Hybrid Vehicle Comparison Testing Using Ultracapacitor vs. Battery Energy Storage

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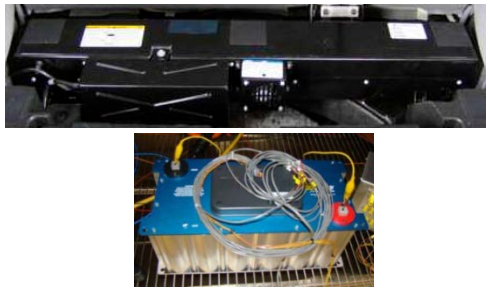
Executive Summary
NREL/GM collaborative project

- Project:

  Converted and tested HEV with three energy storage configurations:
  - NiMH (stock)
  - 1 and 2 Ucap modules



- Findings:

  The HEV performed equal or better with one Ucap module relative to the stock NiMH HEV configuration

- Significance:

  Ucaps could increase HEV market penetration (thus increasing fuel savings)
  - Ucaps possess excellent life and low-temperature performance, and have low long-term projected costs

Presentation Outline

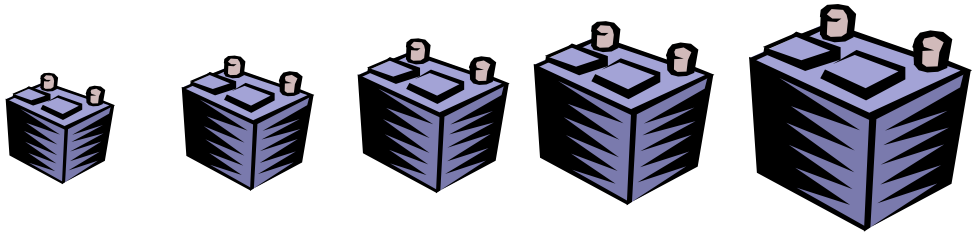
- Background
- Details of vehicle conversion project
  - GM collaboration/vehicle selection
  - System design
  - Hardware bench-top evaluation
  - Vehicle conversion
  - Vehicle test results
  - Comparison with NiMH vehicle
- Summary

Background:

In 2007-2008, NREL performed analysis in support of USABC*/ DOE for revisiting the energy storage requirements for HEVs

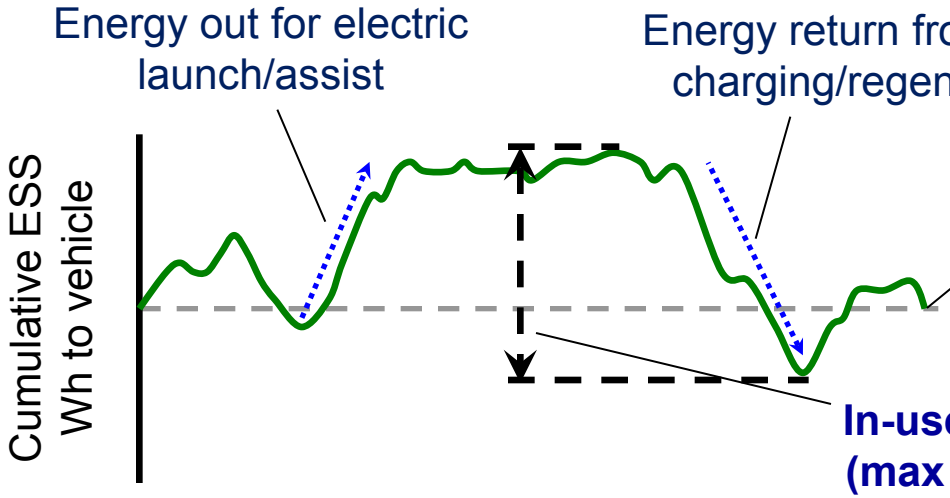
Approach:

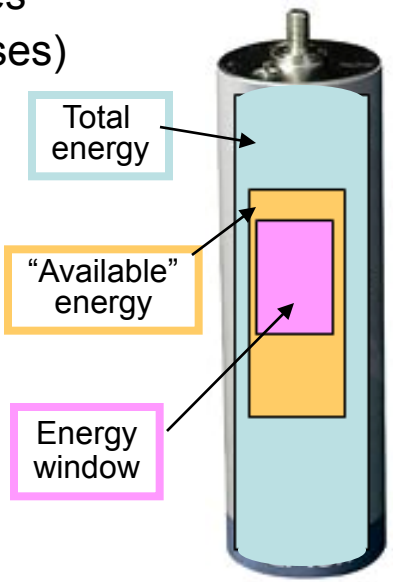
Simulate midsize HEV platform



Use a range of ESS** sizes (different energy content cases)

Observe fuel and ESS energy usage for each case:



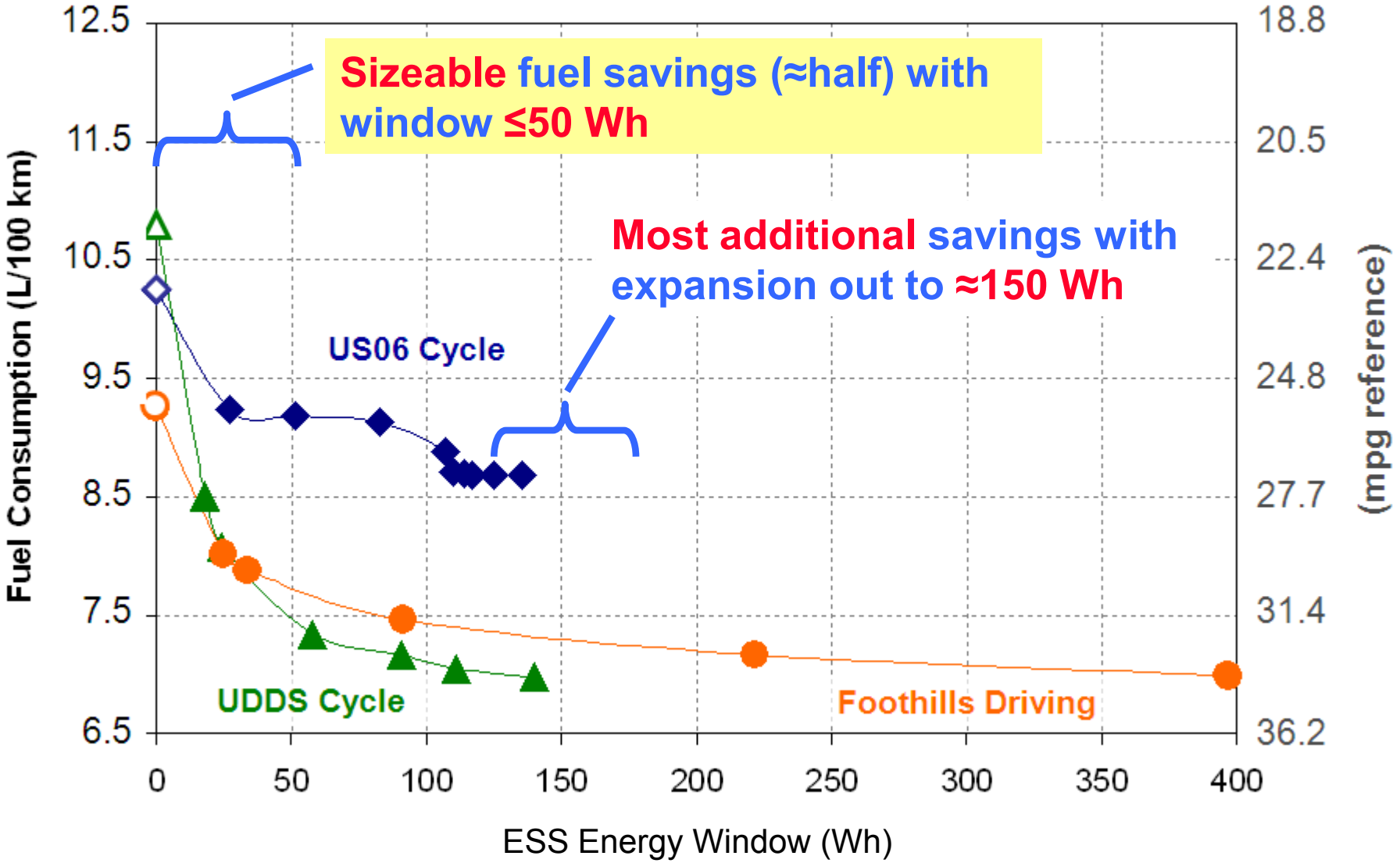


* USABC = United States Advanced Battery Consortium; DOE = U.S. Department of Energy

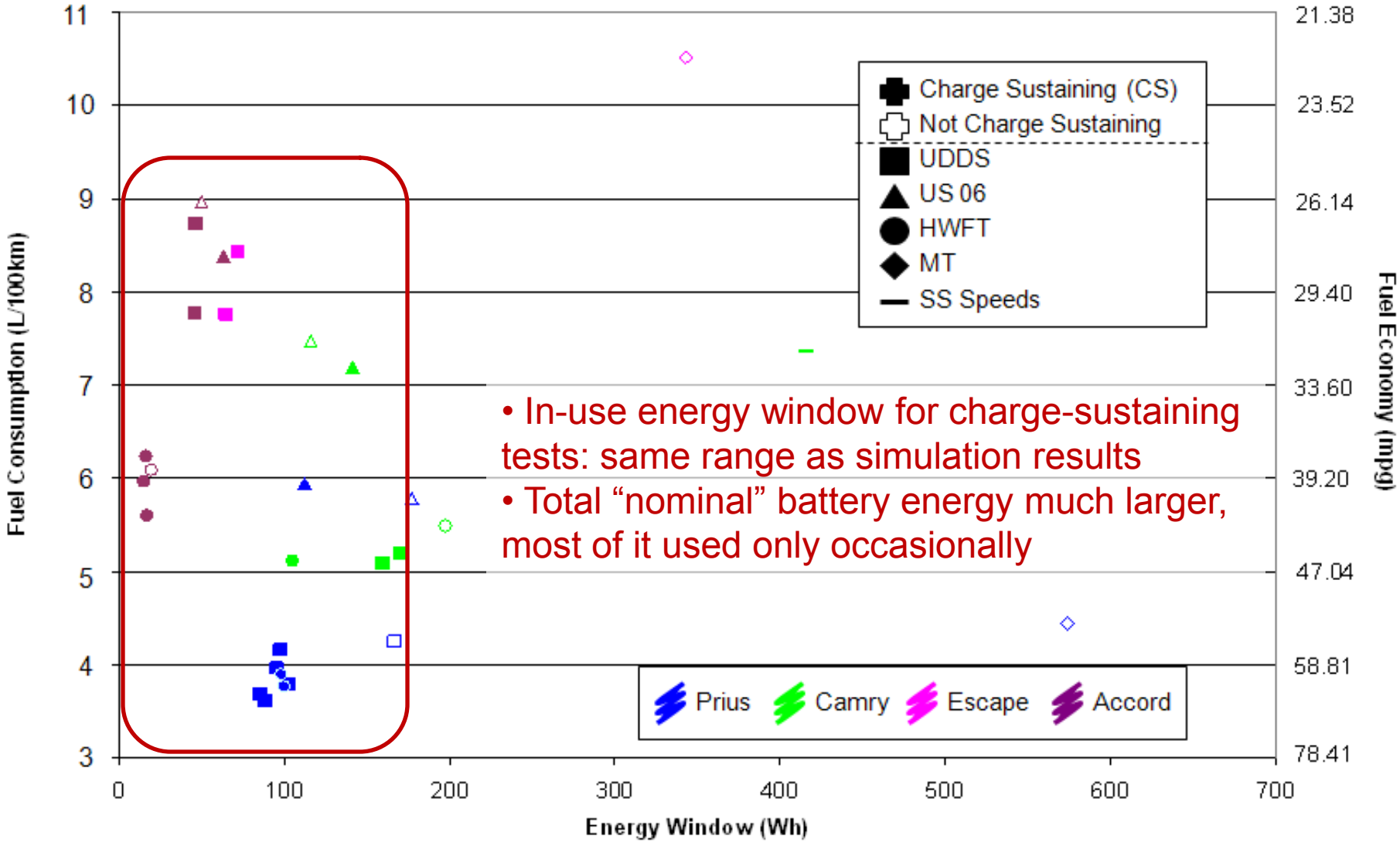
** ESS = energy storage system

Background:

Simulation results for USABC showed similar fuel consumption vs. energy window trends for various drive cycles



Background:
Consistent findings from analysis of production HEV dyno data*



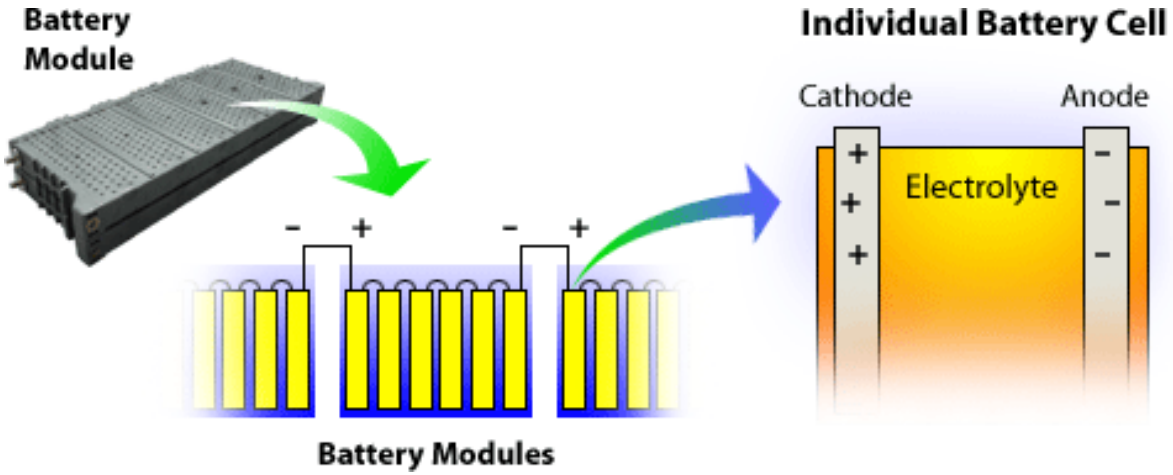
* Thanks to ANL for providing access to some of the raw dynamometer test data
Results adjusted for round-trip efficiency (to provide actual ESS energy state)

Observations from the USABC/DOE HEV Energy Window Study; Discussions with GM led to vehicle conversion and testing project

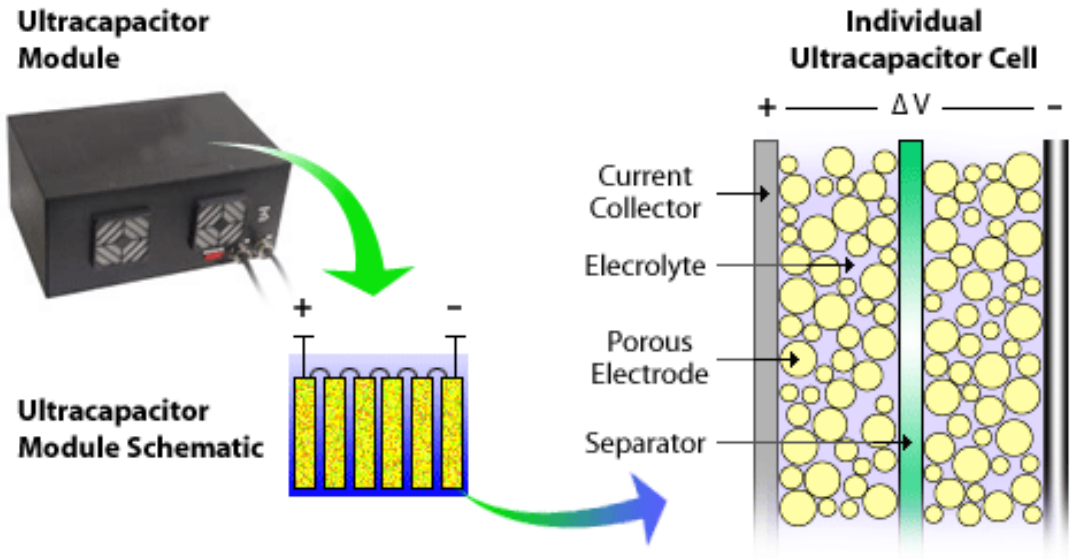
- Hybridization can result in sizable fuel economy improvement even with a small energy window ESS
- Reasons for large total "nominal" energy in present production HEVs
  - Infrequent drive cycle use (e.g., long up/downhill grades)
  - Achieving longer cycle life from reduced SOC swings
    - Though over-sizing adds to battery cost
  - Energy comes with sizing for power requirements (particularly at cold temps)
    - Power dominates cost in HEV (high P/E ratio) batteries
- Ultracapacitors should be considered (acceptable energy, low-temp. performance, long cycle and calendar life and potential of lower $/kW)

- GM interested in further evaluating ultracapacitor technology
  - **Supported project to evaluate use of Ucaps instead of batteries in a Saturn Vue BAS (belt alternator starter) Hybrid**

Battery and Ultracapacitor Technology Differences



Chemical Energy Storage
Ions participate in reversible chemical reactions at the electrodes



Electrostatic Energy Storage
Ions attracted to charged surfaces of porous electrodes, held there electrostatically

Production "Mild" BAS HEV System with a <50 V NiMH Battery Provides Significant Fuel Economy Benefit

Conventional

2007 Saturn Vue FWD

21 Combined

19 City | 25 Hwy

2010 Model

22 Combined

19 City | 26 Hwy

≈ +25% mpg*

HEV

2007 Saturn Vue Hybrid

26 Combined

23 City | 29 Hwy

2010 Model

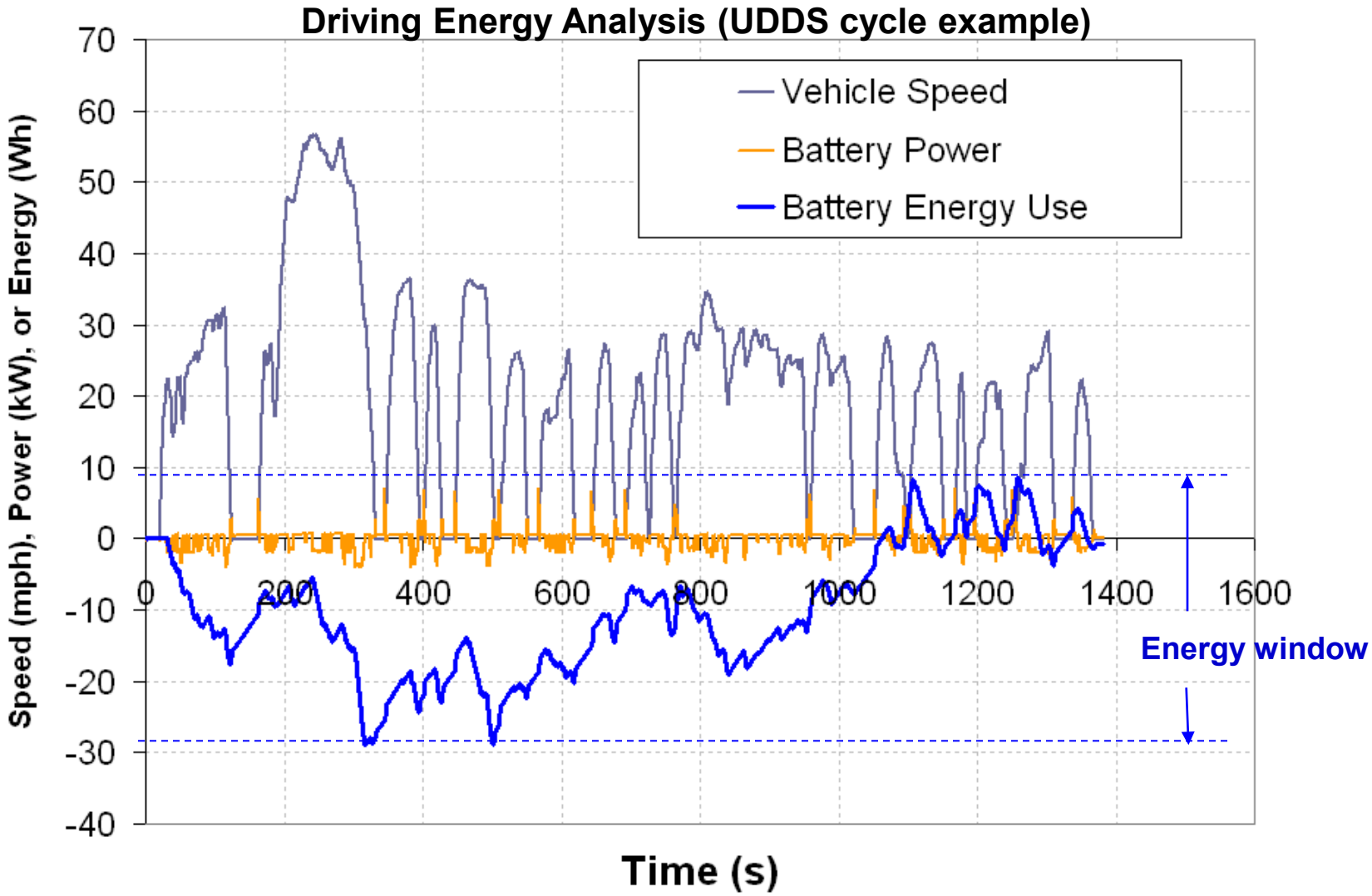
28 Combined

25 City | 32 Hwy

Project shows Ucaps provide similar fuel economy benefit

* Caveat: Window sticker difference does not necessarily equate to hybridization improvement. Data from www.fueleconomy.gov (using updated EPA numbers), accessed December 10, 2009.

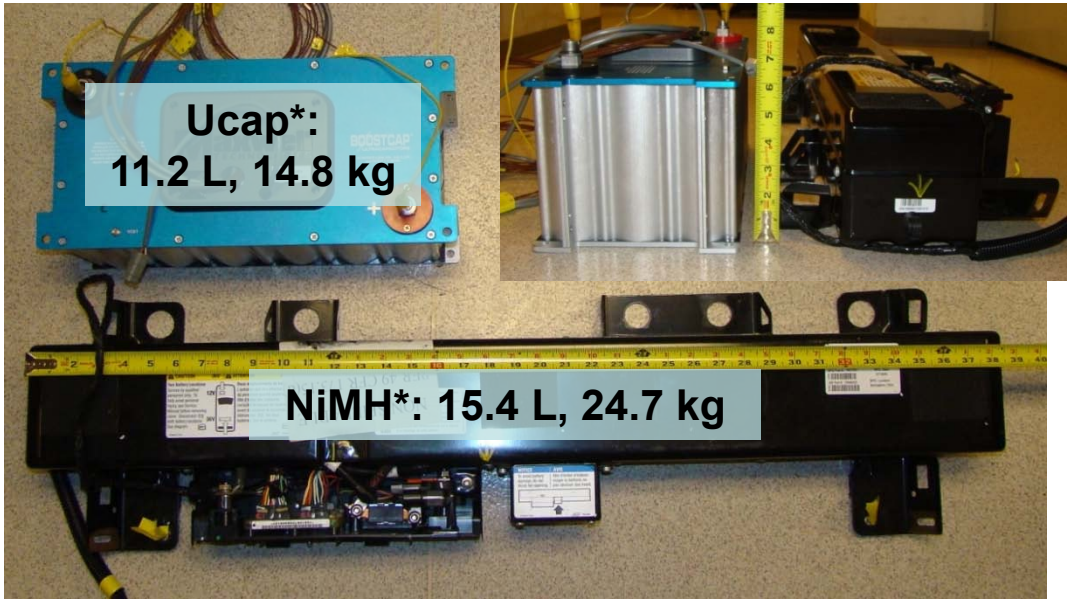
Analysis of Dyno Data* on a 2007 Vue Hybrid Indicated Energy Use ≈50 Wh or Less

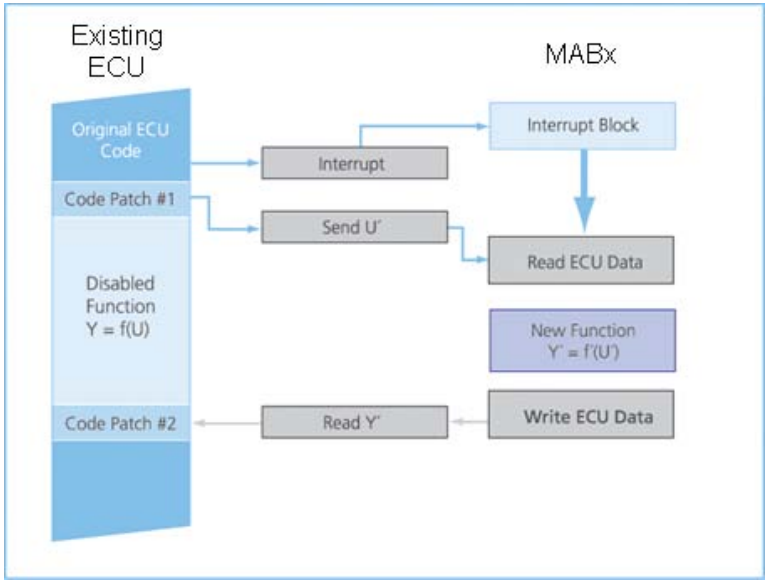


* From the aforementioned DOE-sponsored testing at ANL

System Design: Selected off-the-shelf Maxwell 48 V, 165 F modules (each ≈35 Wh usable)

- Direct NiMH replacement
  - No additional DC/DC converter (surrounding components rated ≈25-48 V)
  - Ability to test single and two (in parallel) module configurations
  - Paired with a spare Energy Storage Control Module (ESCM) – stock NiMH remains in vehicle; can toggle between it and the Ucaps
- Vehicle interface via bypass Rapid Control Prototyping (RCP)
  - Custom Ucap state estimator bypasses code in ECU for stock NiMH

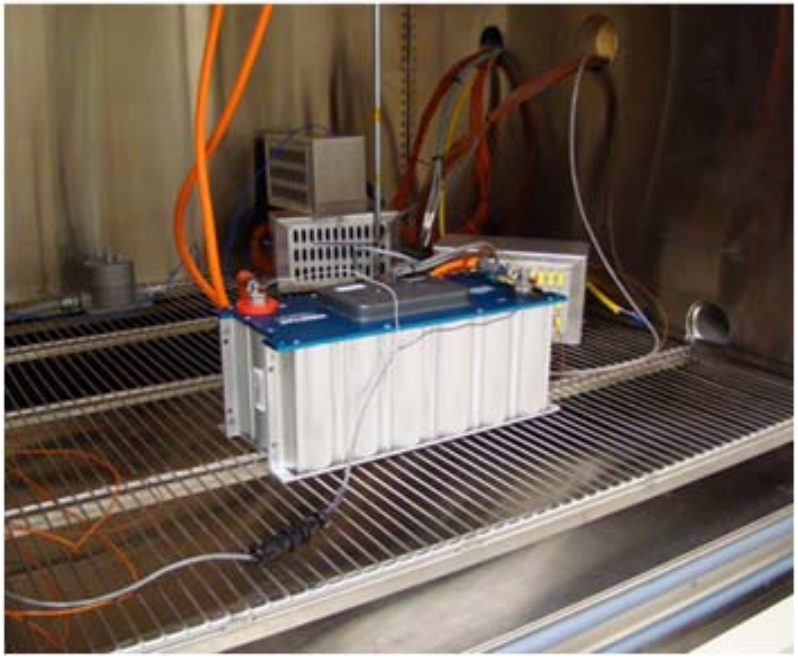


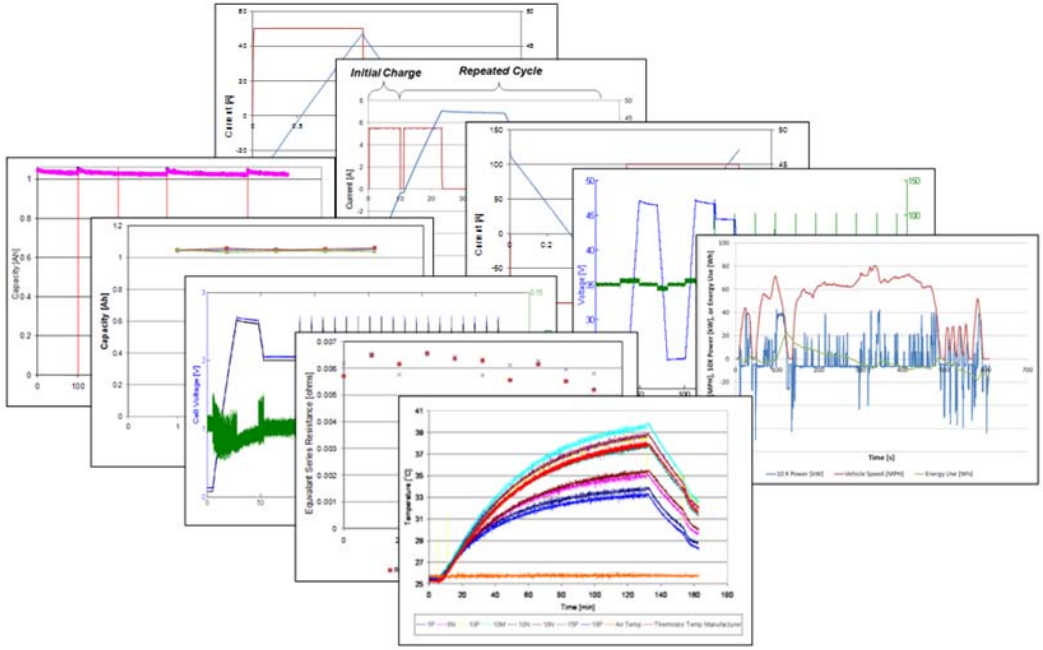


* Electronics, mounting brackets, etc. excluded from volume, but included in this mass comparison.

Performed Ultracapacitor Bench-top Evaluation

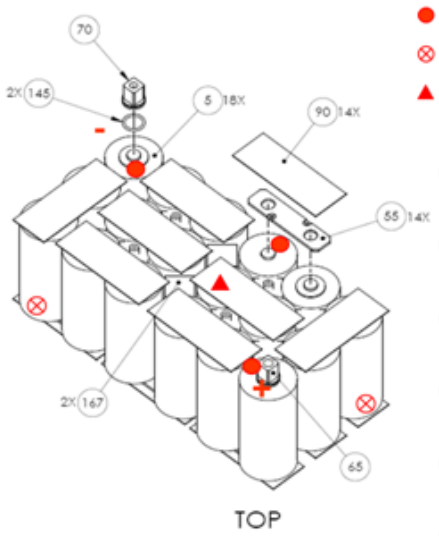
- Confirmed electrical performance
  - Detailed characterization testing on first module (capacity, voltage)
- Characterized thermal behavior of the passively cooled module
- Obtained data set for vehicle Ucap state estimator validation

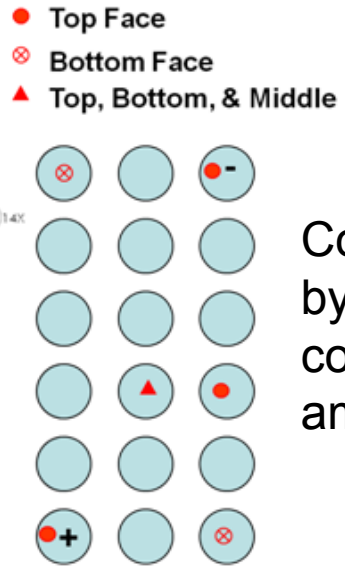




Ucap Module Testing and Instrumentation

- Equipment
  - ABC-1000:
    420 V, 1000 A, 125 kW
  - Environmental Chamber:
    -45°C – 190°C, 64 ft^3
  - Independent DAQ system:
    National Instruments
- Instrumentation
  - K-type thermocouples
  - Voltage on every cell
    (fused probe wires)
- Tests
  - Voltage range chosen for application: 24 V – 47 V
  - Multiple cycles and temperatures evaluated
  - Based on FreedomCAR Ultracapacitor Test Manual



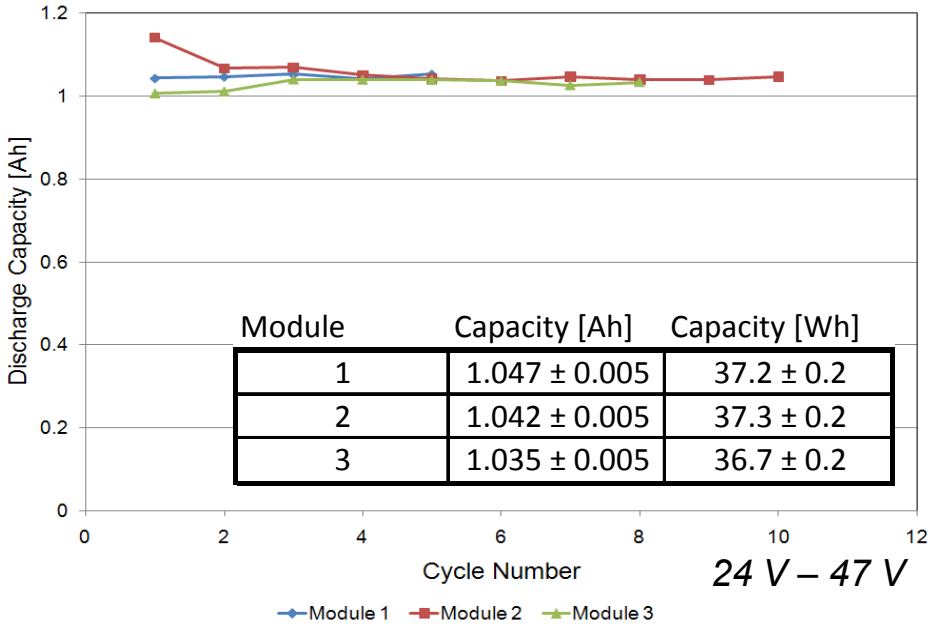


Cooling mostly by heat conduction to ambient

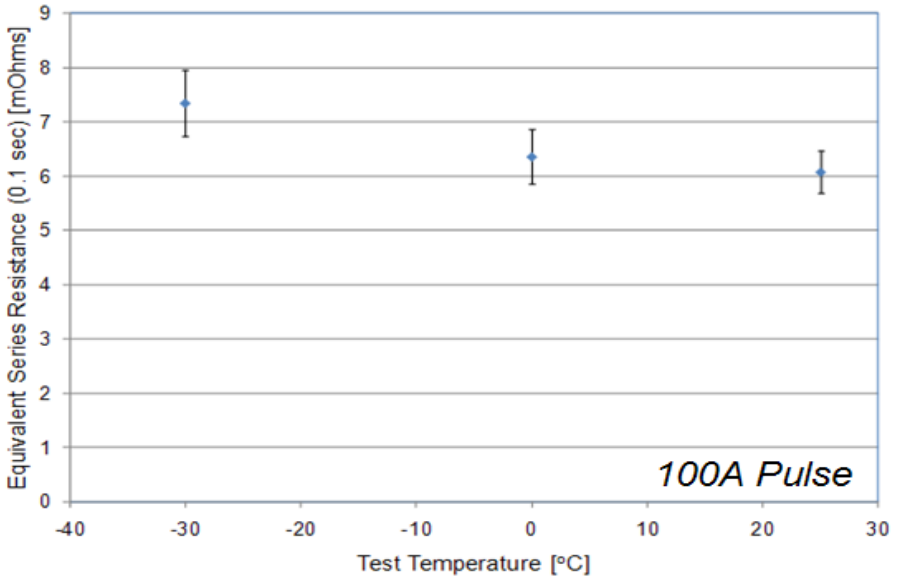
Module Electrical Characterization:

Performed as expected

- Break-in cycling did not have a measurable effect over the first 615 cycles
- Capacity was stable at 1.045 Ah from 24 V–47 V for the first two modules (module 3 was slightly lower)
- ESR of 6.1 mΩ ± 0.4 mΩ measured at 25°C on a 100 A pulse
- Good cold temperature performance measured
- Cell voltage range stayed under 0.1 V during US06 bench top cycle
- Also confirmed stable replacement NiMH module performance at the rated capacity

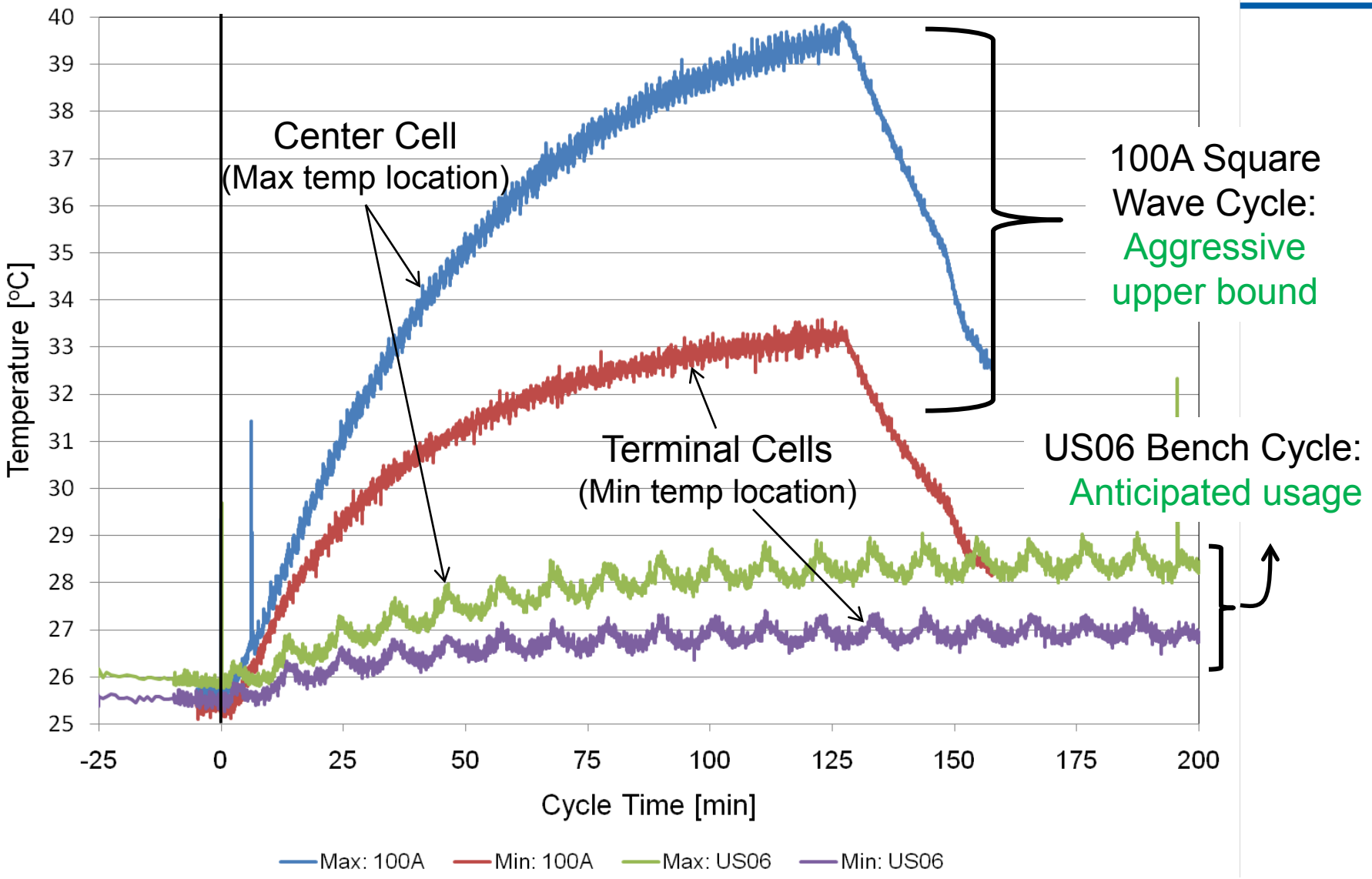


Module	Capacity [Ah]	Capacity [Wh]
1	1.047 ± 0.005	37.2 ± 0.2
2	1.042 ± 0.005	37.3 ± 0.2
3	1.035 ± 0.005	36.7 ± 0.2



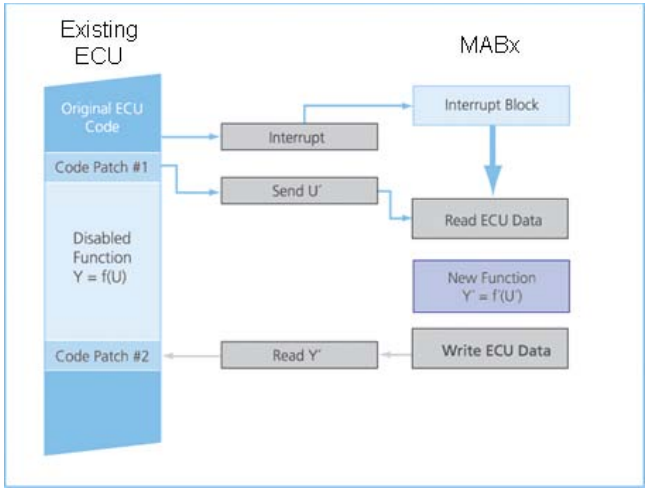
Temperature Performance Summary (25 C ambient)

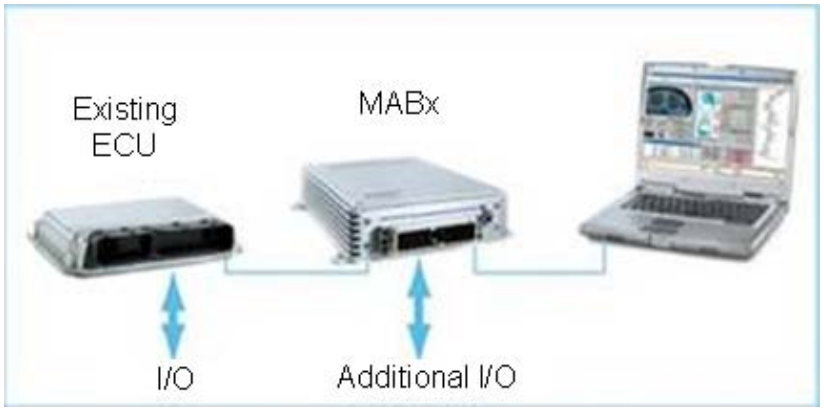
No heating problems anticipated in application

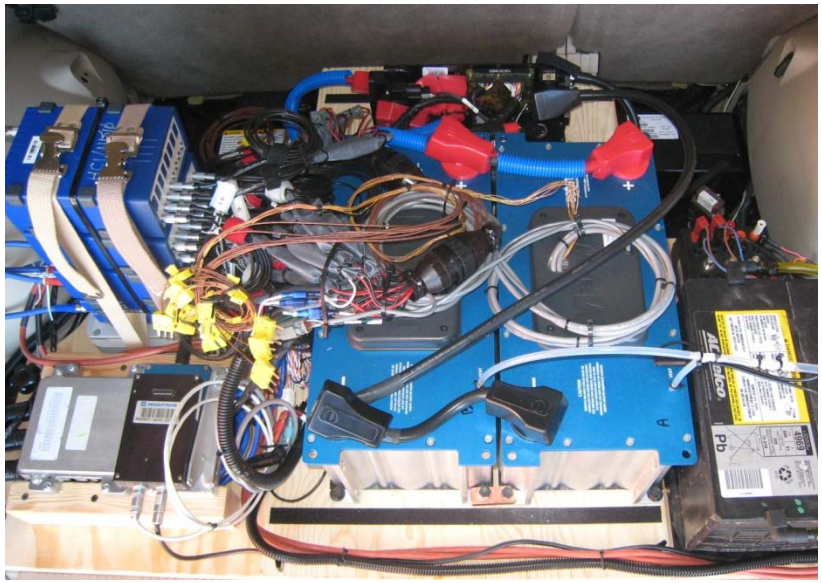


Integration of Ucap System into the Vue Hybrid

- Controls for Ucap state estimation, safety, etc. implemented via rapid control prototyping (RCP) with dSpace MicroAutoBox (MABx)
- Pertinent instrumentation, new NiMH battery and Ucap system all installed
- Electronic control unit (ECU) calibration adjustments and in-vehicle data acquisition via ETAS hardware/INCA software





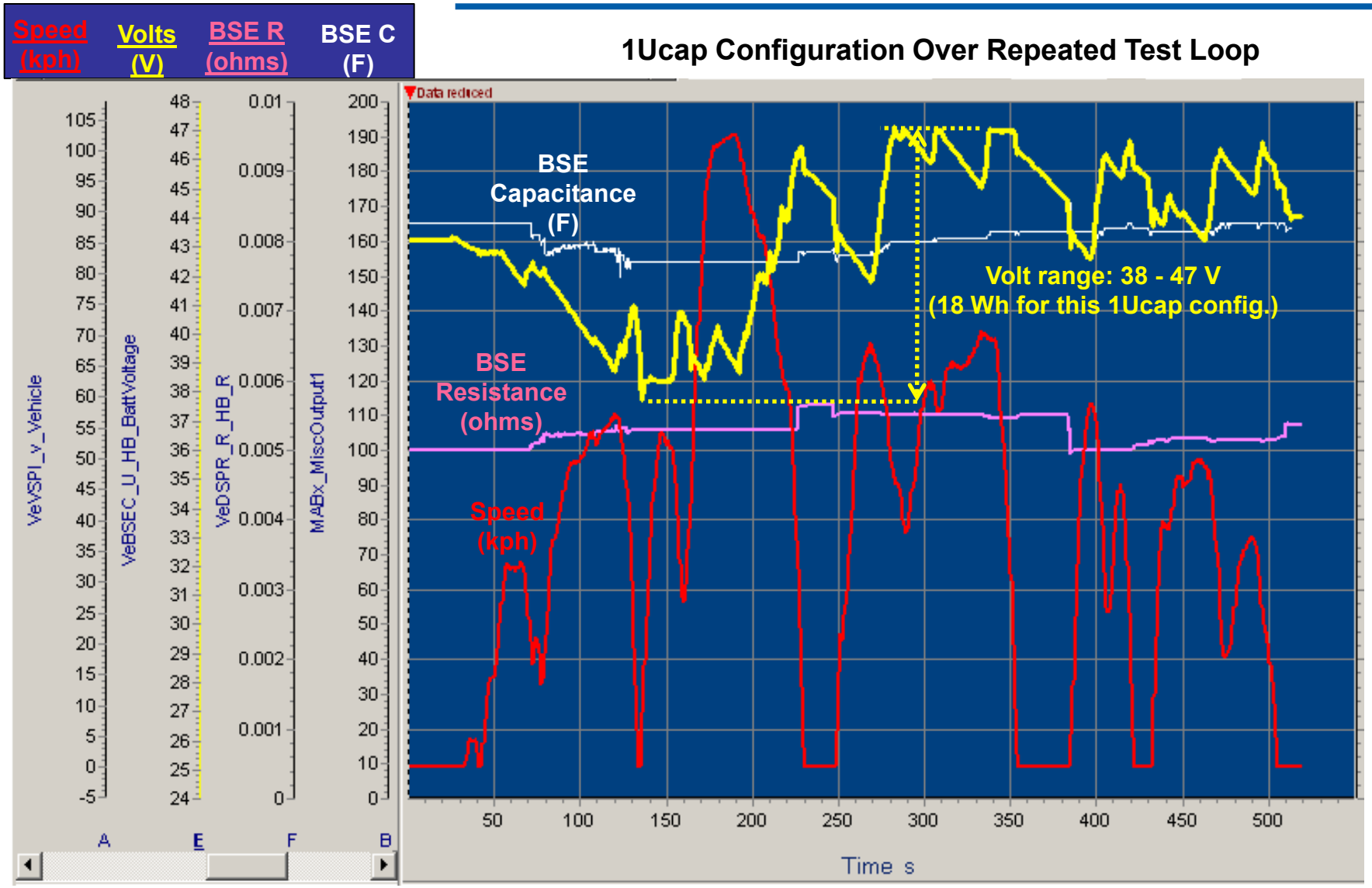


* Support from Jim Yurgil (GM) greatly appreciated

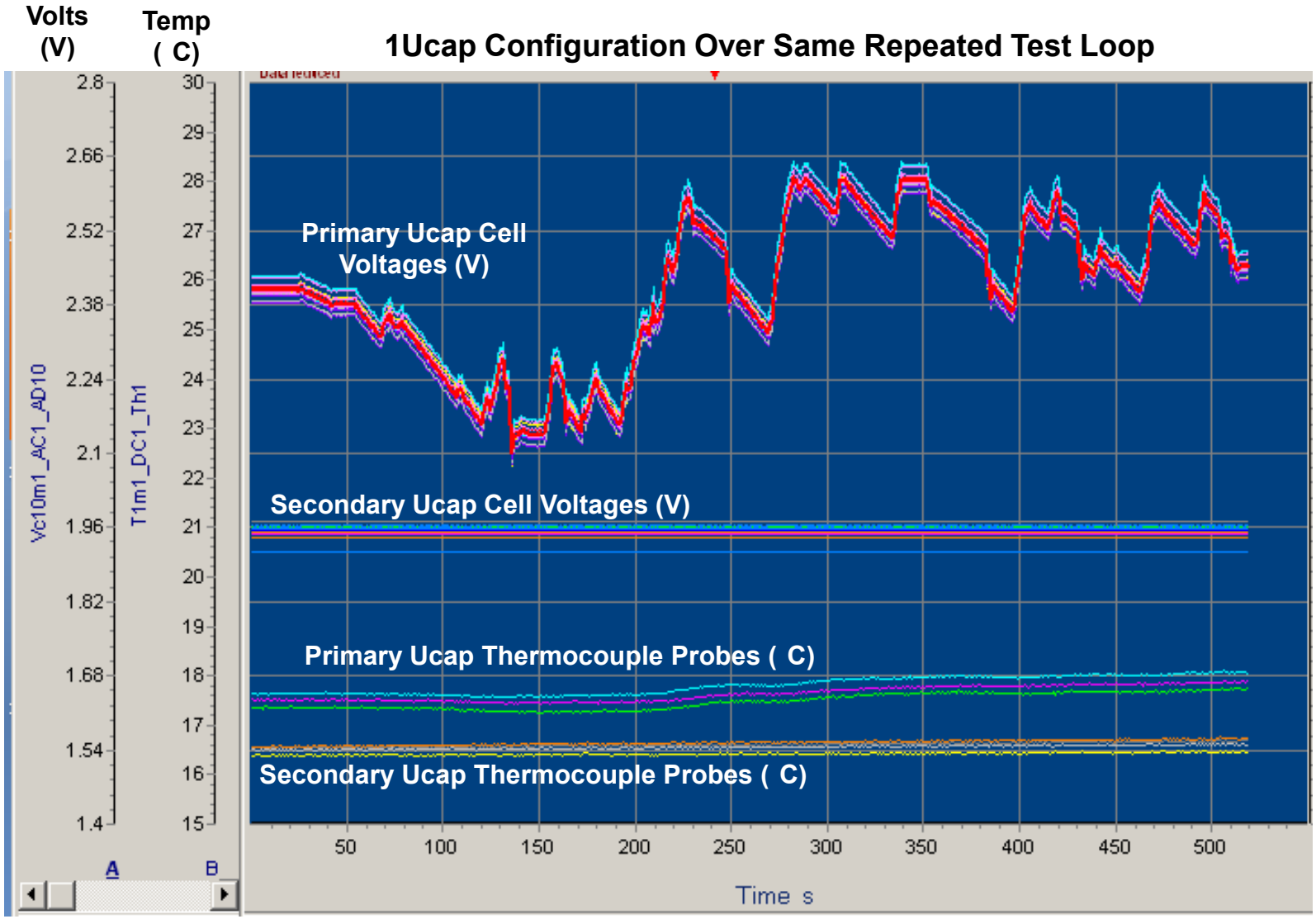
In-Vehicle Testing: Repeated for both baseline NiMH case and Ucap case(s) with adjusted calibrations

- On-road
  - Shakedown testing and calibration setting
- Ambient (24°C) dyno tests
  - City (FTP) cycle
  - Highway (HFET) cycle
  - US06 cycle
- Very cold (-20°C) dyno tests
  - City (-20°C FTP) cycle
- Acceleration comparison
  - ¼ mi time
  - 0-60 mph time
  - 40-60 mph time

On-road Shakedown Testing and Calibration Setting:
Good performance achieved



In-Vehicle Ucap Temperature and Cell Voltage Performance Consistent with Bench Observations



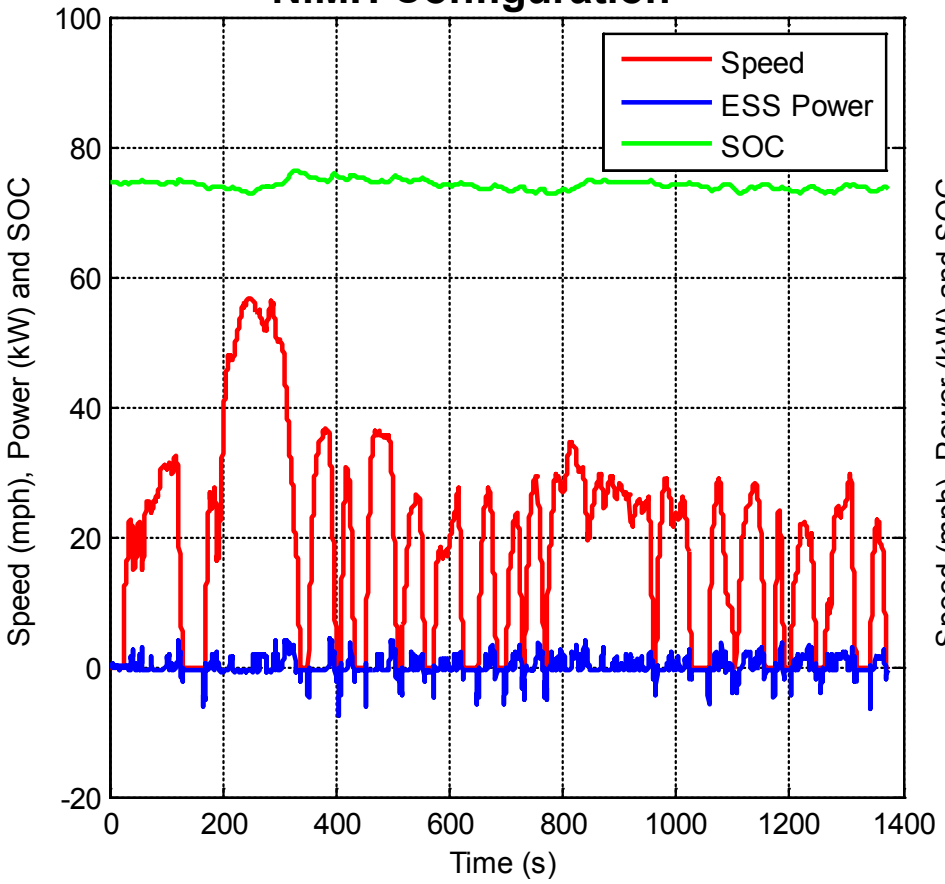
NiMH vs. Ucap In-Vehicle Power Output

Shown for second (hot start) UDDS in FTP-75 test

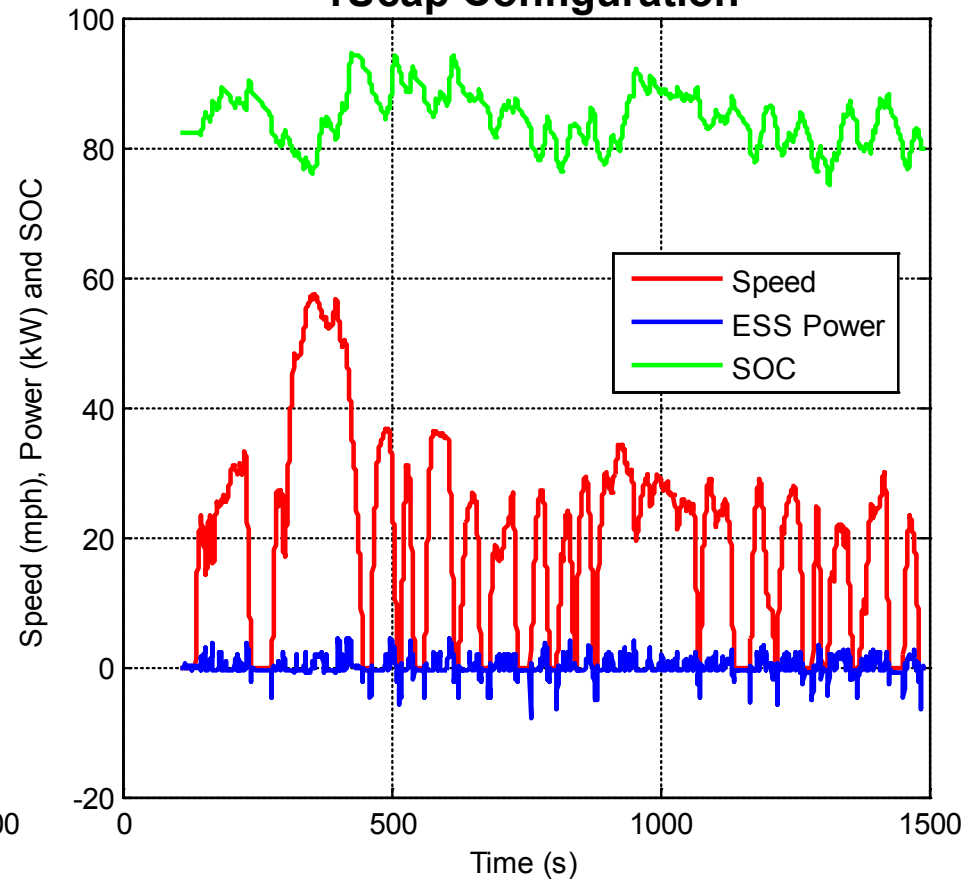
Provided same in-vehicle mpg

35 Wh System

NiMH Configuration



1Ucap Configuration

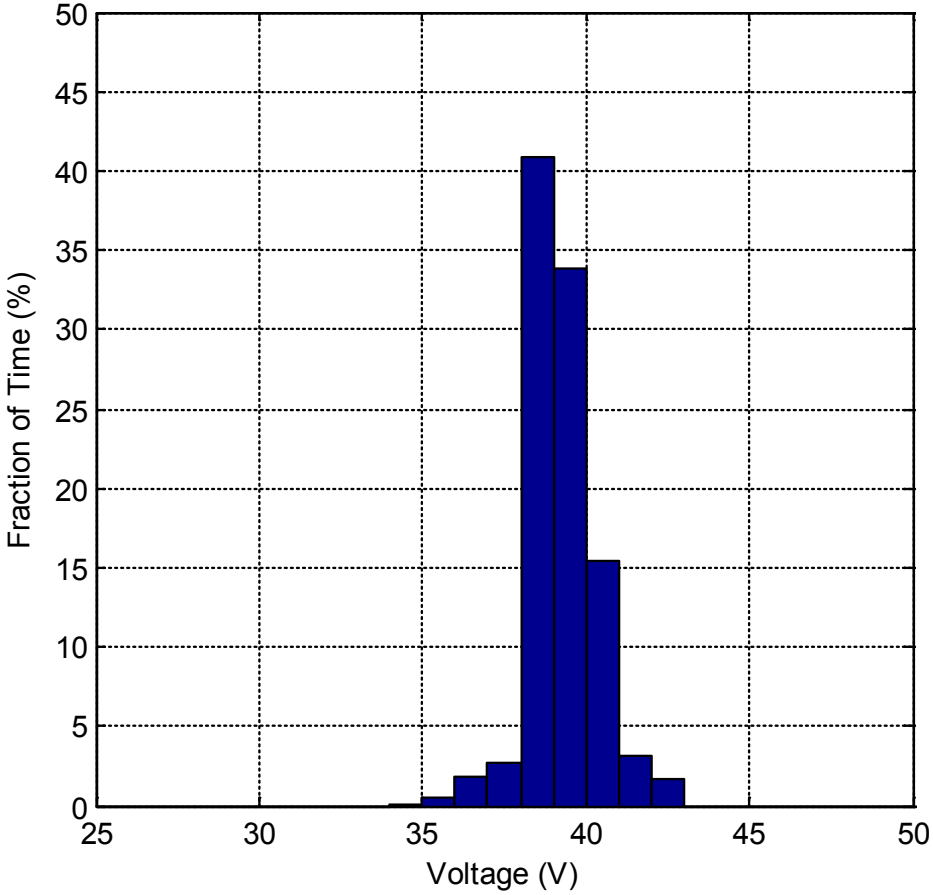


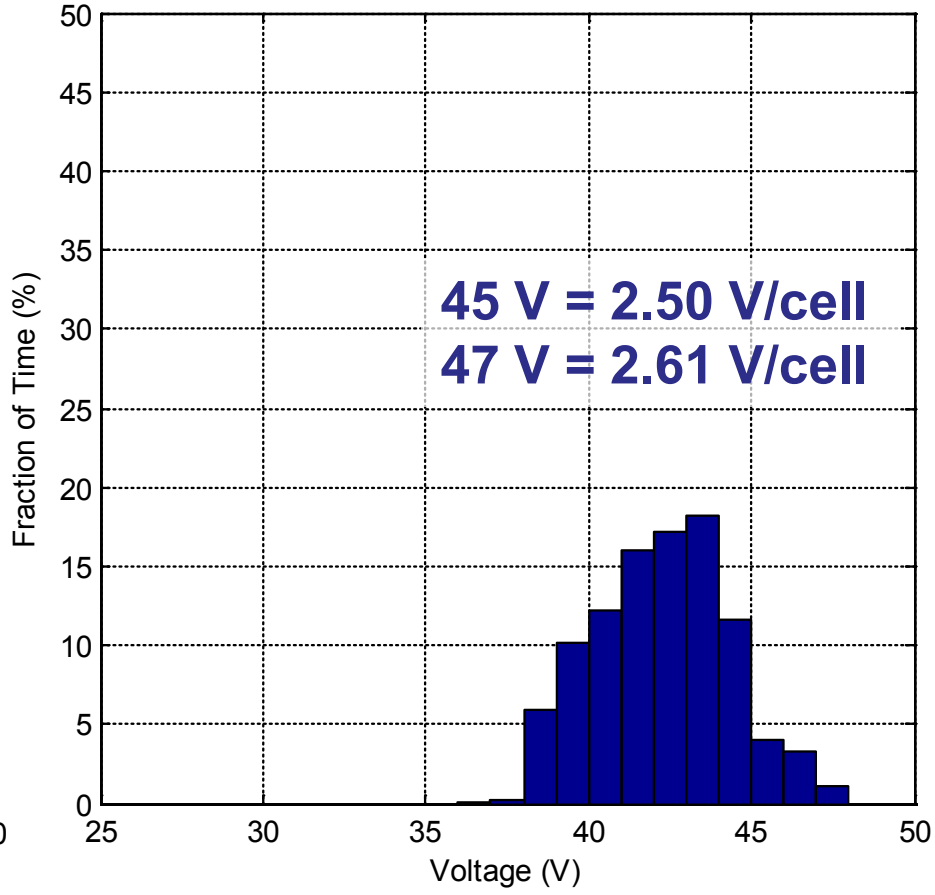
Voltage Histogram Comparison

Shown for second (hot start) UDDS in FTP-75 test

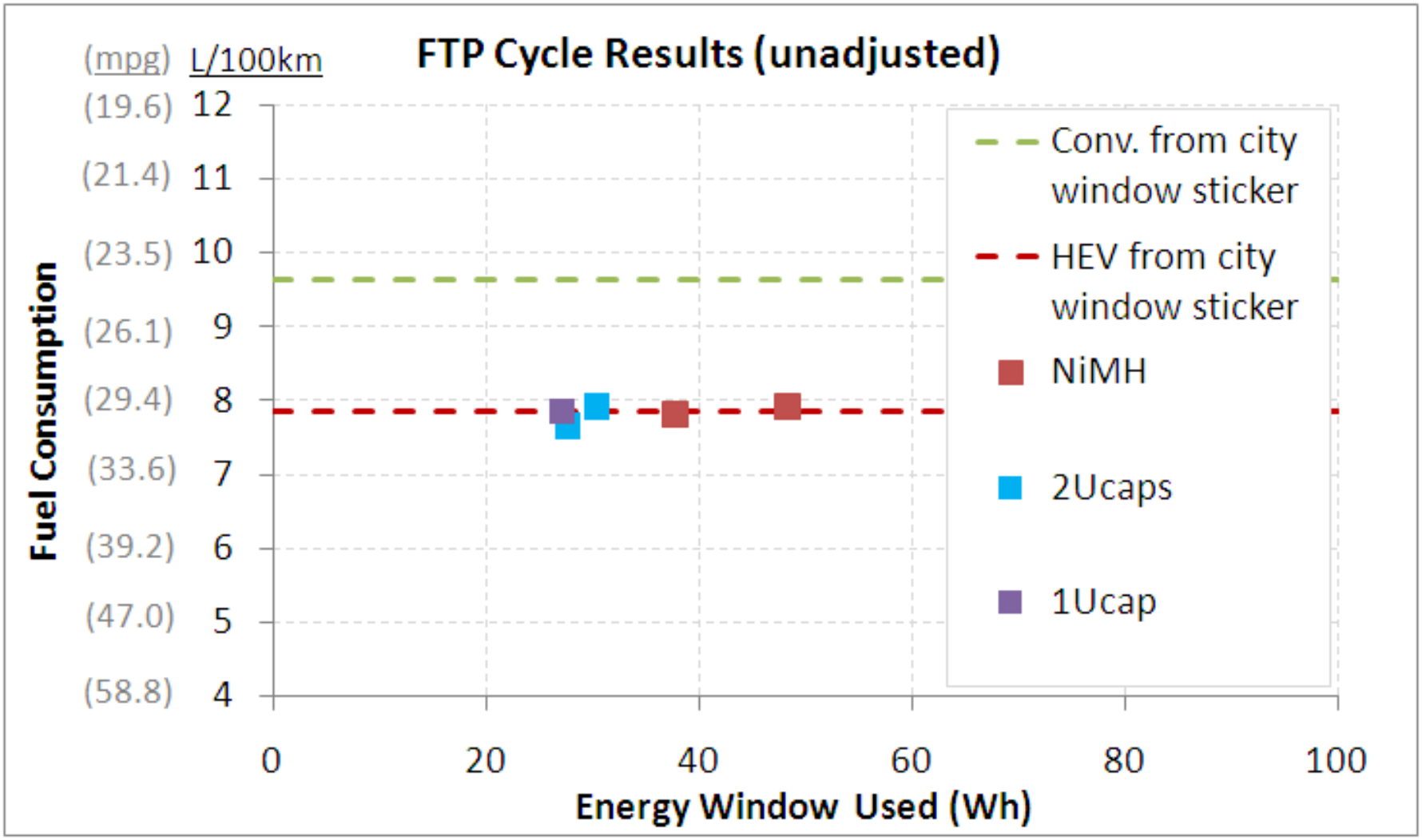
NiMH Configuration

1Ucap Configuration

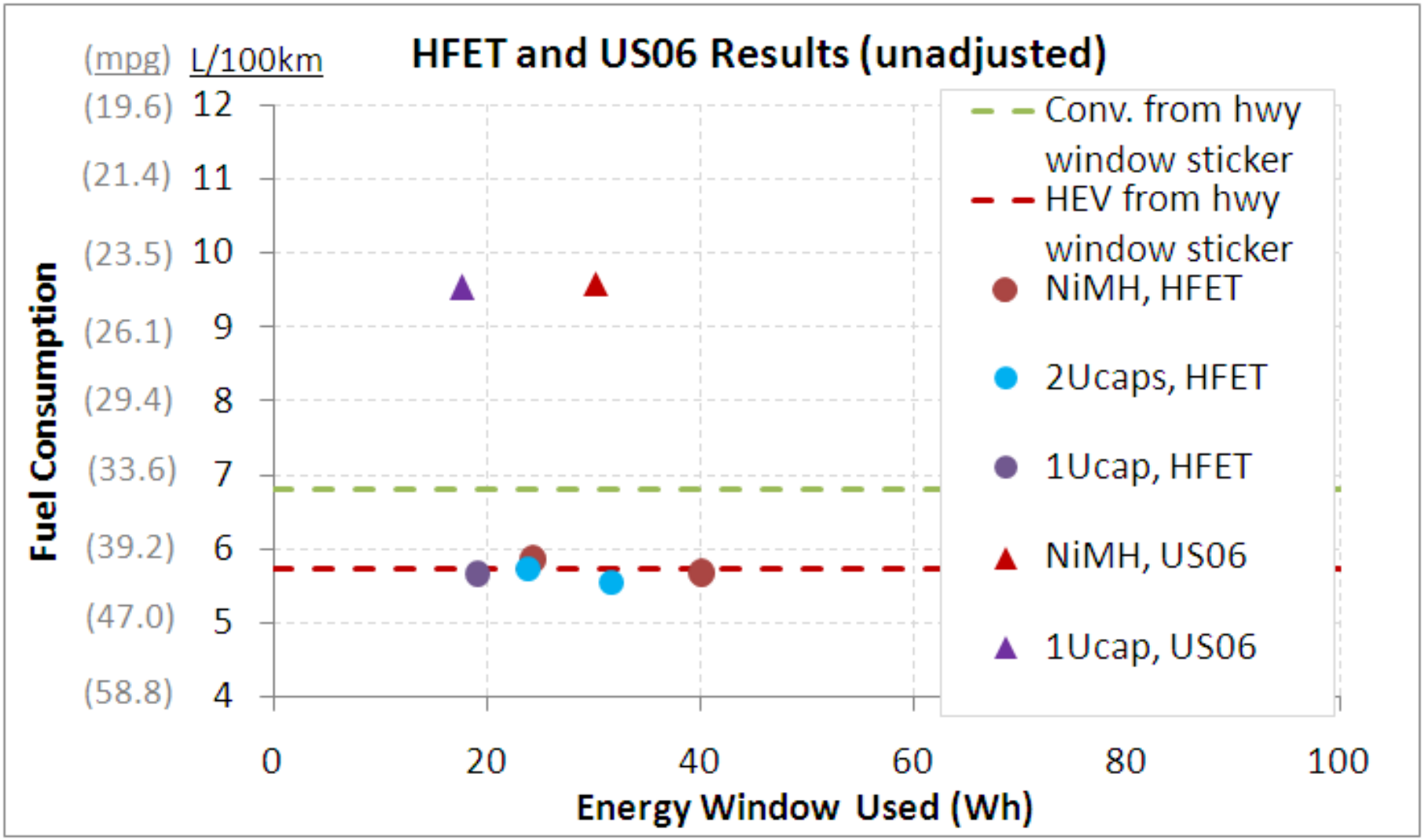




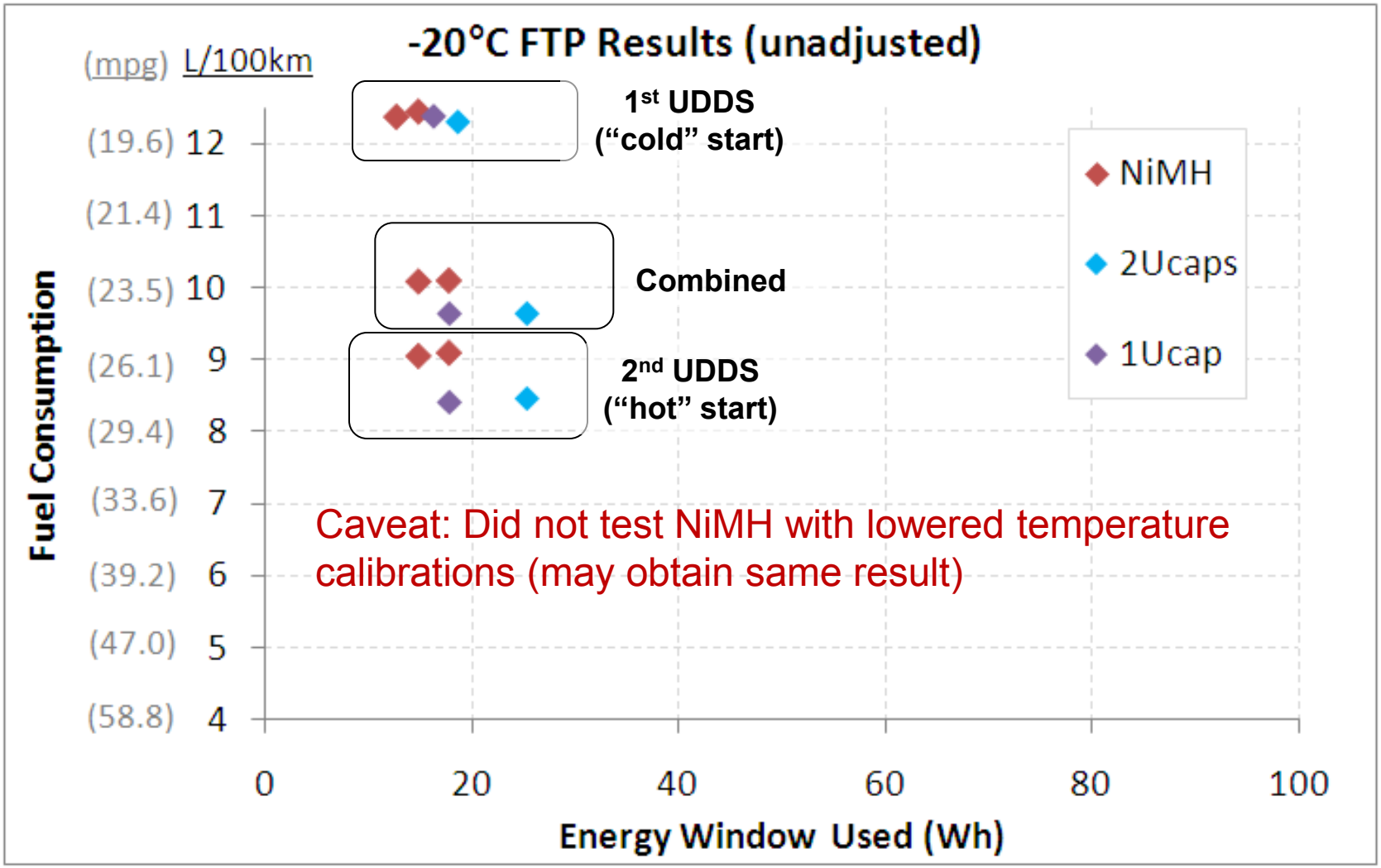
Dyno Testing Comparison for All Three Configurations: FTP drive cycle (24 C ambient)



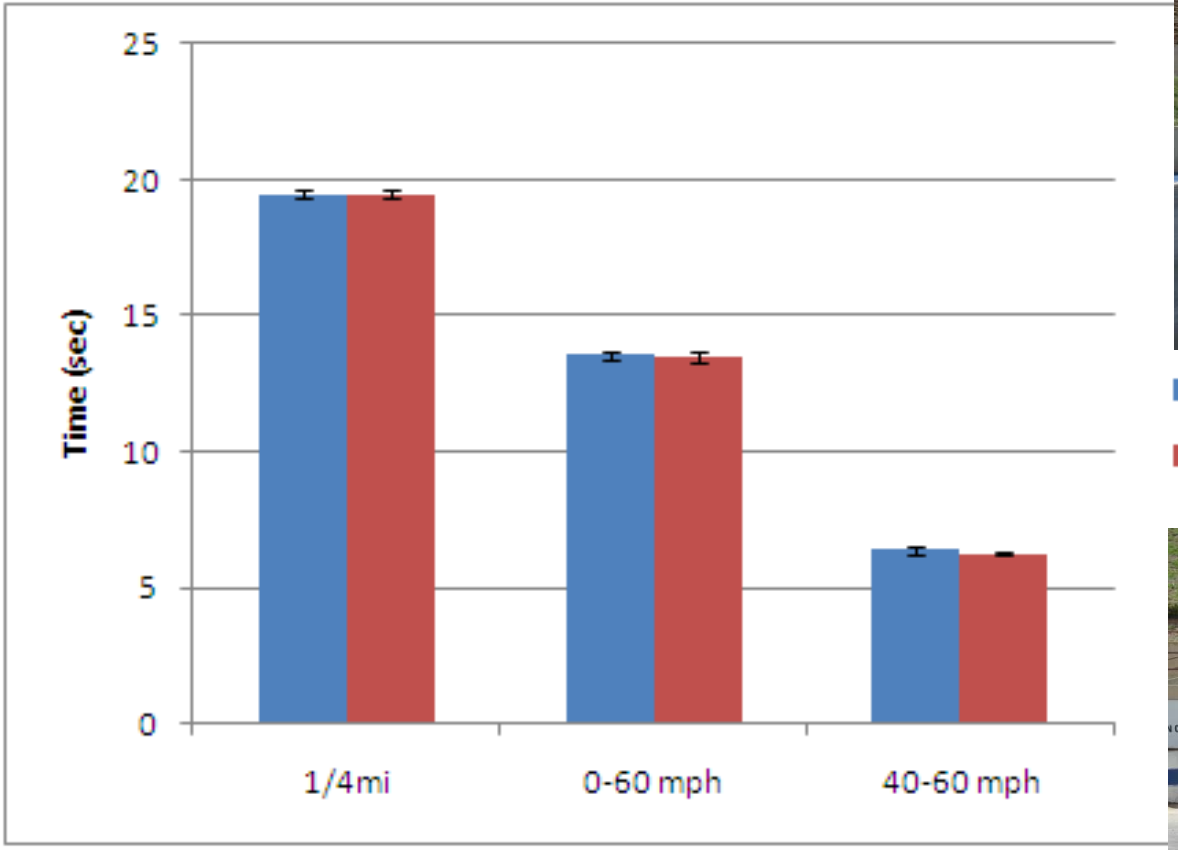
Dyno Testing Comparison for All Three Configurations: Highway and US06 drive cycles (24 C ambient)



Very Cold Dyno Testing Comparison:
Lowered temperature calibrations enabled a difference in operation



Acceleration Performance Comparison:
No difference between NiMH and Ucap configurations



Summary

- BAS system provides significant benefit (25% window sticker mpg rise*)
- Successfully completed Saturn Vue BAS HEV conversion
  - Bench tested and integrated low-energy Ucaps
  - No additional DC/DC converter required
  - Able to switch between three energy storage configurations
- Found Ucap HEV performance comparable to stock NiMH HEV
  - Achieved same fuel economy (generally only using 18-25 Wh)
  - Matched driving performance
- Room for further exploration
  - Larger motor? Smaller Ucap?
  - Look more at cold temp and off-cycles
  - Try a different vehicle platform

The Ucap HEV performed equal to or better than the stock battery HEV configuration

* Caveat: Window sticker difference does not necessarily equate to hybridization improvement.

Acknowledgements

- GM
  - Jim Yurgil, Damon Frisch
  - Mike Reynolds, Andrew Namou
  - Mark Verbrugge, Shawn Hawkins
  - Bret Detrick (on-site with dSPACE)
- Maxwell
  - Michael Everett, John Miller
  - Uday Deshpande
- NREL
  - Mark Mihalic, John Ireland
  - Kristin Day, Charlie King
- Department of Energy
  - David Howell (funding for initial USABC/ DOE simulations laid the groundwork for the vehicle conversion project)

Extra Slides

Project Approach

Project Phase	Related Activities
System Design	Ucap energy storage system design study
Hardware Bench-top Evaluation	Hardware acquisition and bench-top verification
Vehicle Conversion	Acquiring vehicle and integration of Ucap system into vehicle
Vehicle Test Results & NiMH Comparison	Baseline testing; Ucap system in-vehicle performance testing; Modeling; Trade-off analysis of different system designs

NiMH vs. Ucap Voltage and Cumulative Energy Comparison

Shown for second (hot start) UDDS in FTP-75 test