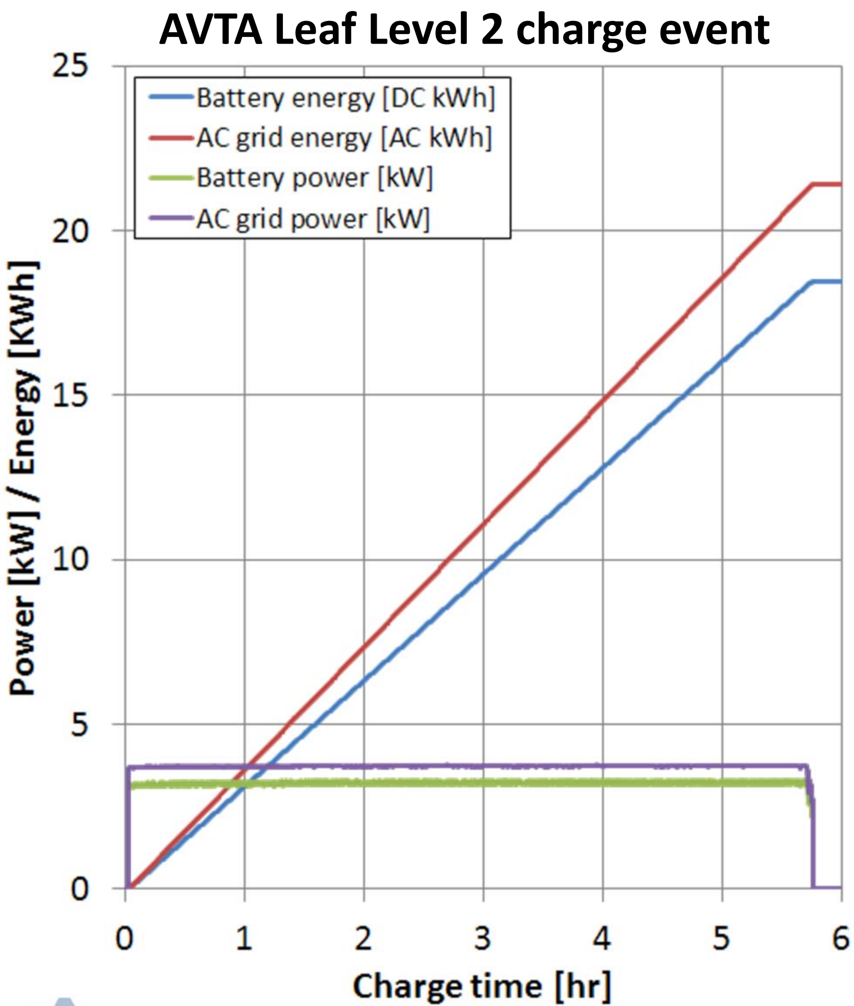
AVTA Leaf

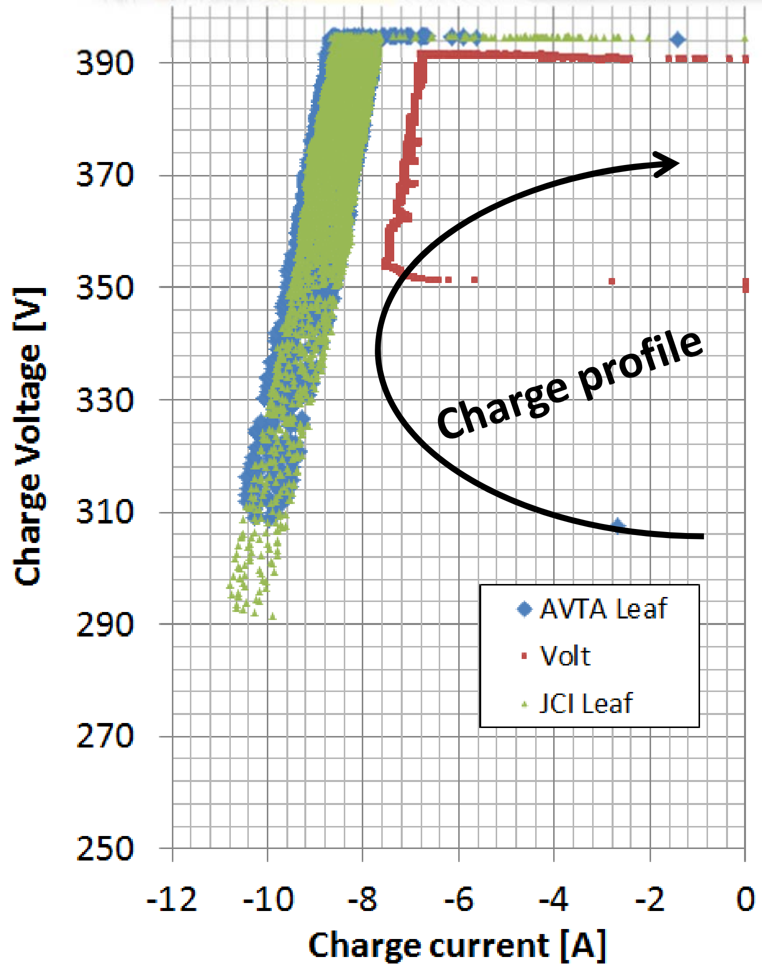




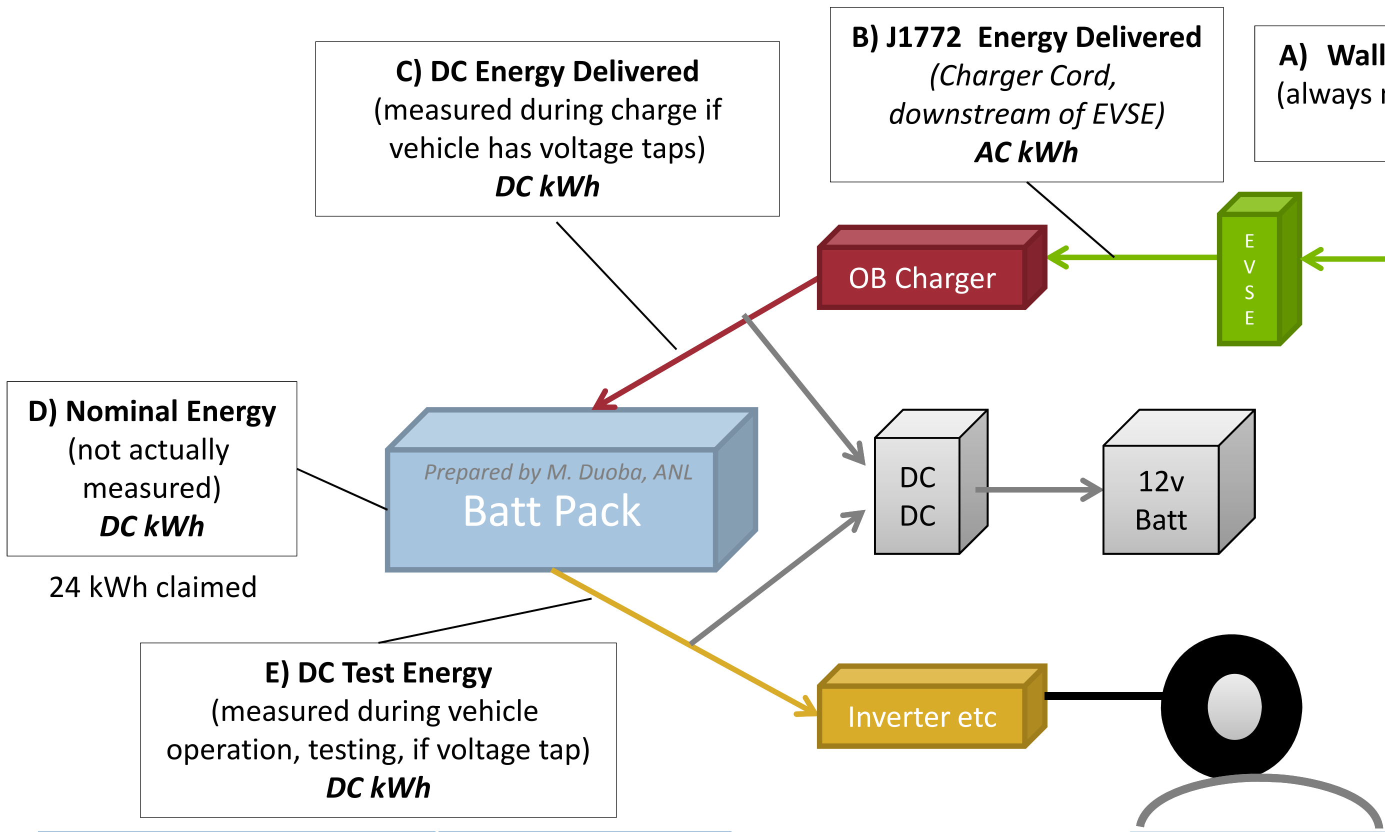
Battery Charge Profile at 72F

Charged through an ‘AV Aeroviroment EVSE’
and the energy limiter box set to 12hr.





AVTA Leaf Charge Energy and Efficiency Analysis



AVTA Leaf

Measurement point	Average value
A) Wall Plug energy	21.722 AC kWh
C) DC energy to pack	18.529 DC kWh
E) DC Test energy *	17.957 DC kWh

Analysis Note:
Values are based on 13 **level 2 battery charge events** from completely depleted to fully charged

Draft terms	Math	Value
Charger efficiency	C/B	N/A
Charger & EVSE efficiency	C/A	85.3%
Overall Trip Efficiency	E/A	82.7%
Battery efficiency	E/C	96.9%
Pack Utilization	E/D	74.8%

AVTA Leaf Accessory Load Characterization

Action	Net Power [W]	
Vehicle ON	280	
The power numbers below this row are in addition to the base 280W load		
Brakes	10	
Further detail on climate control power consumption is provided later	Peak	Settled
AC ON max cool auto	2000	1800
	Pulse min	Pulse max
Heater Cabin warm up	4000	6000
Maintaining cabin temperature	2000	4000
	Pulse min	Pulse max
Front window defroster* (pulsing)	1420	3420
Rear window defroster	200	Tested at 20F
	Peak	Settled
Panic brake	457	70
Running lights	10	
Full lights	60	
Full bright	190	

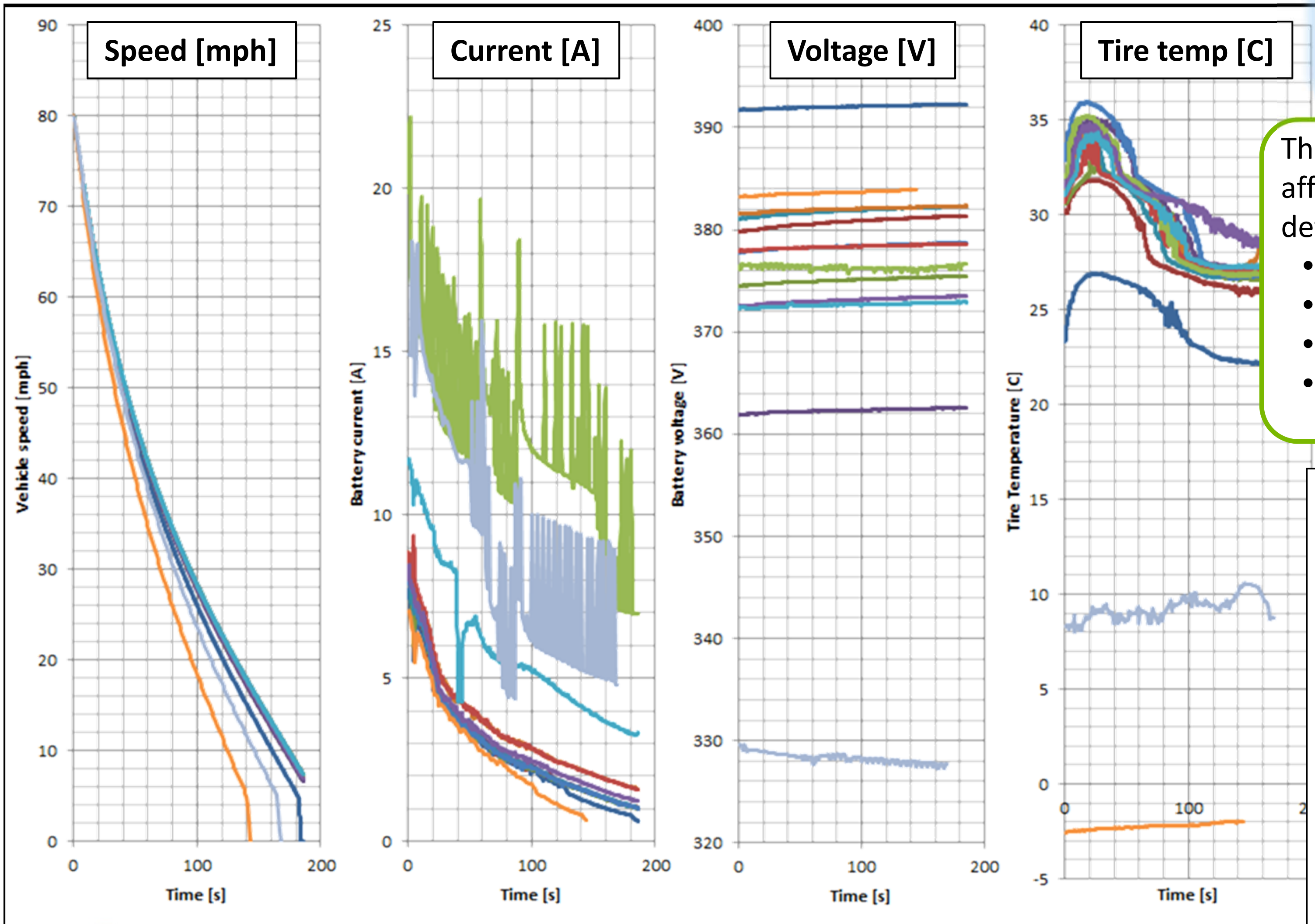
Note: Further heater and Air conditioning are presented in later slides

Powertrain efficiencies of BEVs are higher compared to the engine powered counterparts, therefore the accessory loads are significant for some drive styles.

Cycle	Avg net cycle power [W]
UDDS	3800
Highway	10800
US06	16000

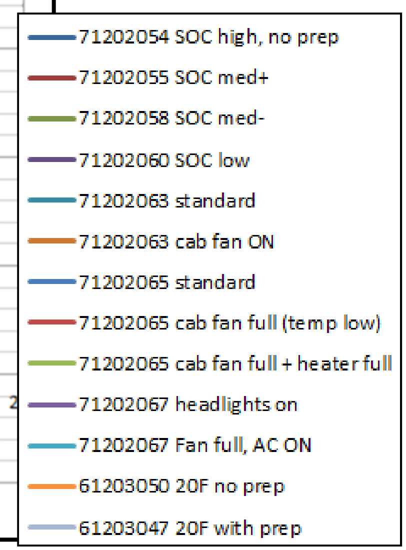
BEV Coast Down Study Conclusion: Only the Thermal State of the Vehicle Matters

AVTA Leaf



The following does ***not*** affect the vehicle loss determination on the dyno

- SOC level
- AC loads
- Headlights
- Cabin vents

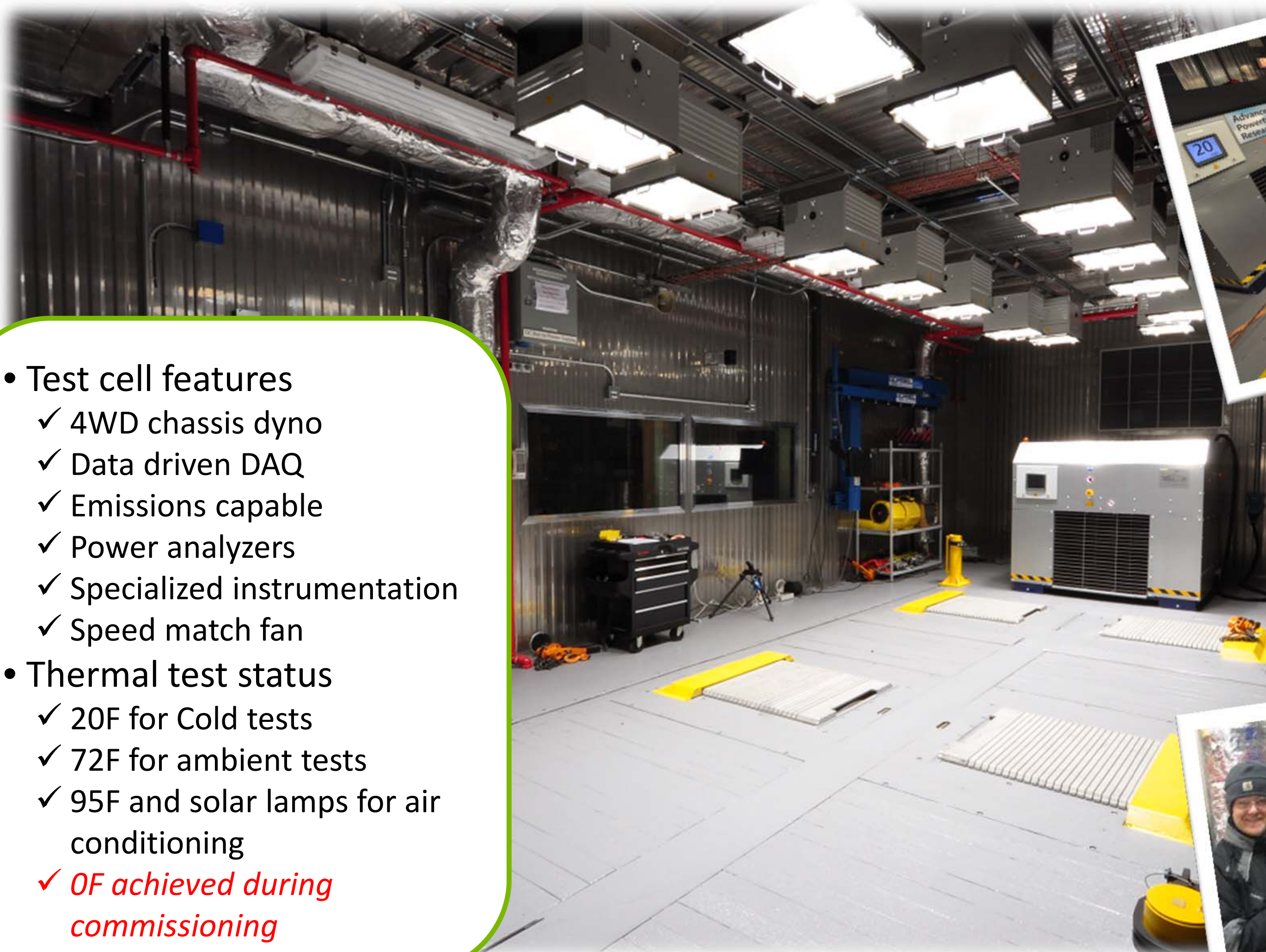


Coast down (vehicle loss determination) tests was preceded with by required double highway warm ups

The APRF's New Test Dimension: *Temperature!*

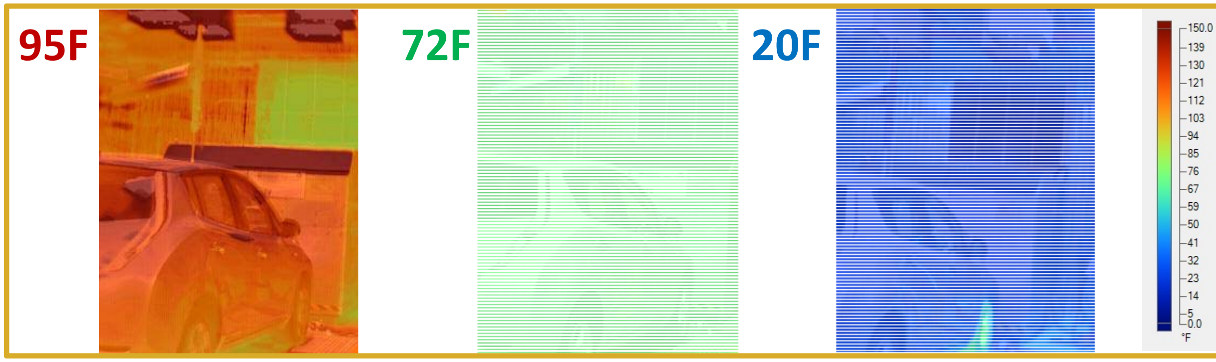
Advanced Powertrain Research Facility

U.S. DOE's Advanced Powertrain Research Facility is Now *'5 Cycle'* Capable!



- Test cell features
  - ✓ 4WD chassis dyno
  - ✓ Data driven DAQ
  - ✓ Emissions capable
  - ✓ Power analyzers
  - ✓ Specialized instrumentation
  - ✓ Speed match fan
- Thermal test status
  - ✓ 20F for Cold tests
  - ✓ 72F for ambient tests
  - ✓ 95F and solar lamps for air conditioning
  - ✓ *0F achieved during commissioning*

Instrumentation - Temperatures



IR camera

Under hood

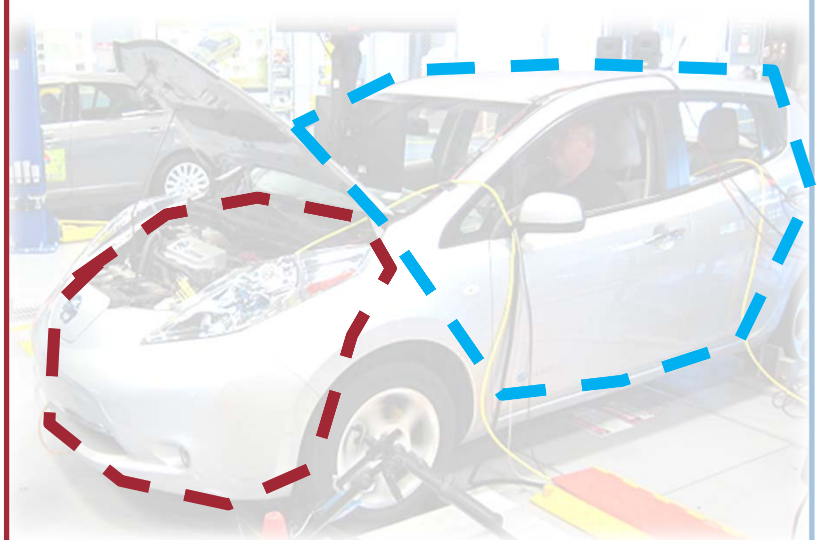
Main radiator fin

Vehicle grill

Motor inverter cooling hose
(with insulation)

Heater core hose
(with insulation)

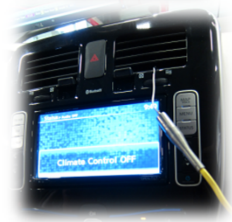
Temperature sensor locations



Note: The instrumentation was non-invasive and limited as the vehicle is going into the AVTA fleet test with INL

Cabin

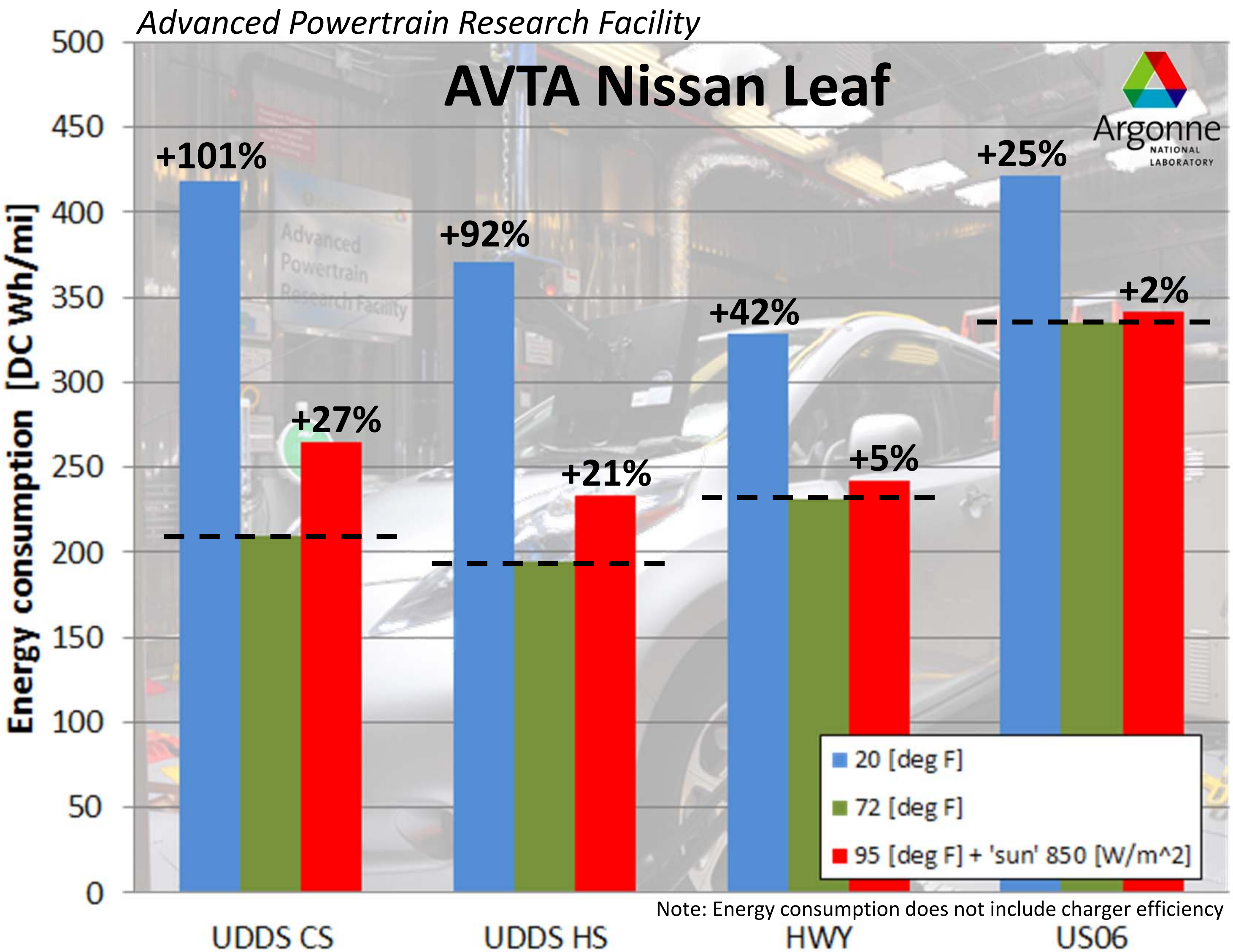
Passenger head rest (cabin)



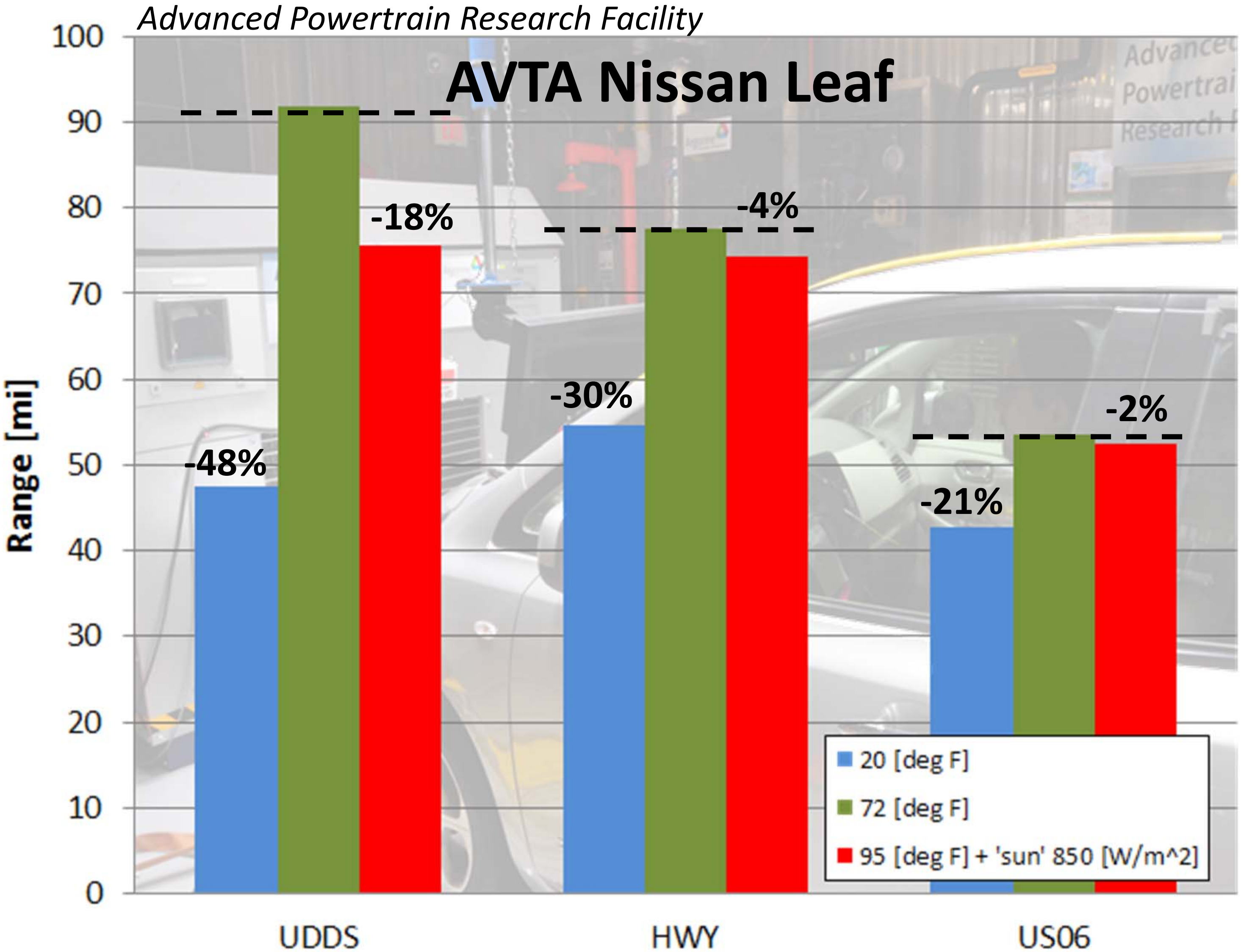
Main cabin air vent

Battery case
(with insulation)

Impact of Temperature on Energy Consumption



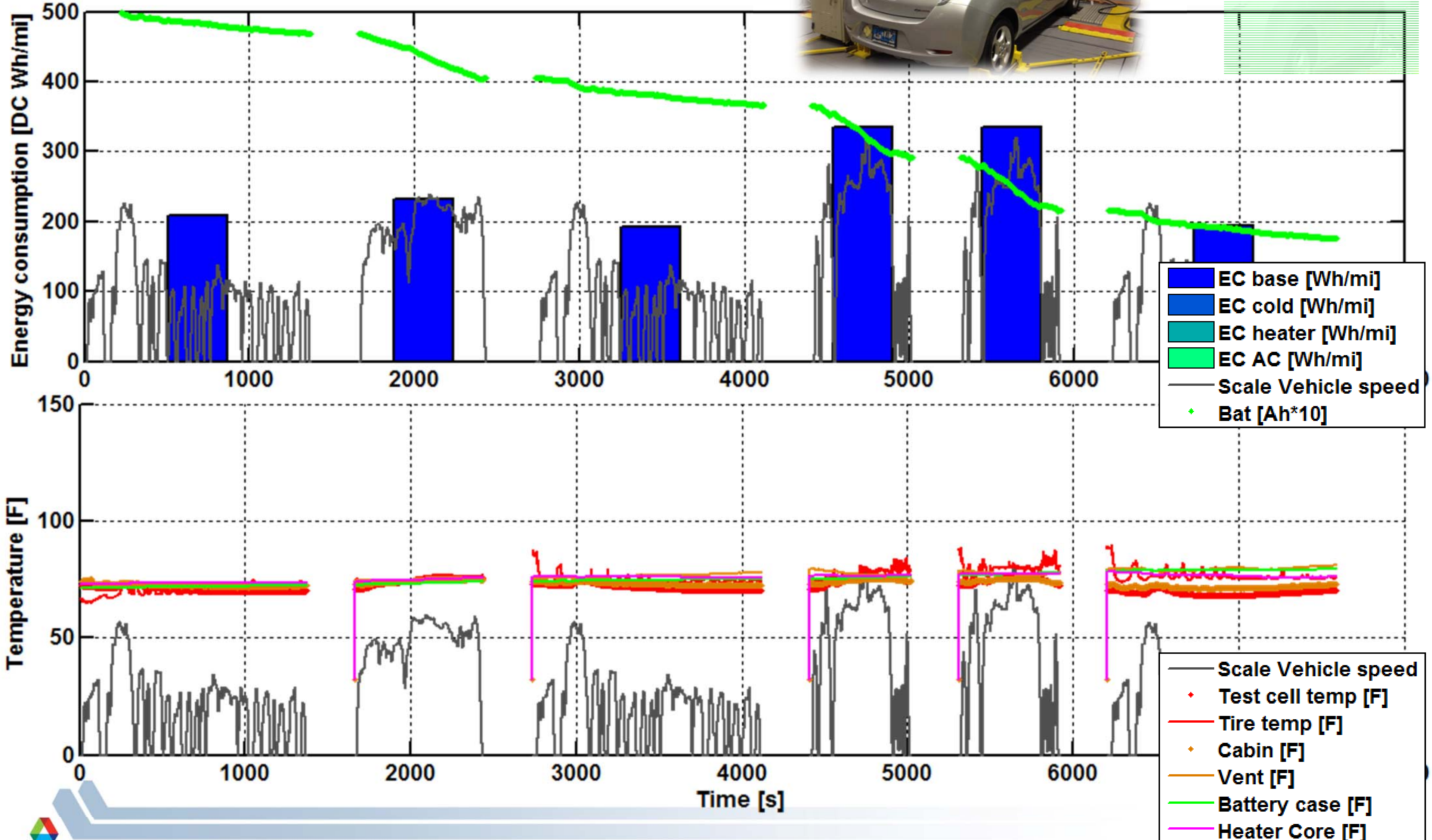
Impact of Temperature on Range



72F Baseline test

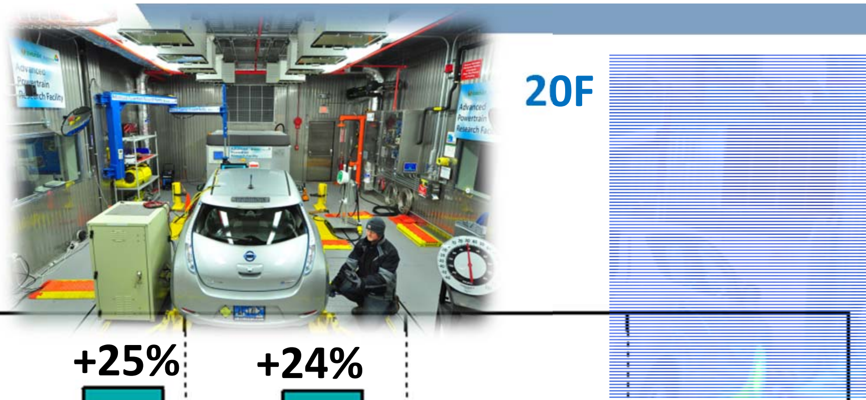
Vehicle was soaked at the test temperature for 12 hours
Hood closed, Test cell fan in vehicle speed match ,
Windows down, Climate control OFF

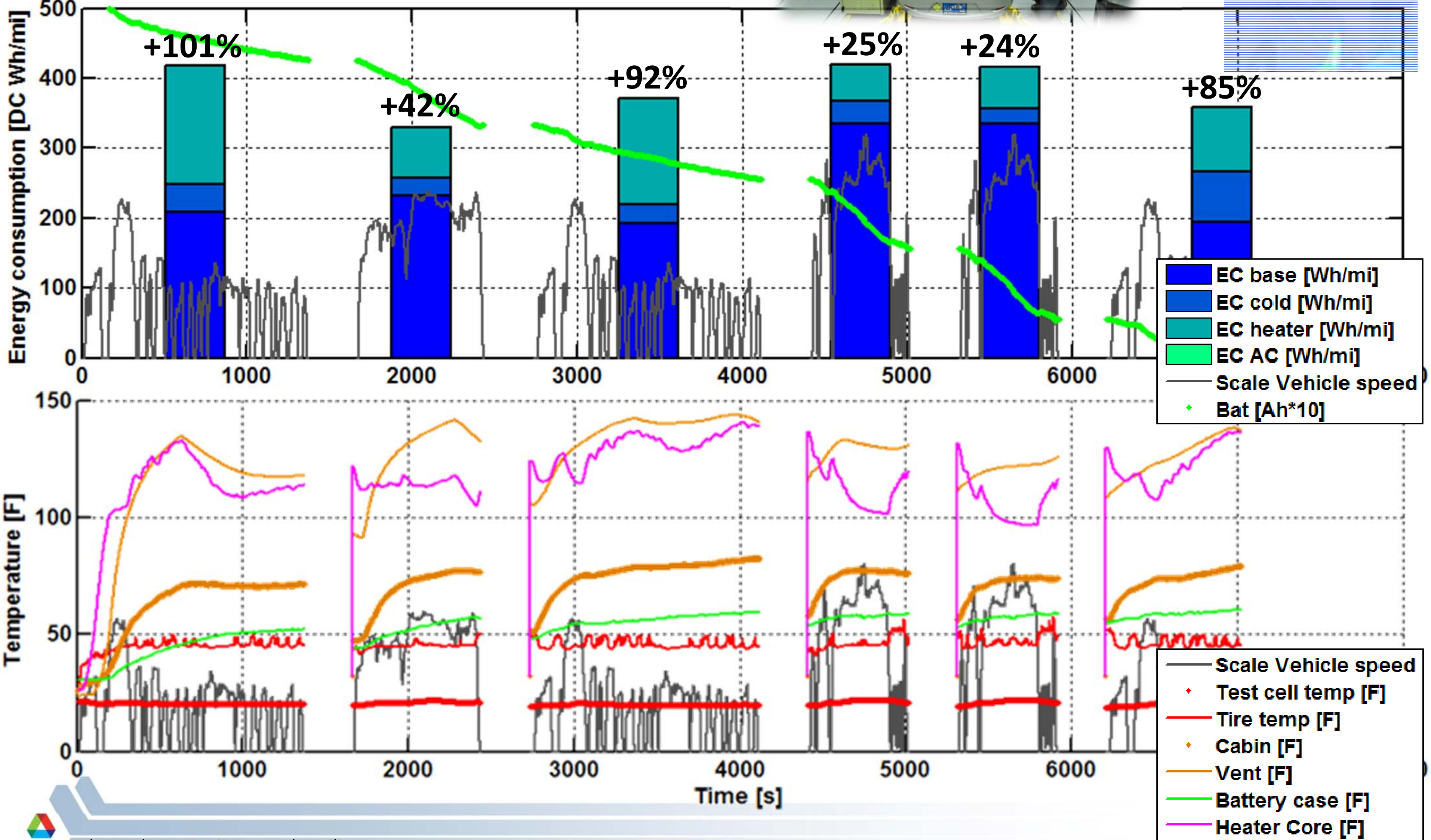
72F



20F Heater test

Vehicle was soaked at the test temperature for 12 hours
Hood closed, Test cell fan in vehicle speed match ,
Windows up, Climate control set to ‘72F auto mode’ (Heater ON)

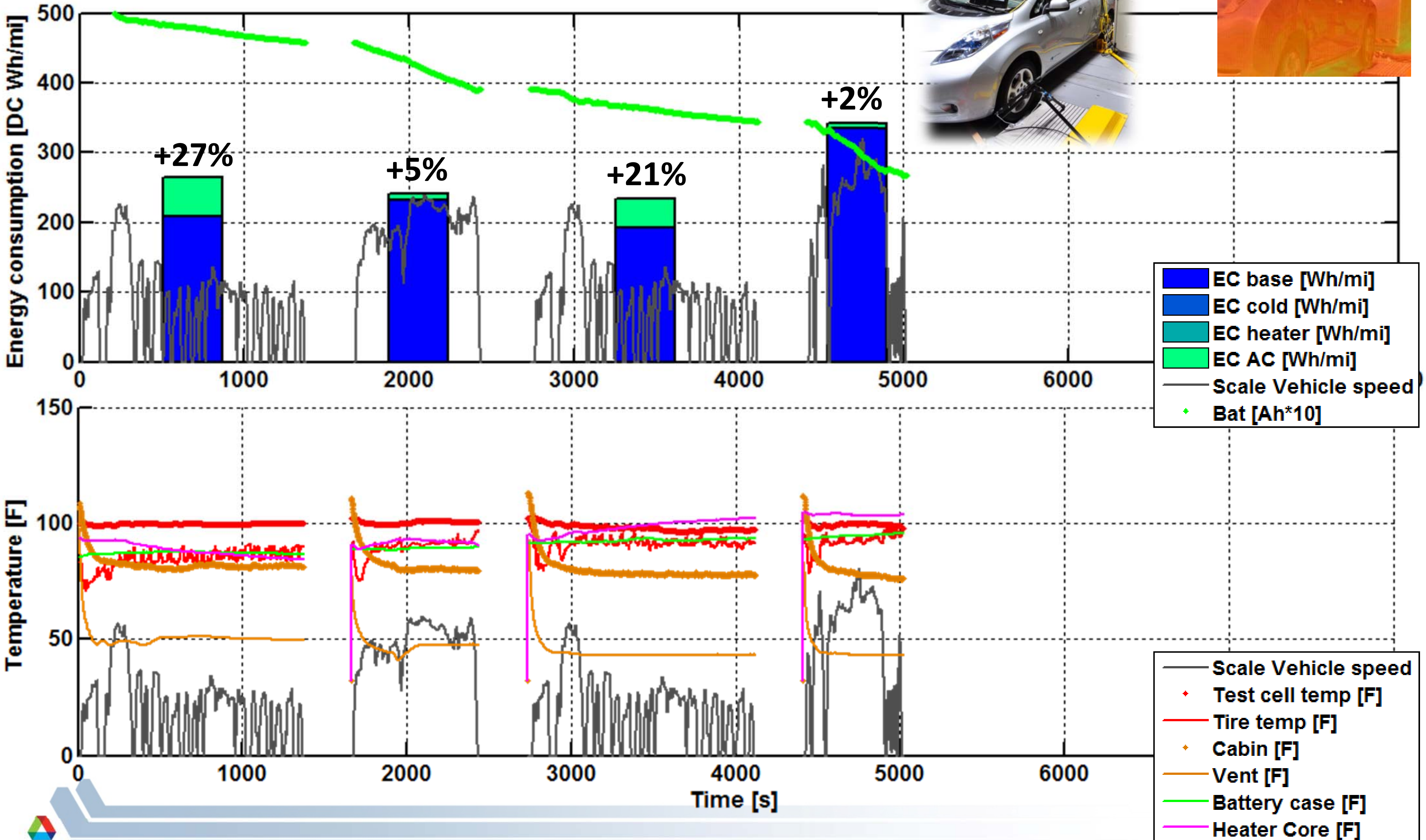




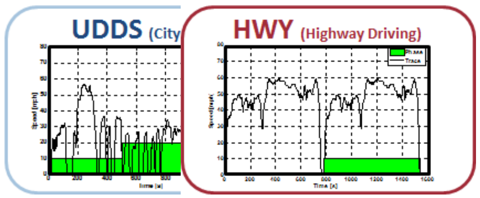
95F AC test with solar load

Vehicle was soaked at the test temperature for 12 hours
Hood closed, Test cell fan in vehicle speed match, 853W/m^2 sun emulation,
Windows up, Climate control set to ‘72F auto mode’ (AC ON)

95F



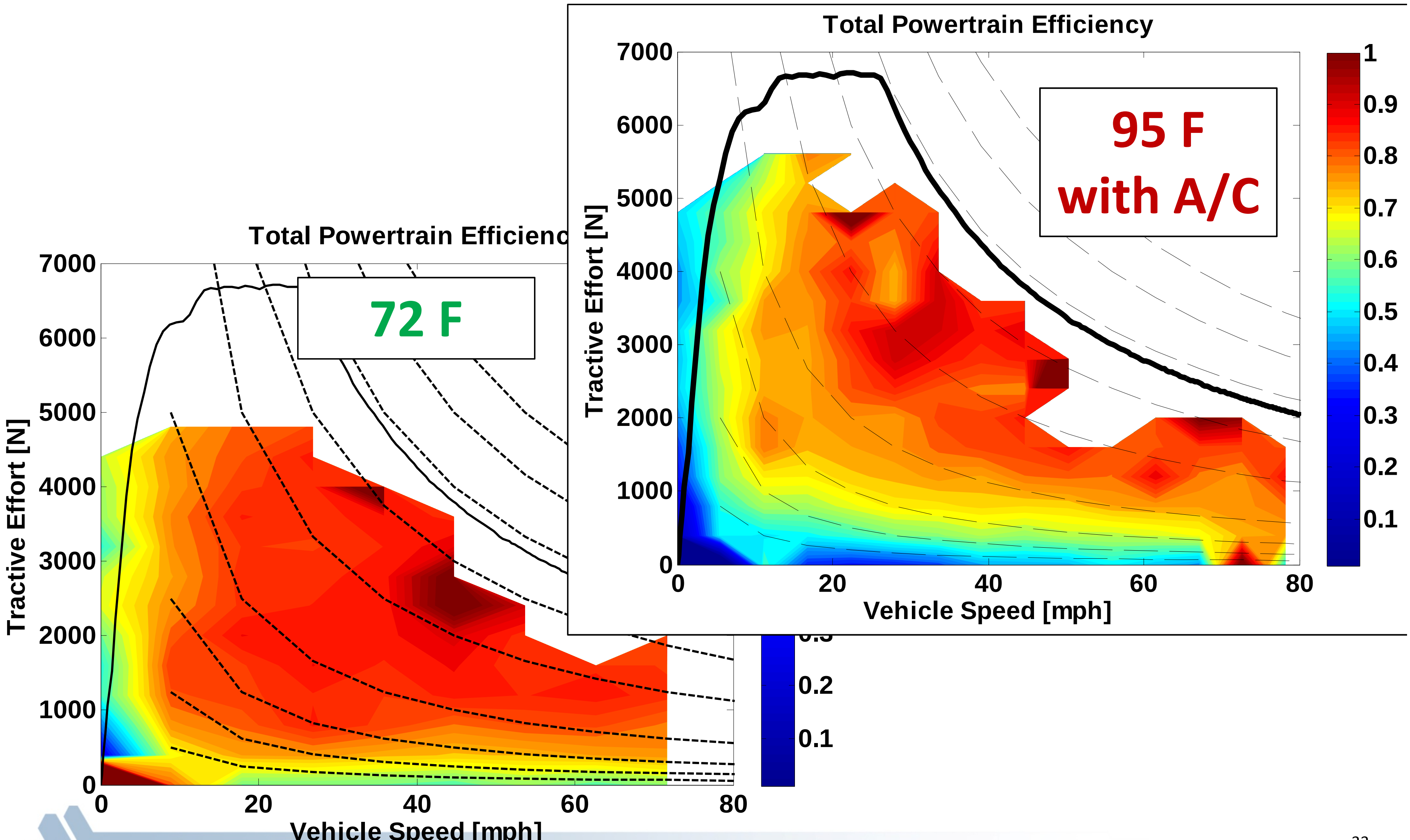
Energy flow at a Range of Test Temperatures in a Battery Electric Vehicle



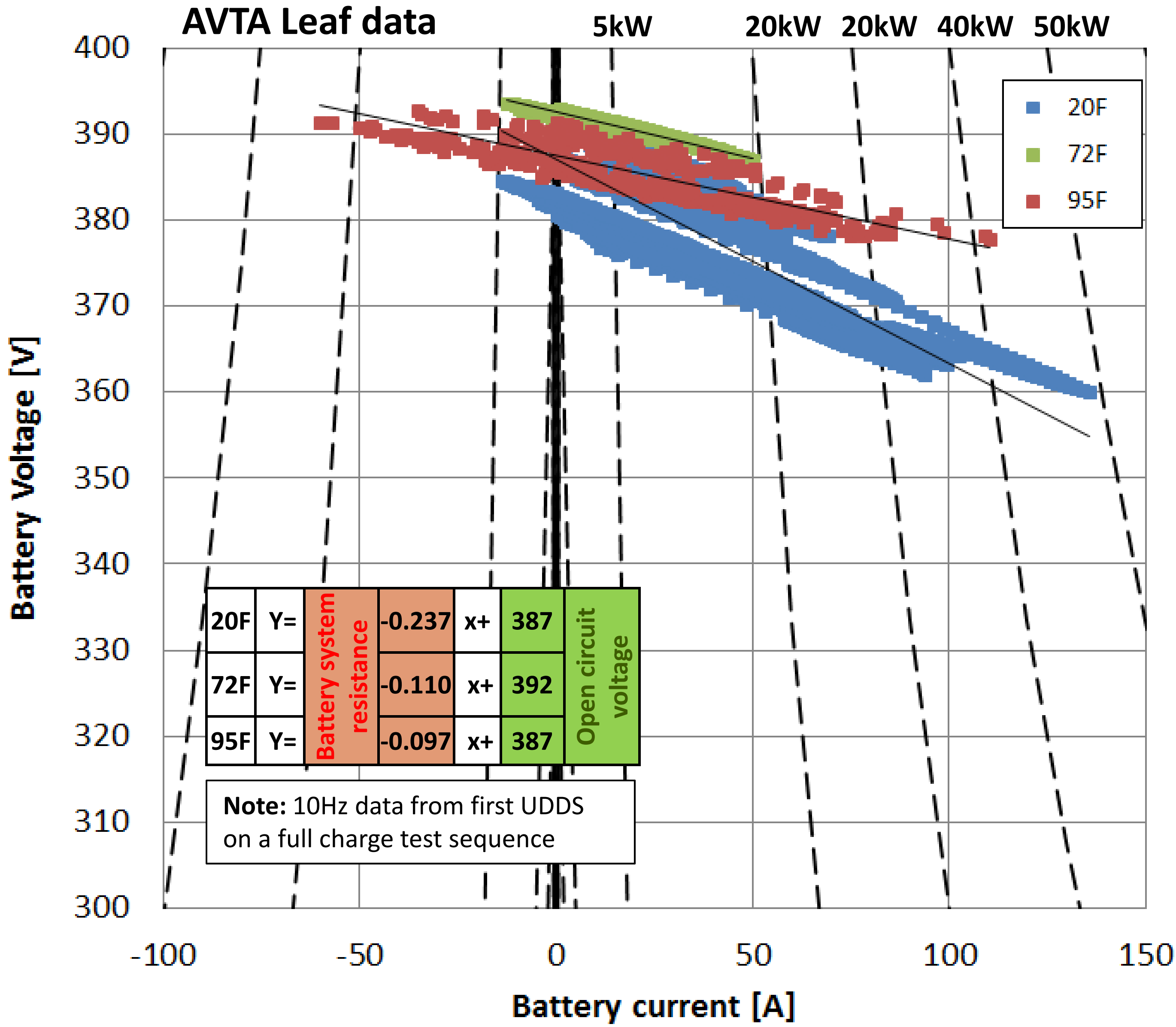
	City			Highway		
Energy portion [kWh] with respect to Net DC battery energy — Ambient temperature	20F	72F	95F	20F	72F	95F
Battery energy (Net DC battery energy used to completed the drive cycle)	2.737	1.436	1.716	3.346	2.353	2.455
Accessory loads (Vehicle Climate control set to 72F auto)	1.365	0.064	0.345	1.036	0.042	0.145
Inertia energy to Wheel (Positive power integrated)	0.928	0.928	0.928	0.354	0.354	0.354
Inertia energy to Battery (Regenerative breaking recovered)	-0.544	-0.544	-0.544	-0.159	-0.159	-0.159
Road load energy to Wheel (Aerodynamic drag and rolling resistance)	0.673	0.673	0.673	1.714	1.714	1.714
Powertrain losses	0.316	0.316	0.316	0.402	0.402	0.402

Note: Results based on 72F temperature
Test data for the AVTA Nissan Leaf
Hot tests with no regen limitation

Effective powertrain efficiency impacted by temperature effects and climate control usage



Battery Characteristics are Temperature Dependent

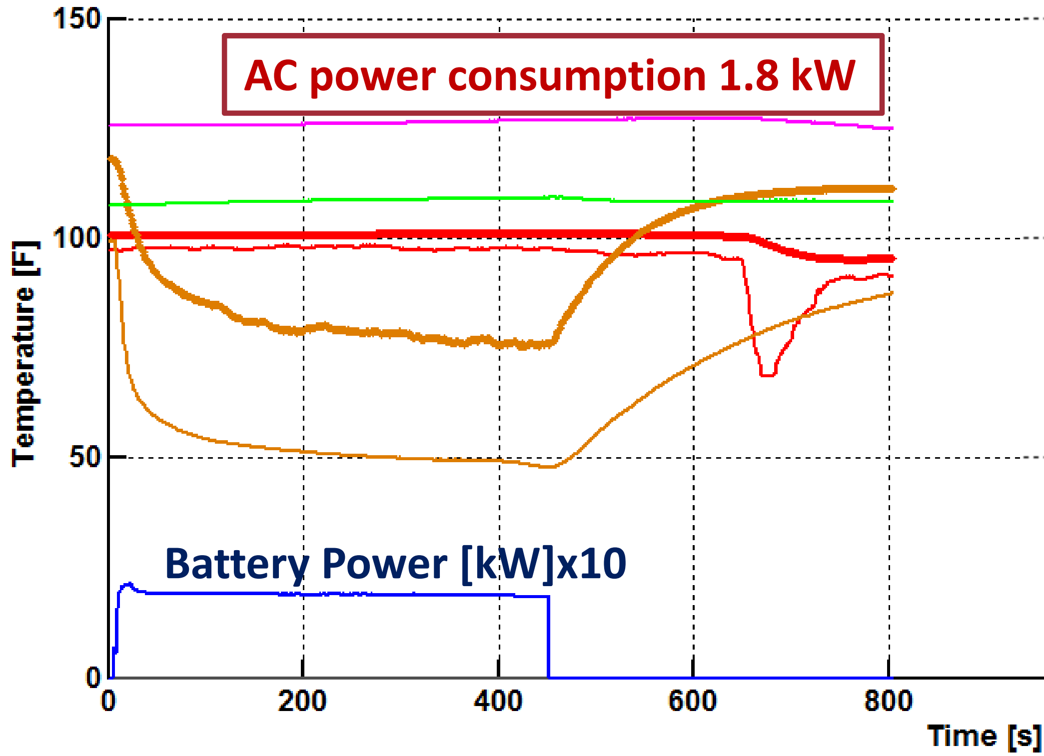


Air Conditioning Pull Down Test
at 95F with 853 W/m² of Solar emulation

The vehicle was stopped during the entire test to isolate climate control system

The photovoltaic cell in the spoiler charges the 12V battery (less than 100W)

Hood closed, Test cell fan OFF, 850W/m^2 sun emulation, Windows up, Climate control set to '72F auto mode' (AC ON)



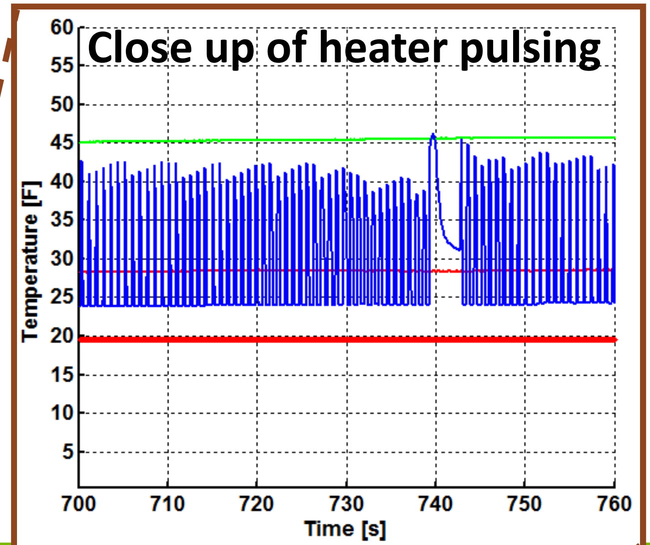
Vehicle was soaked for only 30 min at 95 with 850 W/m^2

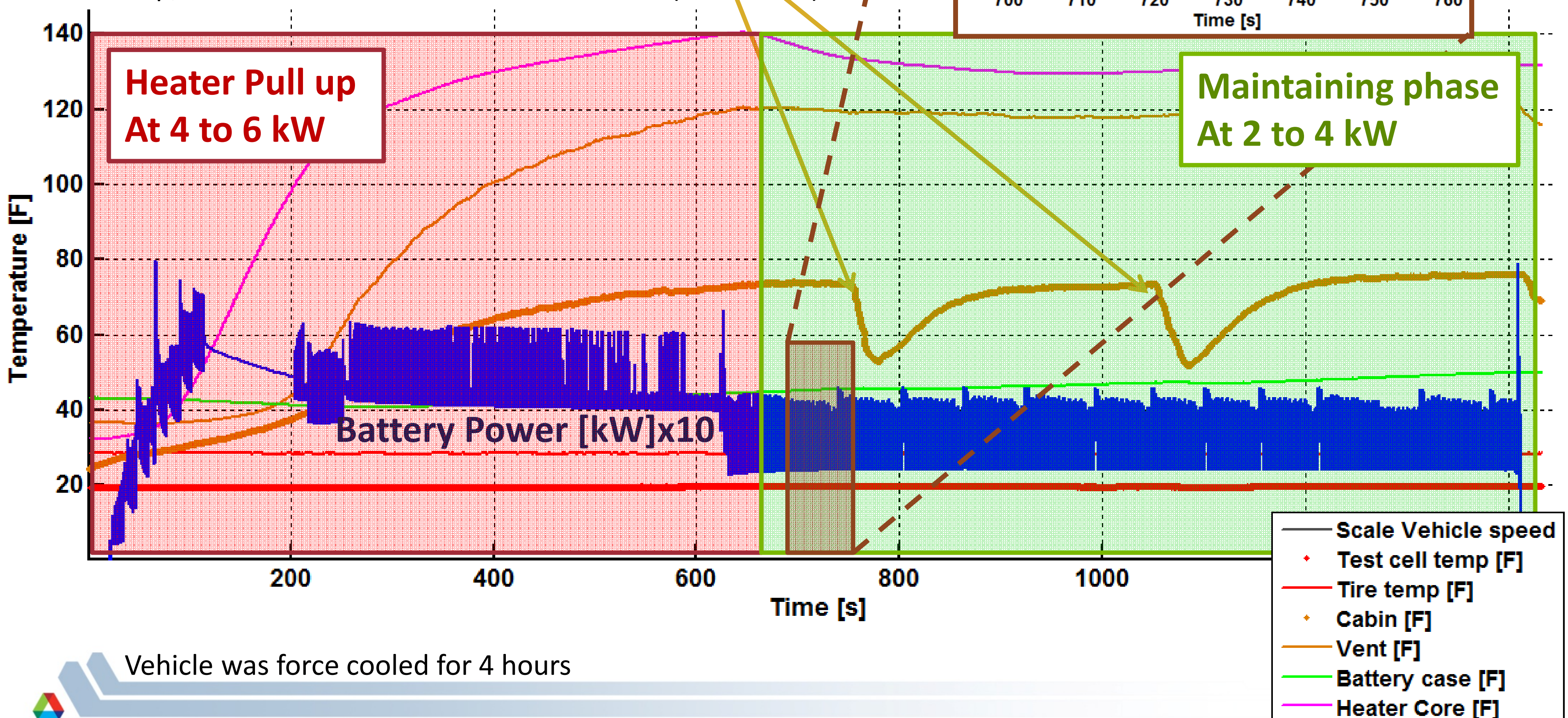
Heater Pull Up Test in 20F

The vehicle was stopped during the entire test to isolate climate control system

Door were open to simulate someone leaving the vehicle (like a taxi dropping of the fare)

Hood closed, Test cell fan OFF,
Windows up, Climate control set to '72F auto mode' (Heater ON)

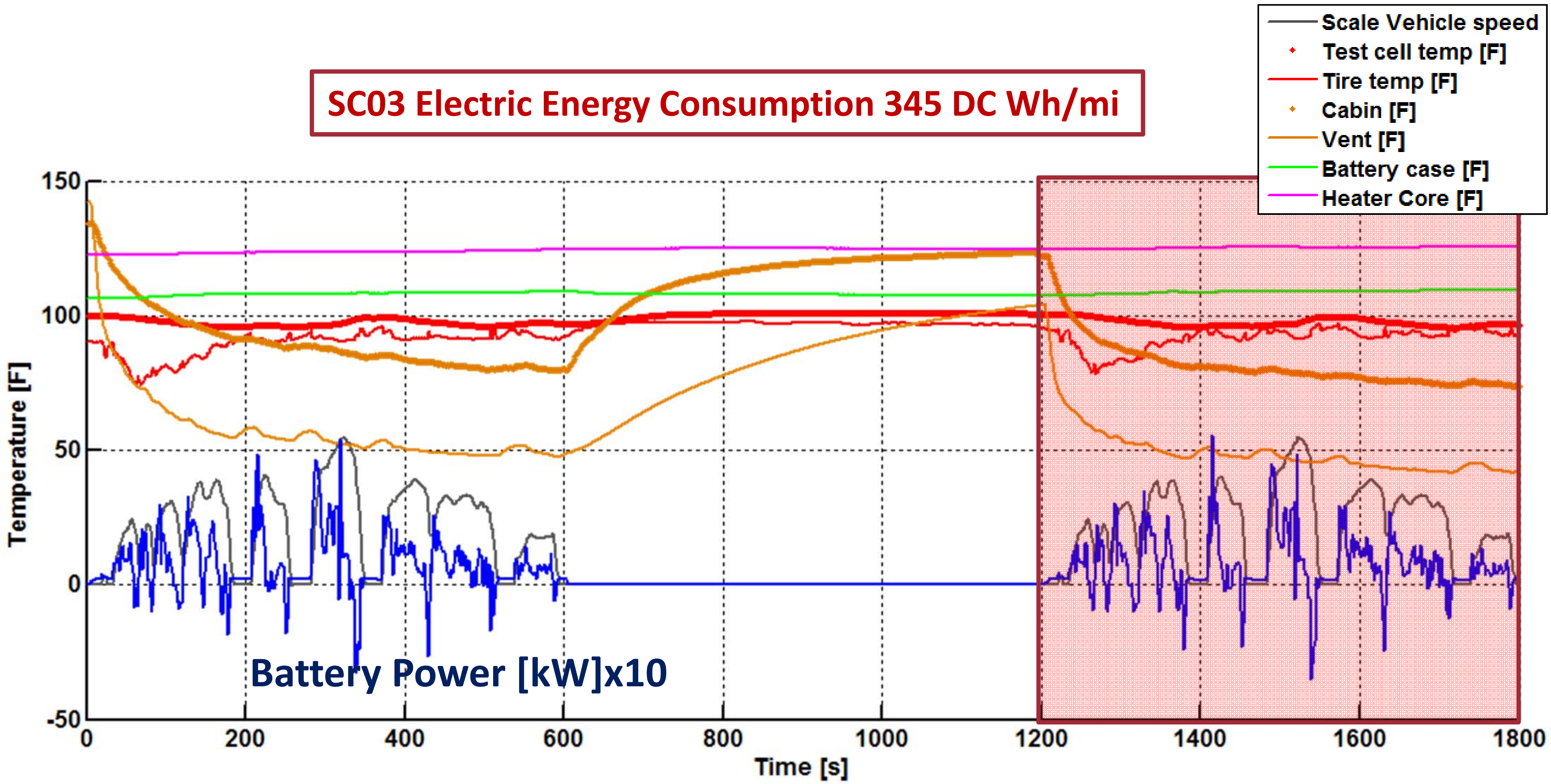




Vehicle was force cooled for 4 hours

SC03 test at 95F with 853 W/m^2

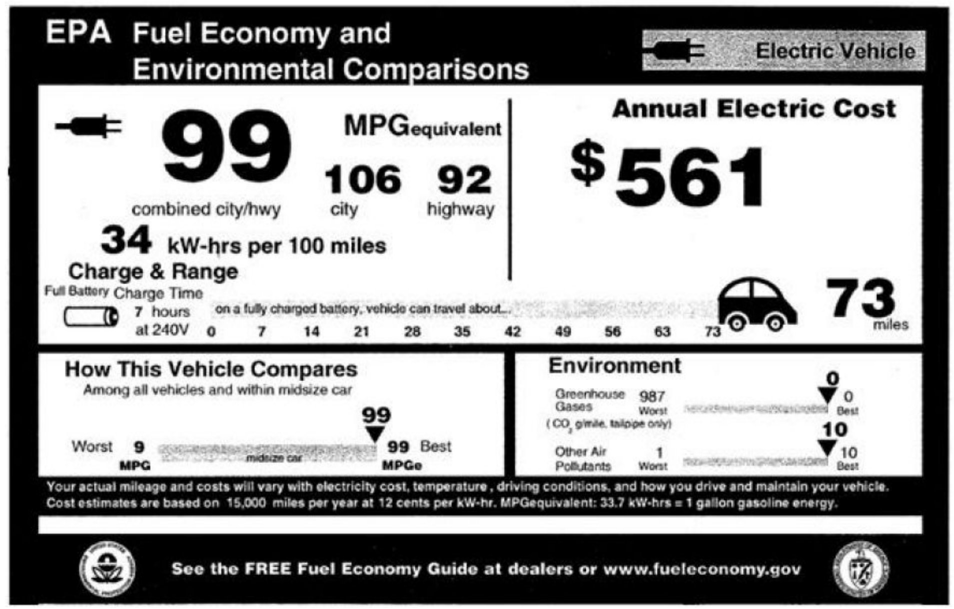
SC03 Electric Energy Consumption 345 DC Wh/mi



Vehicle was soak at the test temperature with the solar lights ON at 853W/m^2 for 12 hours before the test

Leaf hypothetical full 5 cycle EPA label calculation and comparison of ANL data to actual label

- Current EPA label method for EVs takes uncorrected FTP and HWFET AC Wh/mi result and reduces MPGge rating by 30 %
- Result is *lower* MPGge than using full 5-cycle equations (but we didn't use Cold CO ABCs)
- ANL Data [AC Wh/mi] = [DC Wh/mi] / [85 %] (charging efficiency)



Method	City MPGge	Highway MPGge	Combined MPGge
EPA Published Label	106	92	99
EPA Label Method - Argonne Data	102	86	96
Full 5-cycle - Argonne Data	111	99	105

Conclusions

- Established the energy consumption and range on standard drive cycles for the AVTA Leaf
  - UDDS 233 AC Wh/mi and 92 miles
  - US06 395 AC Wh/mi and 54 miles
- Characterized battery capacity and performance
- Established the accessory loads power levels
- In 20F weather the heater can double the energy consumption and cut the range in half
- In hot and sunny conditions, the air conditioning can increase the energy consumption by 25% with a hot cabin but the extra load is 5% or less for highway driving
- Characterized the heat power requirements to warm up the cabin 72F from 20F → 3 to 6 kW
- Characterized the air conditioning requirements to cool the cabin to 72F from 95F with solar load → 2 kW