Fuel Economy and Performance of Mild Hybrids with Ultracapacitors

Simulations and Vehicle Test Results

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Presentation Outline

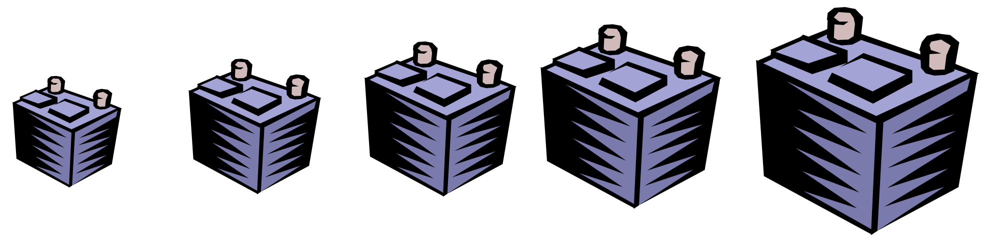
- Background
- Project Overview and Objectives
- Details of Project Phases
  - System design
  - Hardware bench-top evaluation
  - Vehicle conversion
  - Vehicle test results
  - Comparison with NiMH vehicle
- Summary

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

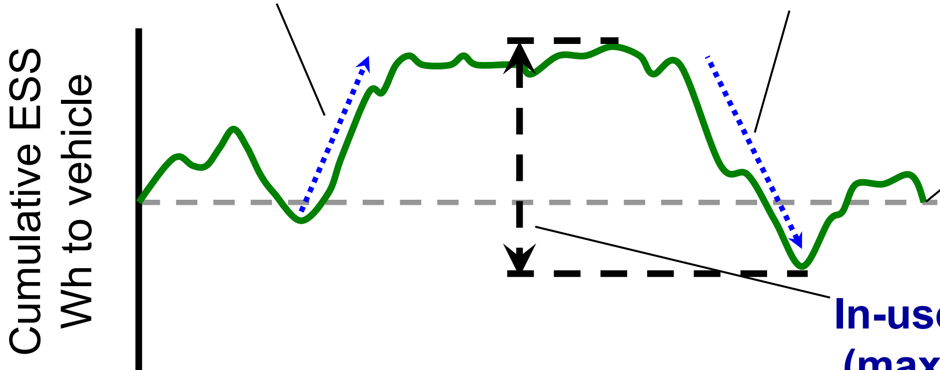


Use a range of ESS** sizes (different energy content cases)

Observe fuel and ESS energy usage for each case:

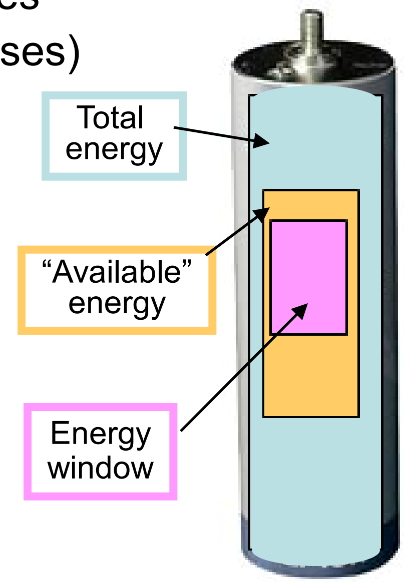
Energy out for electric launch/assist

Energy return from charging/regen.



Charge sustaining over cycle

(no net energy use)

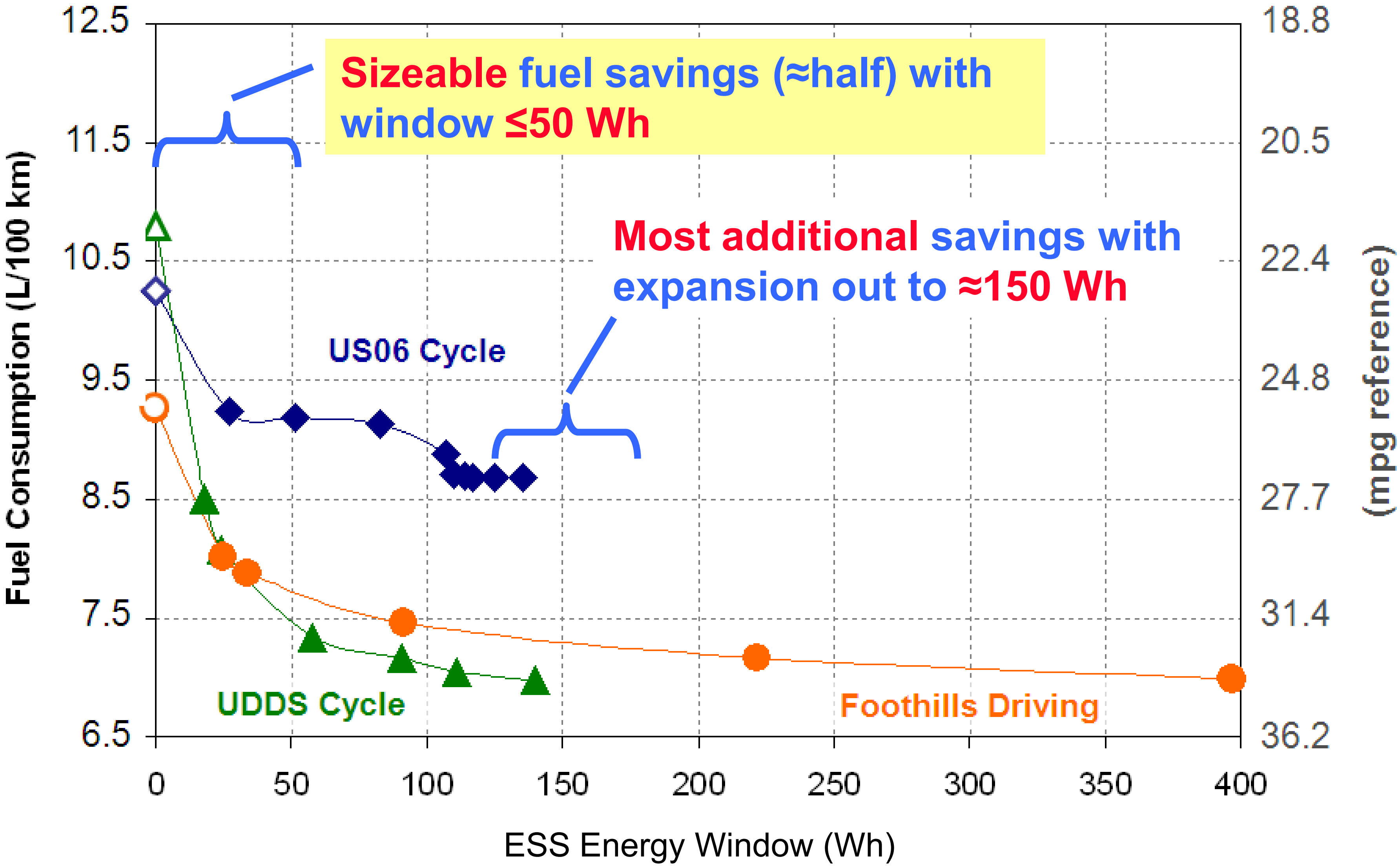


In-use "Energy Window" defined by (max – min) for the particular cycle

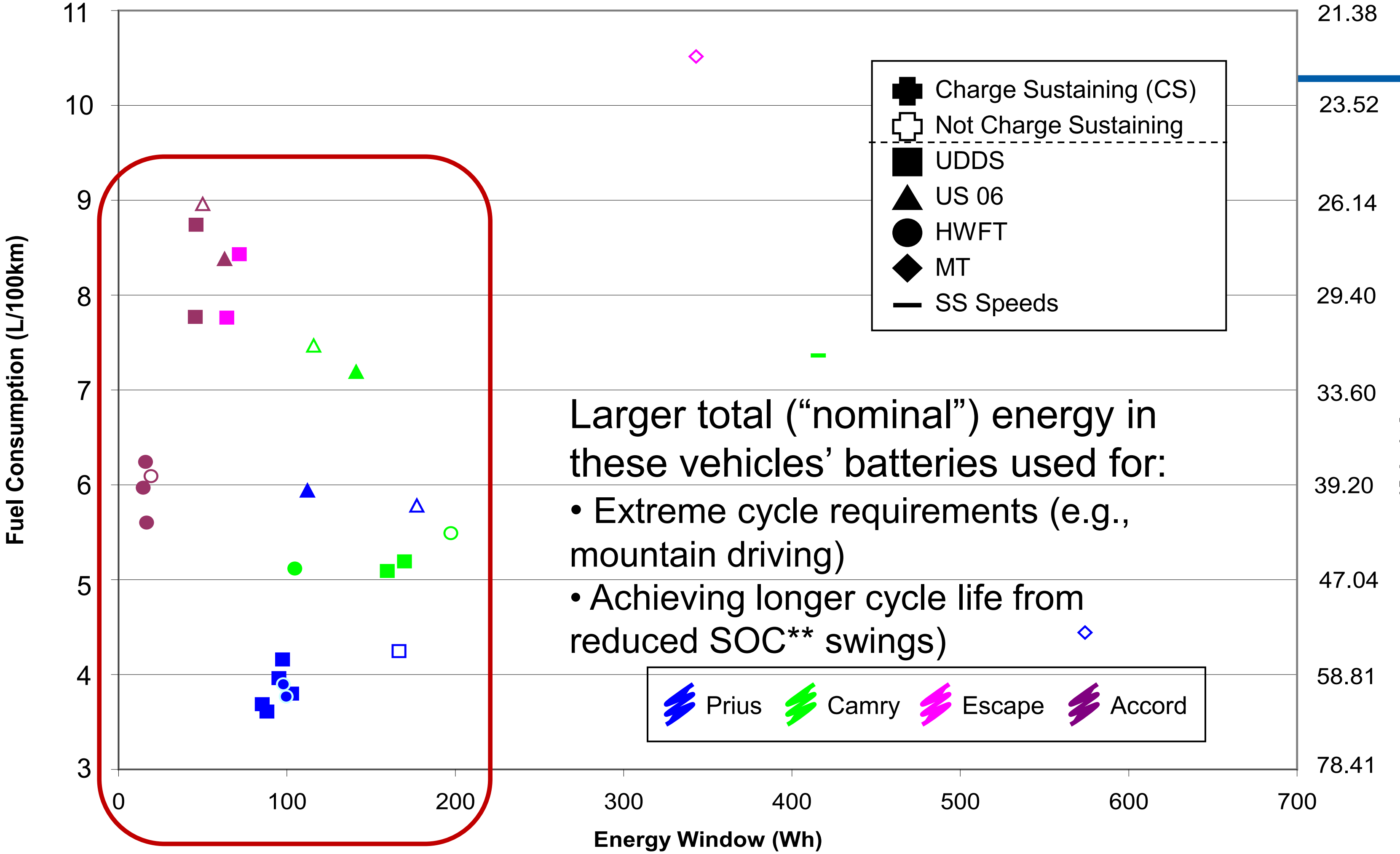
* USABC = United States Advanced Battery Consortium; DOE = U.S. Department of Energy

** ESS = Energy Storage System

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



Background:
Results consistent with production HEV dyno test data*



- Data analysis confirmed **<u>in-use energy window <200 Wh</u>** in all charge sustaining tests for these vehicles and drive cycles

* Mike Duoba, ANL provided access to some of the raw dynamometer test data

** SOC = State of Charge

Background:
Observations from the USABC/DOE HEV energy window study

- Hybridization can result in sizable fuel economy improvement even with a small energy window ESS
- Significant fuel savings could be achieved with a 150 Wh high power ESS, with fuel savings tapering off at energy windows >200 Wh
- 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
  - Energy comes along with sizing for power requirements (particularly at cold temperatures)
- Required over-sizing to achieve cycle life and power capability contributes to battery cost
  - 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)

Ultracapacitor Conversion and Vehicle Testing Project

- NREL discussed with GM the rationale of demonstrating a mild hybrid with Ucaps instead of batteries
  - Reasonable fuel economy
  - Lower long-term projected costs
  - Superior cycle life
  - Better cold temperature performance

- A project plan was formulated to replace batteries with Ucaps in a mild hybrid vehicle and evaluate its fuel economy and performance
- GM supported the project and provided funding, a vehicle, and technical support beginning in summer 2008
- Objective
  - **Evaluate use of ultracapacitors instead of batteries in a Saturn Vue BAS (belt alternator starter) Hybrid**

Production “Mild” BAS HEV System with NiMH Batteries Provides Significant Fuel Economy Benefit

Conventional

2007 Saturn Vue FWD

21 Combined

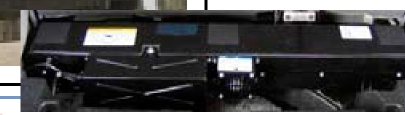
19 City

25 Hwy

≈ +25% mpg*

HEV

2007 Saturn Vue Hybrid



26 Combined

23 City

29 Hwy

2009 Model

22 Combined

19 City

26 Hwy

2009 Model

28 Combined

25 City

32 Hwy

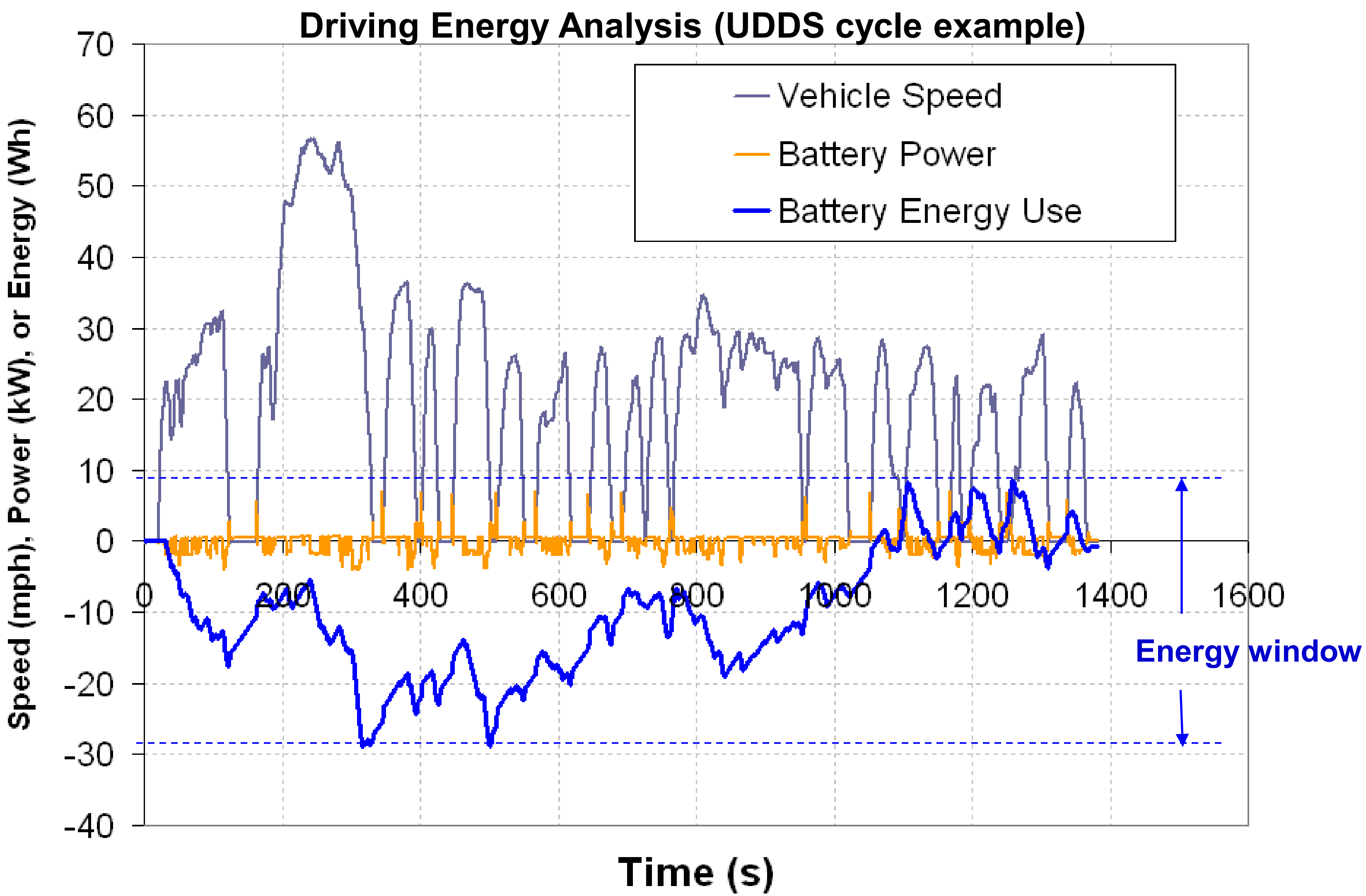
Could Ucaps provide similar fuel economy benefit? – YES!

* Caveat: Window sticker difference does not necessarily equate to hybridization improvement.
Data from www.fueleconomy.gov (using updated EPA numbers), accessed April 23, 2009.

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

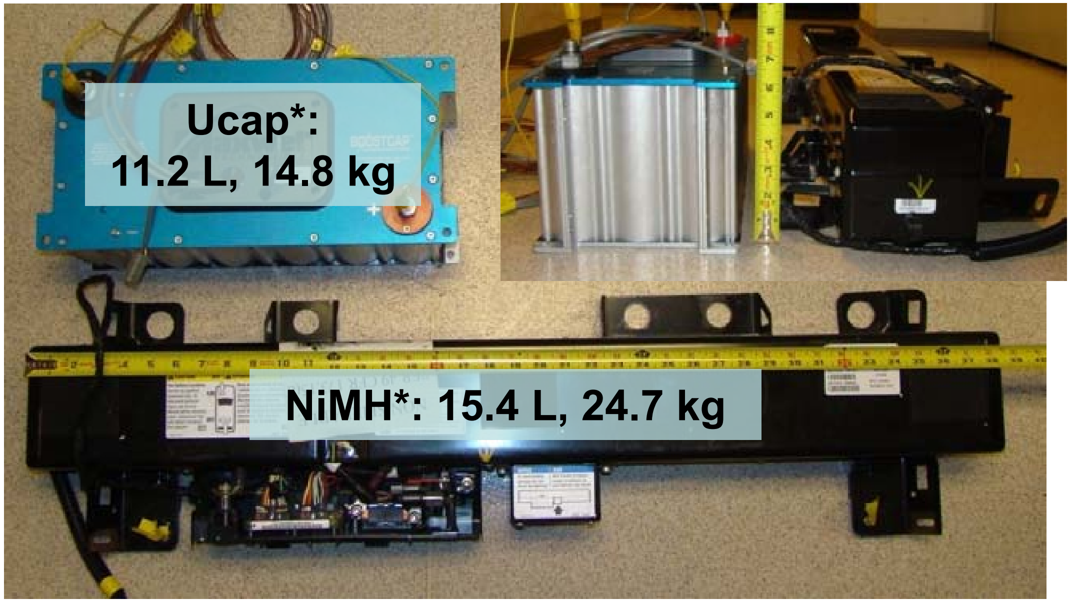
Analysis of Dyno Data* on a 2007 Vue Hybrid Indicated Energy Use ≈50 Wh or Less

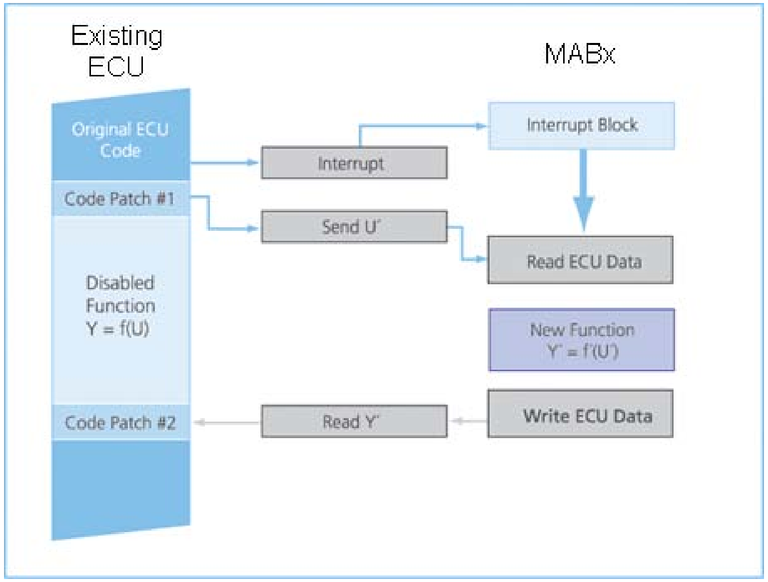


* From the aforementioned DOE-sponsored testing at ANL

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

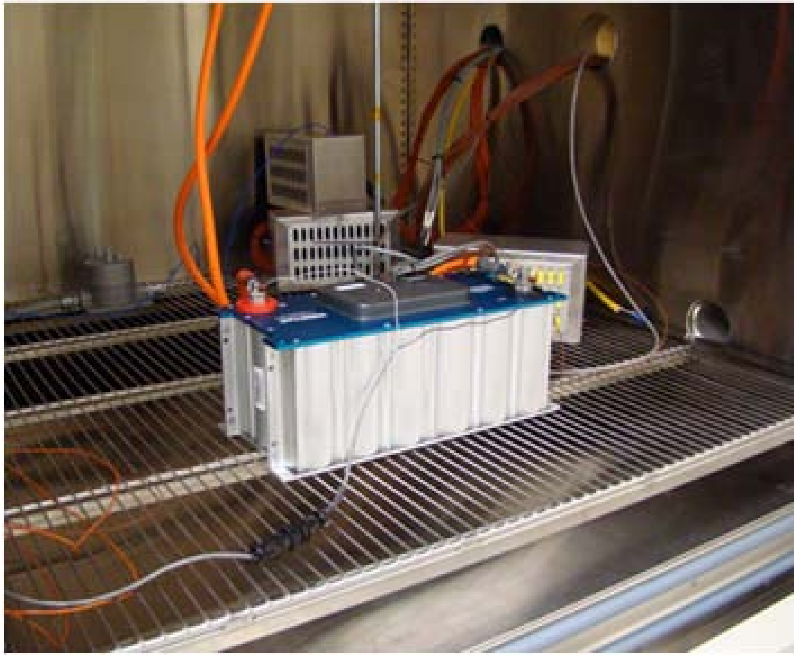


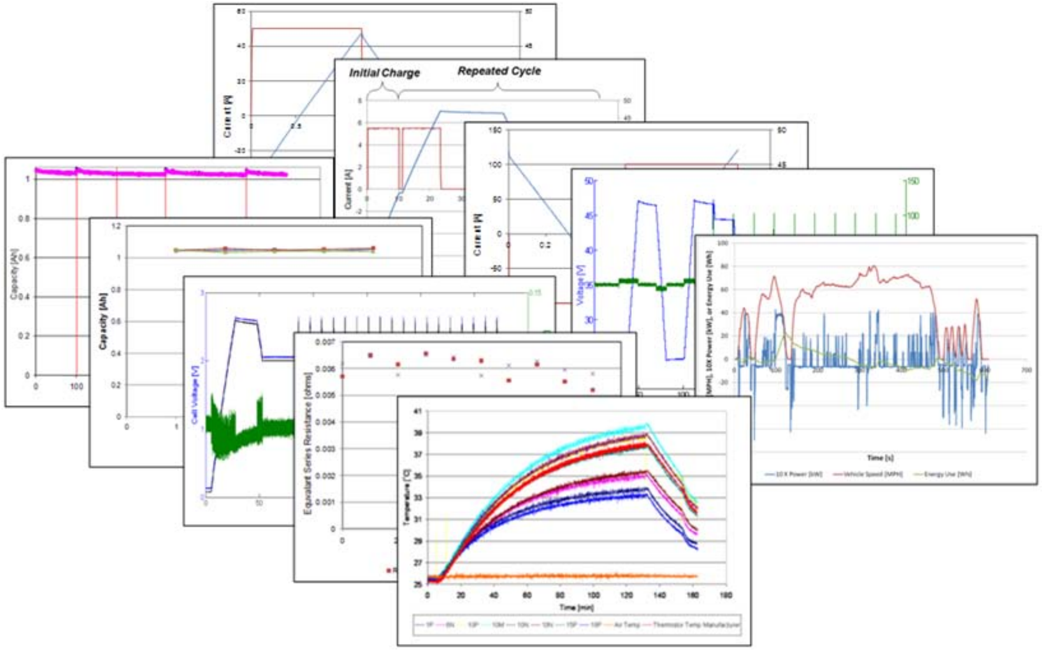


* Electronics, mounting brackets, etc. excluded from volume, but included in this mass comparison.

Performed Ultracapacitor Bench-top Evaluation

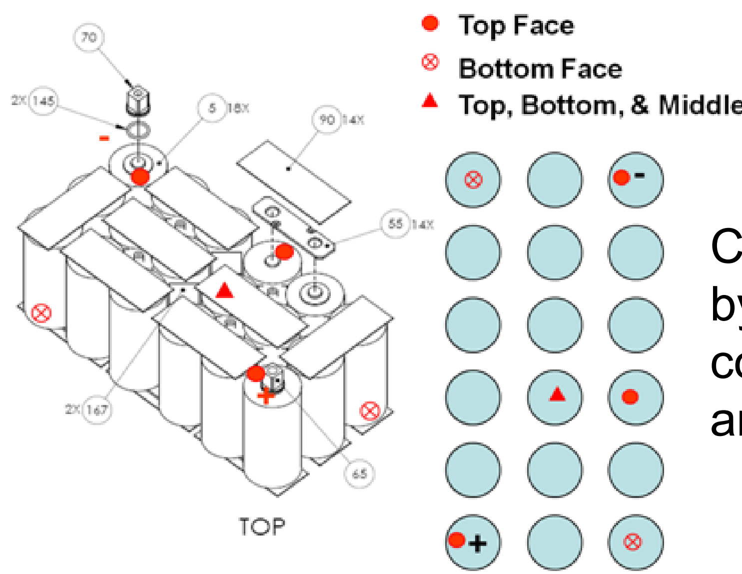
- Confirmed electrical performance
  - Detailed characterization testing on first module (capacity, voltage)
- Characterized thermal behavior of the passively cooled module
- Obtained data set for vehicle Ucap state estimator validation





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)
- Tests
  - Voltage range chosen for application: 24 V – 47 V
  - Multiple cycles and temperatures evaluated
  - Based on FreedomCAR Ultracapacitor Test Manual

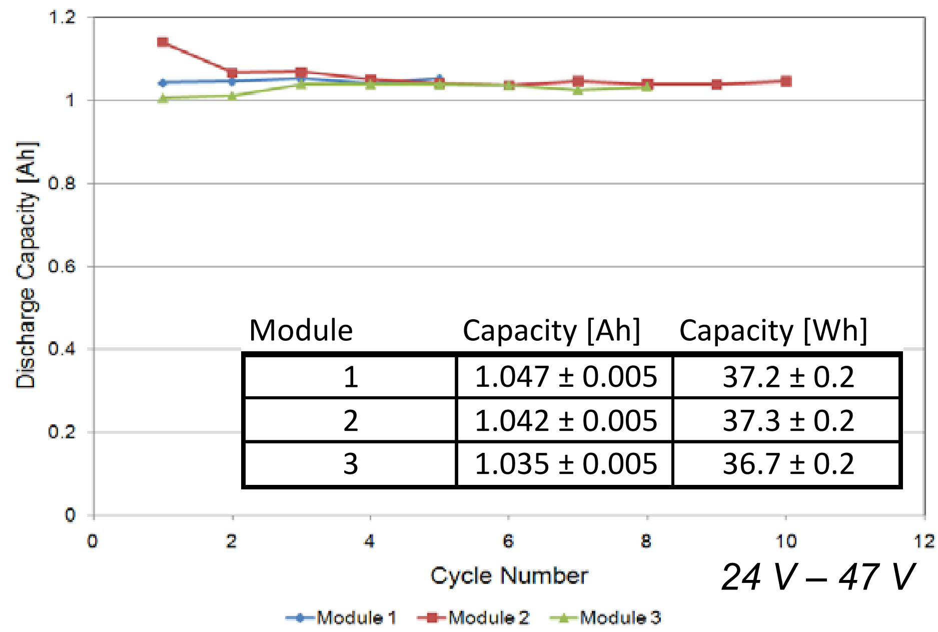


Cooling mostly by heat conduction to ambient

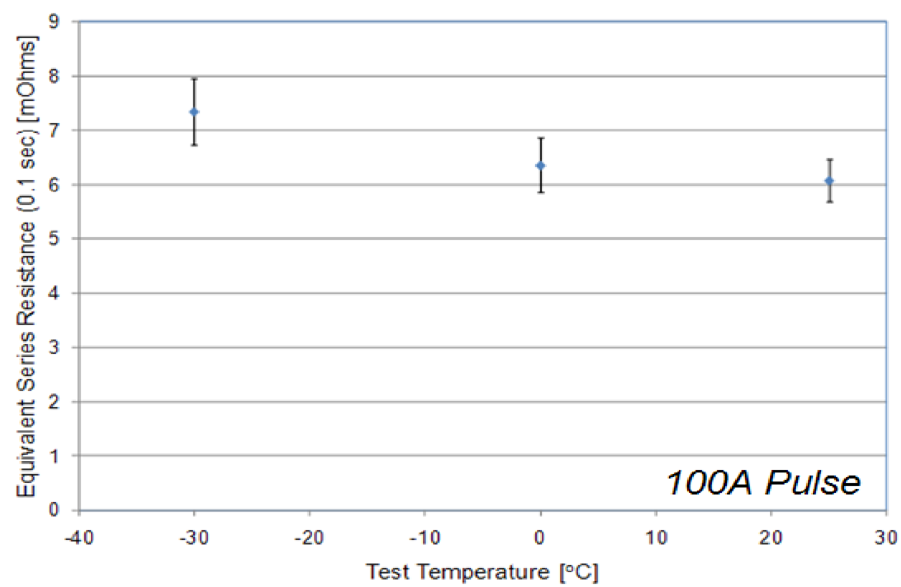
Module Electrical Characterization:

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

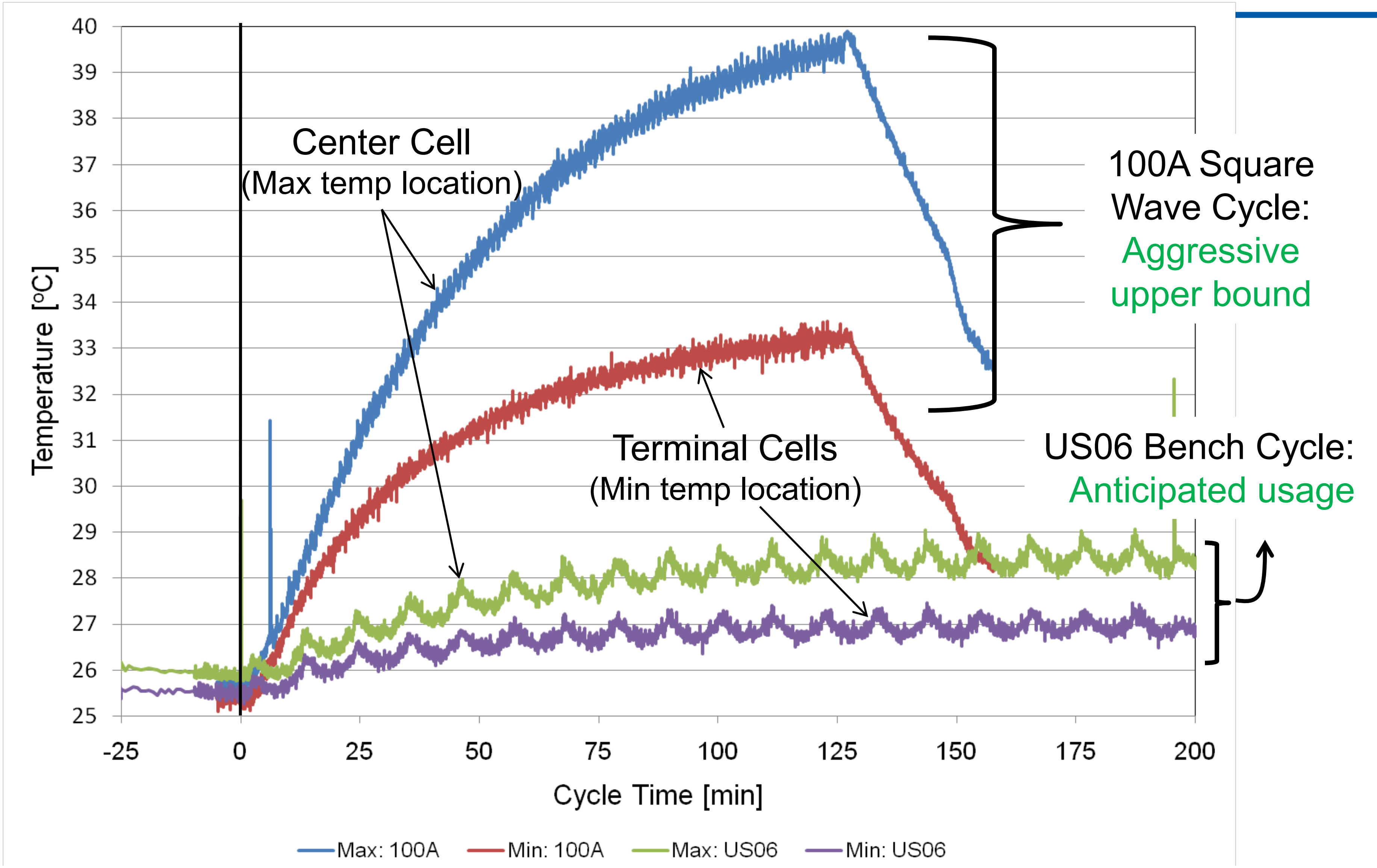


Module	Capacity [Ah]	Capacity [Wh]
1	1.047 ± 0.005	37.2 ± 0.2
2	1.042 ± 0.005	37.3 ± 0.2
3	1.035 ± 0.005	36.7 ± 0.2



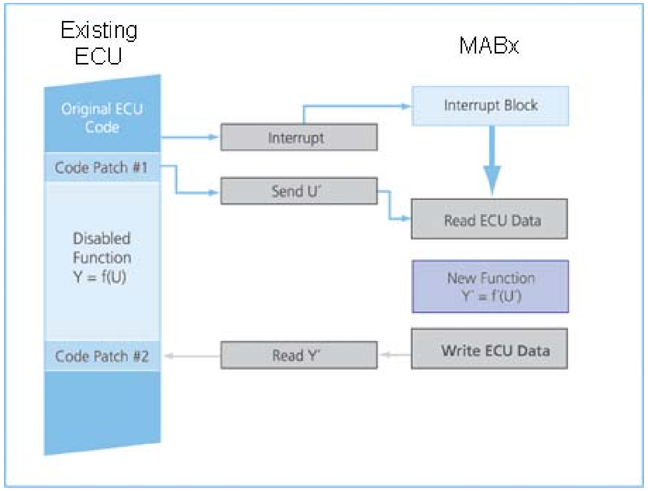
Temperature Performance Summary (25 C ambient)

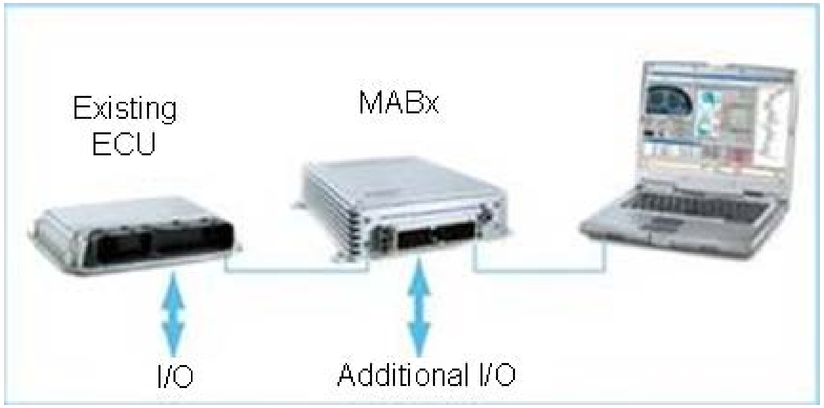
No heating problems anticipated in application



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

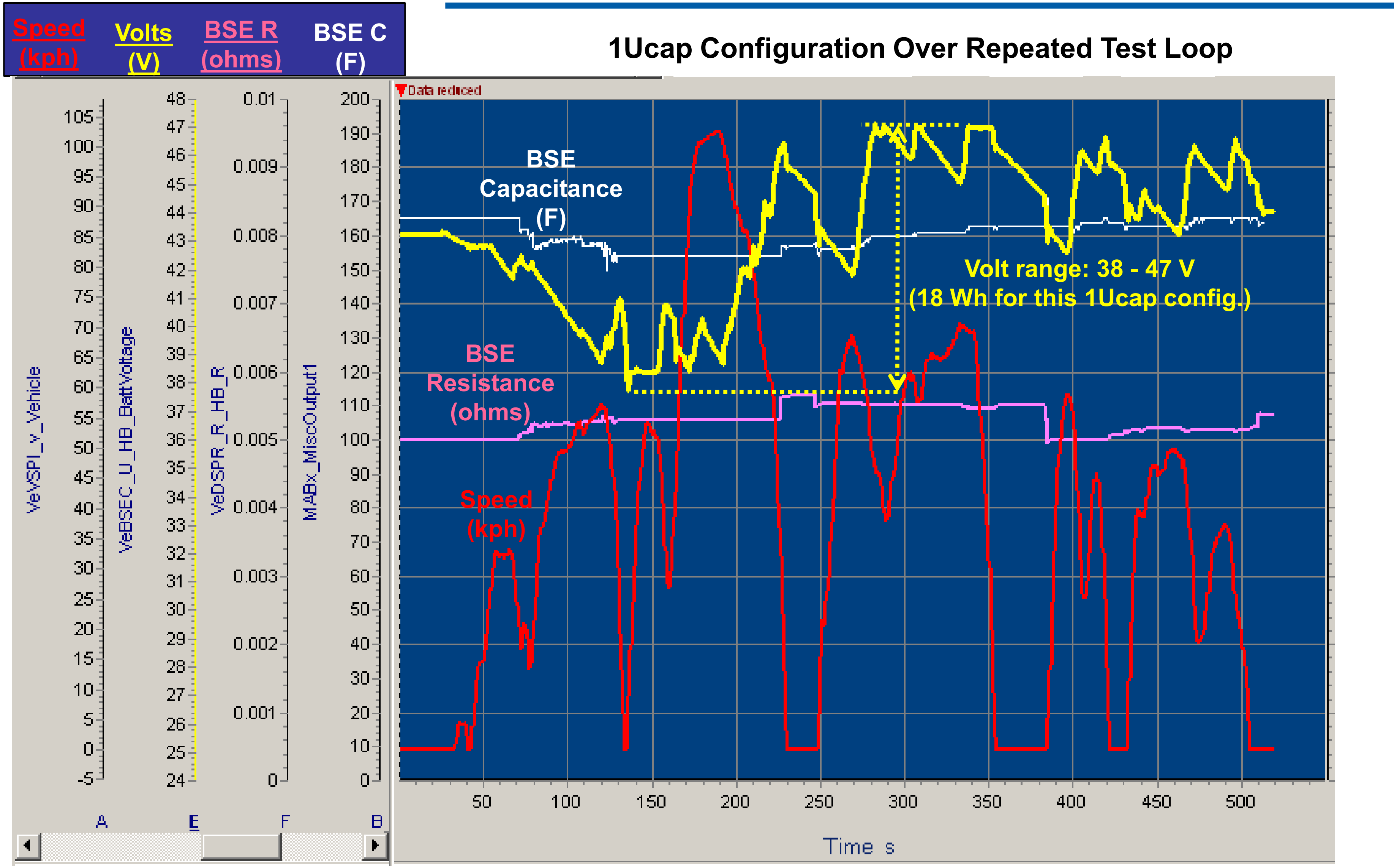
In-Vehicle Testing: Repeated for both baseline NiMH case and Ucap case(s) with adjusted calibrations

- On-road

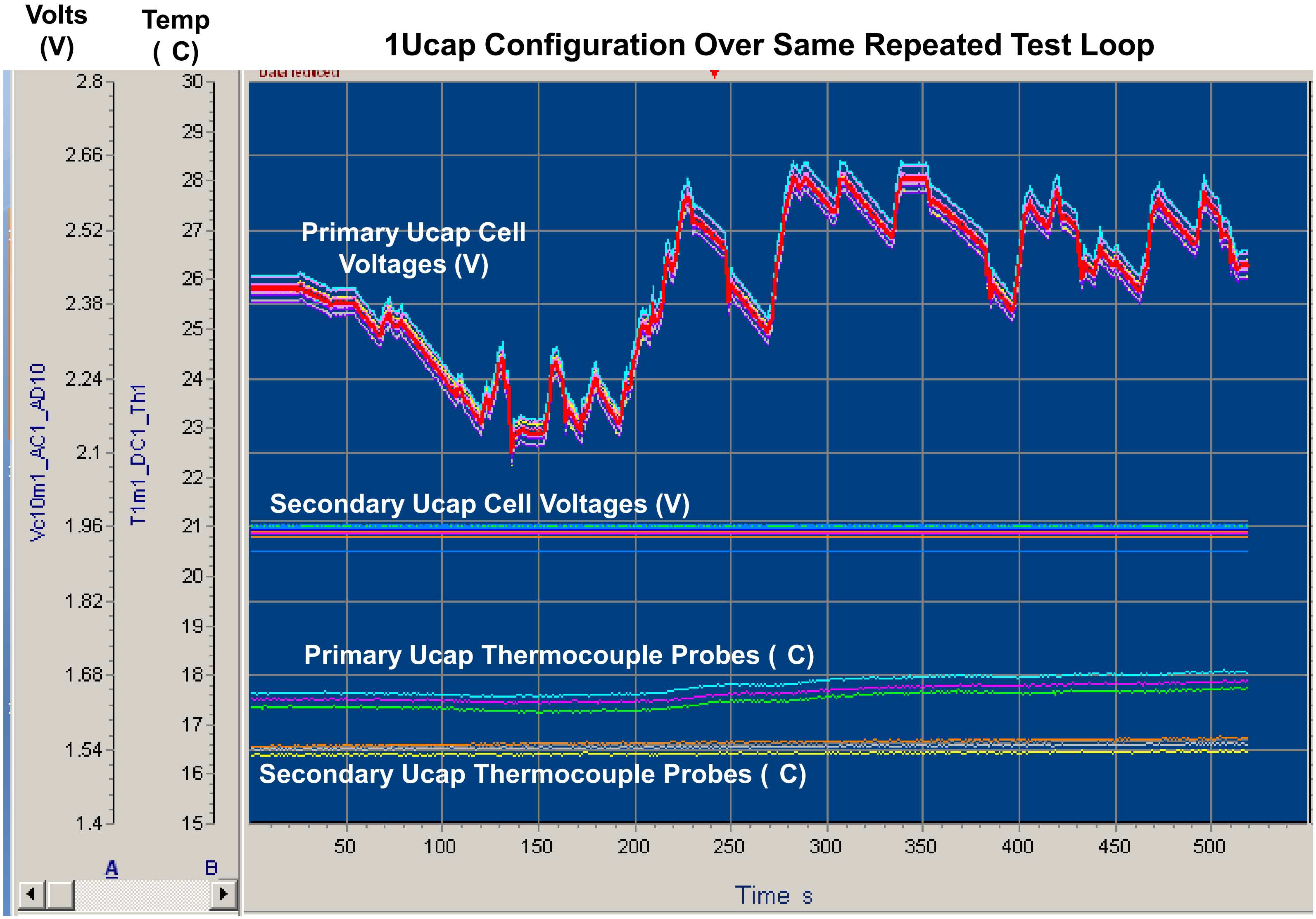
  - Shakedown testing and calibration setting
- Ambient (24°C) dyno tests
  - City (FTP) cycle
  - Highway (HFET) cycle
  - US06 cycle
- Very cold (-20°C) dyno tests
  - City (-20°C FTP) cycle
- Acceleration comparison
  - 0-60 mph
  - 40-60 mph

On-road Shakedown Testing and Calibration Setting

Good performance achieved



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

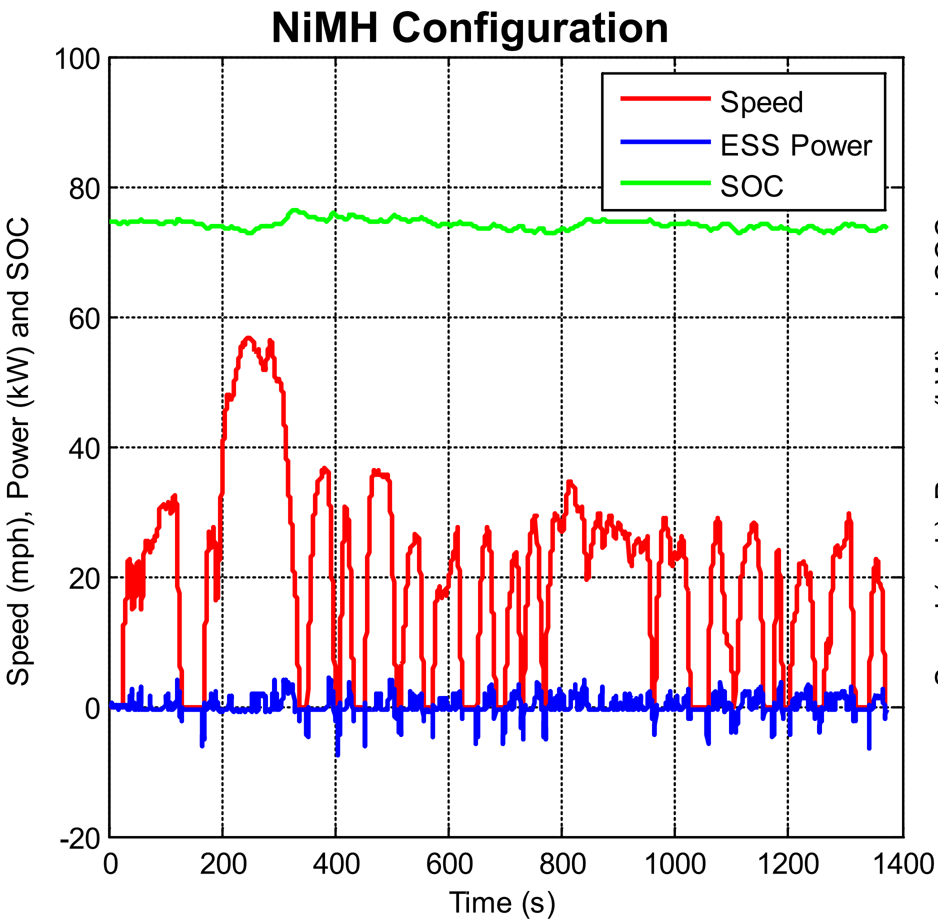


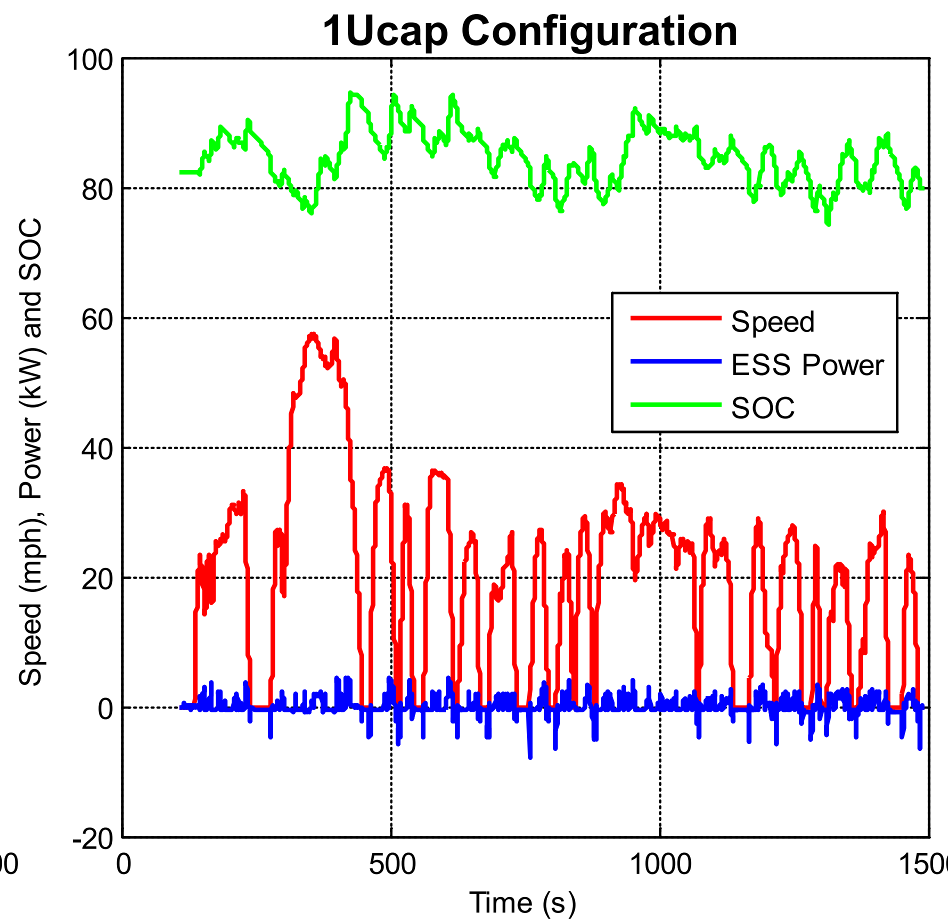
NiMH vs. Ucap In-Vehicle Power Output

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

← Provided same in-vehicle mpg →

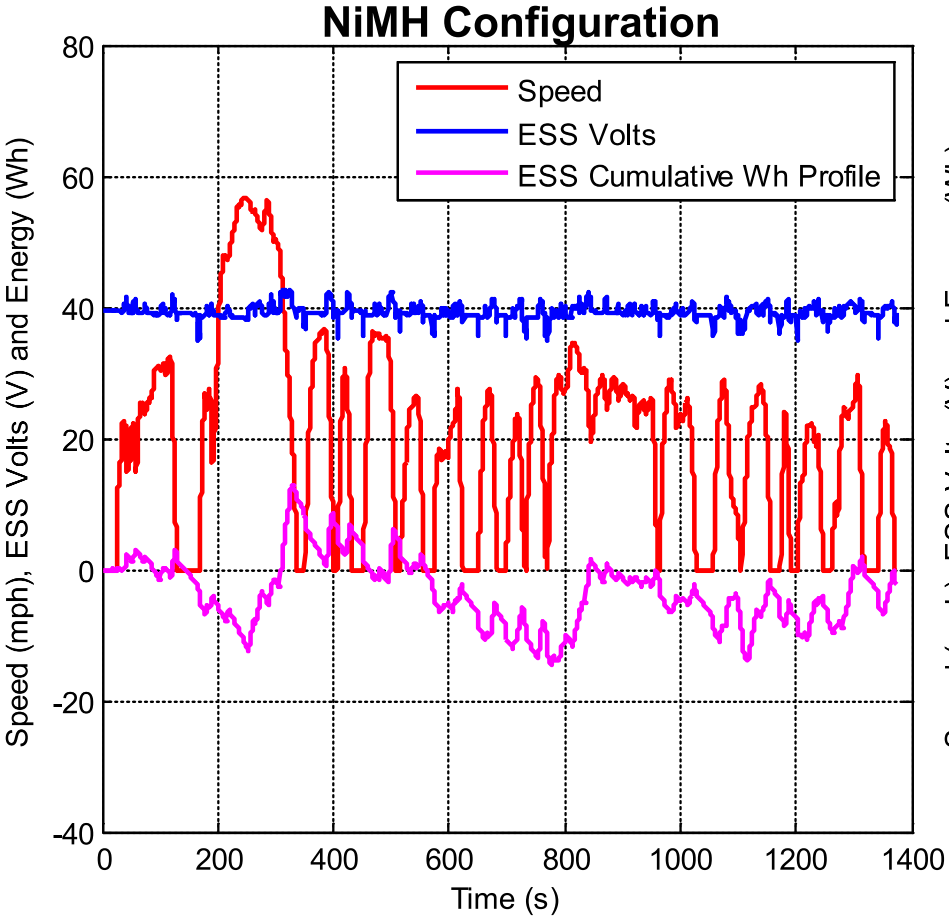
35 Wh System

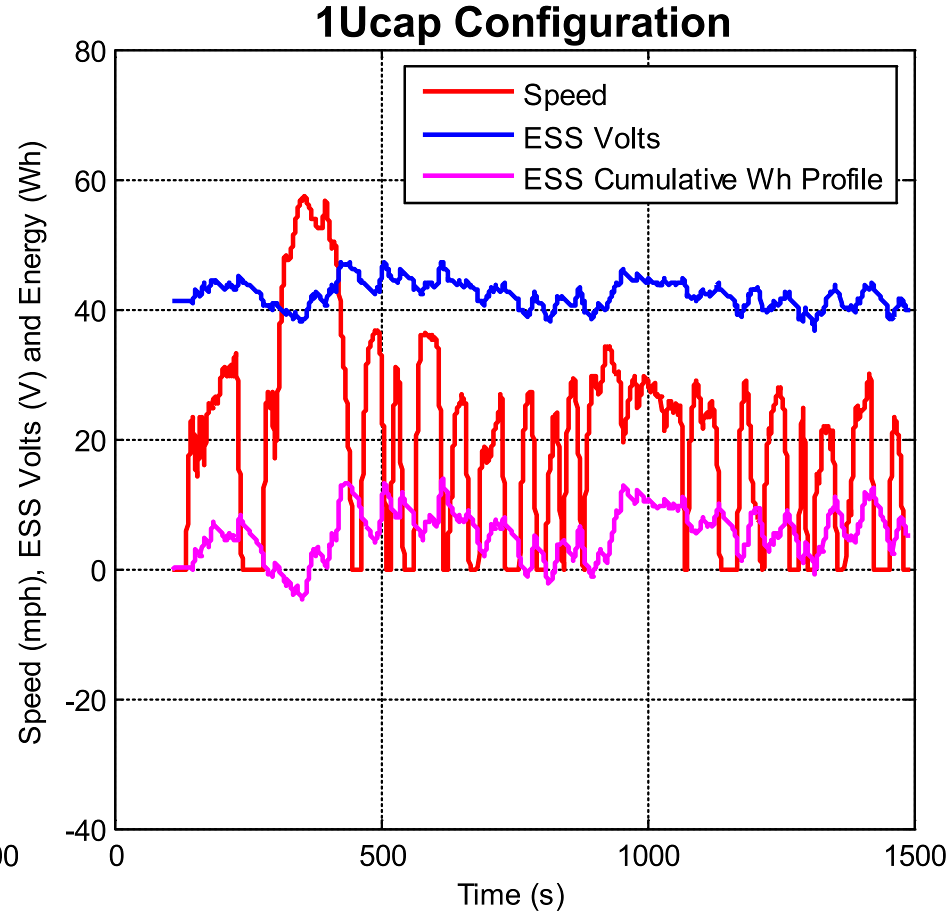




NiMH vs. Ucap Voltage and Cumulative Energy Comparison

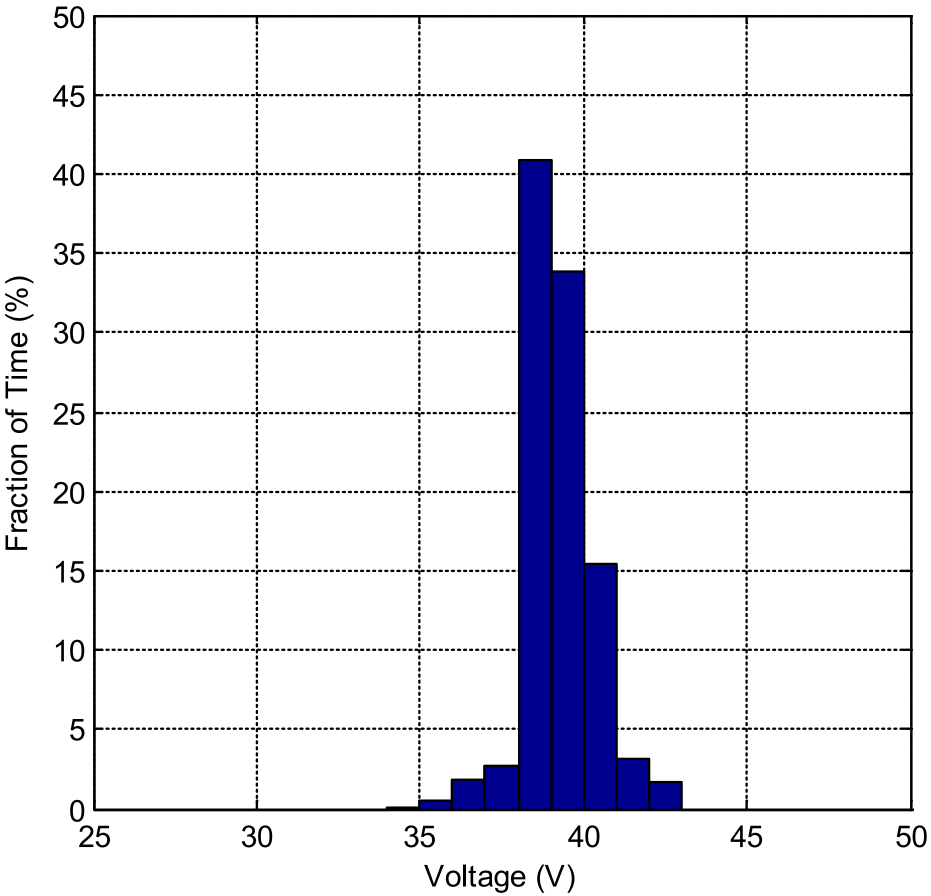
Shown for second (hot start) UDDS in FTP-75 test



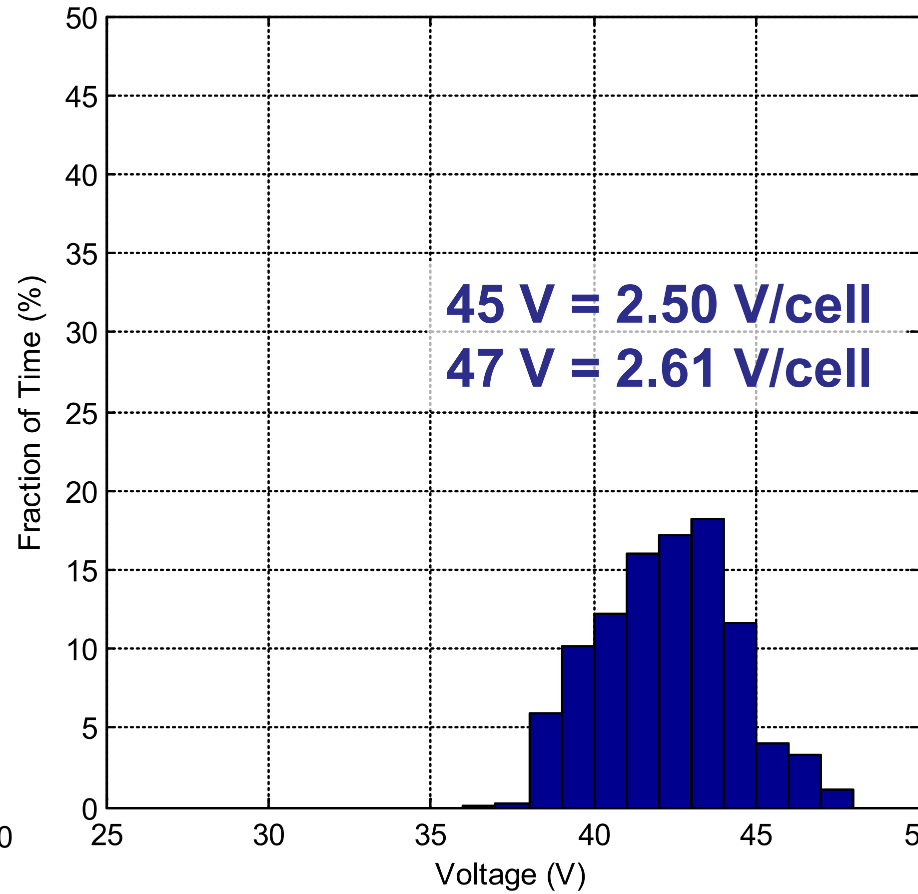


Voltage Histogram Comparison
Shown for second (hot start) UDDS in FTP-75 test

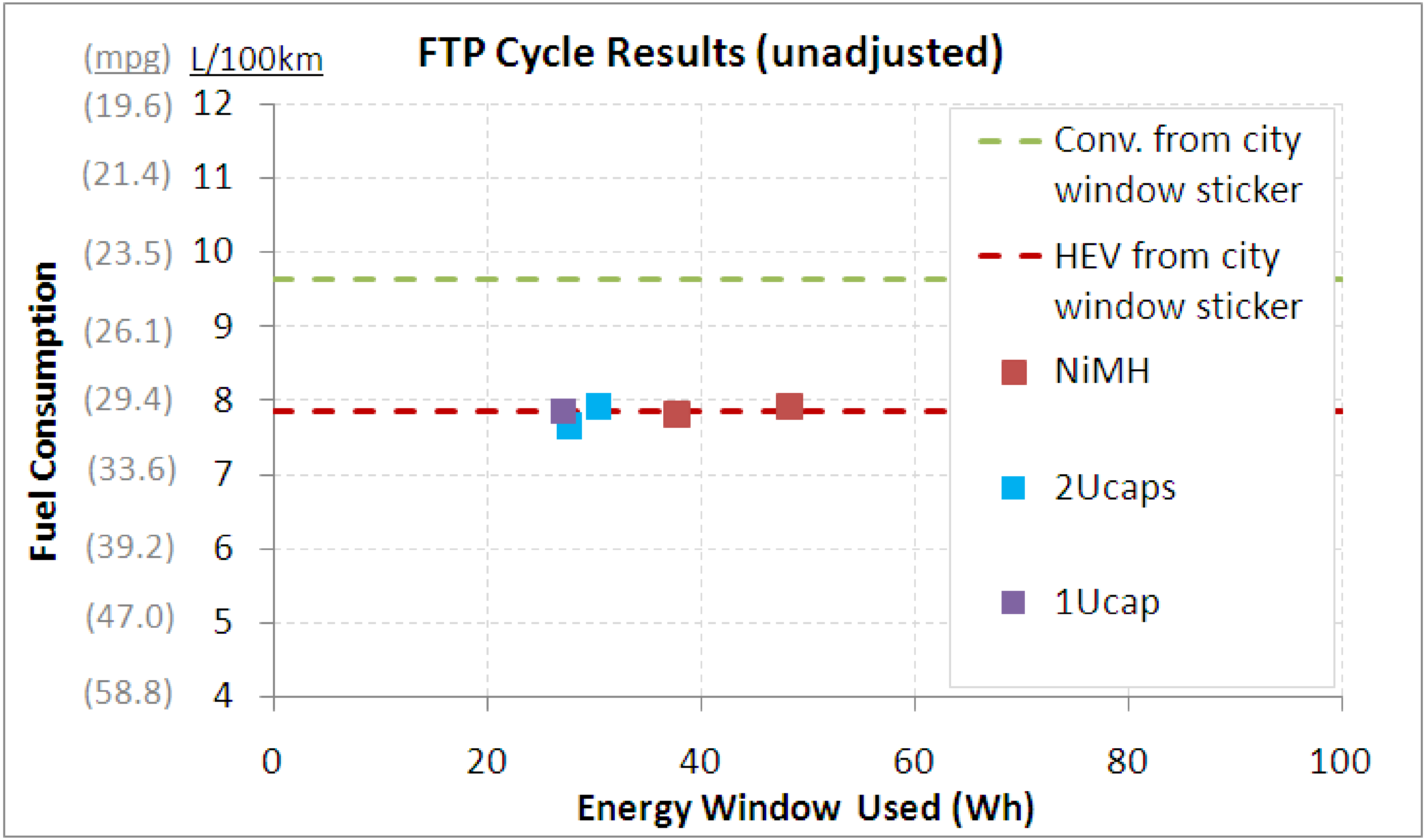
NiMH Configuration



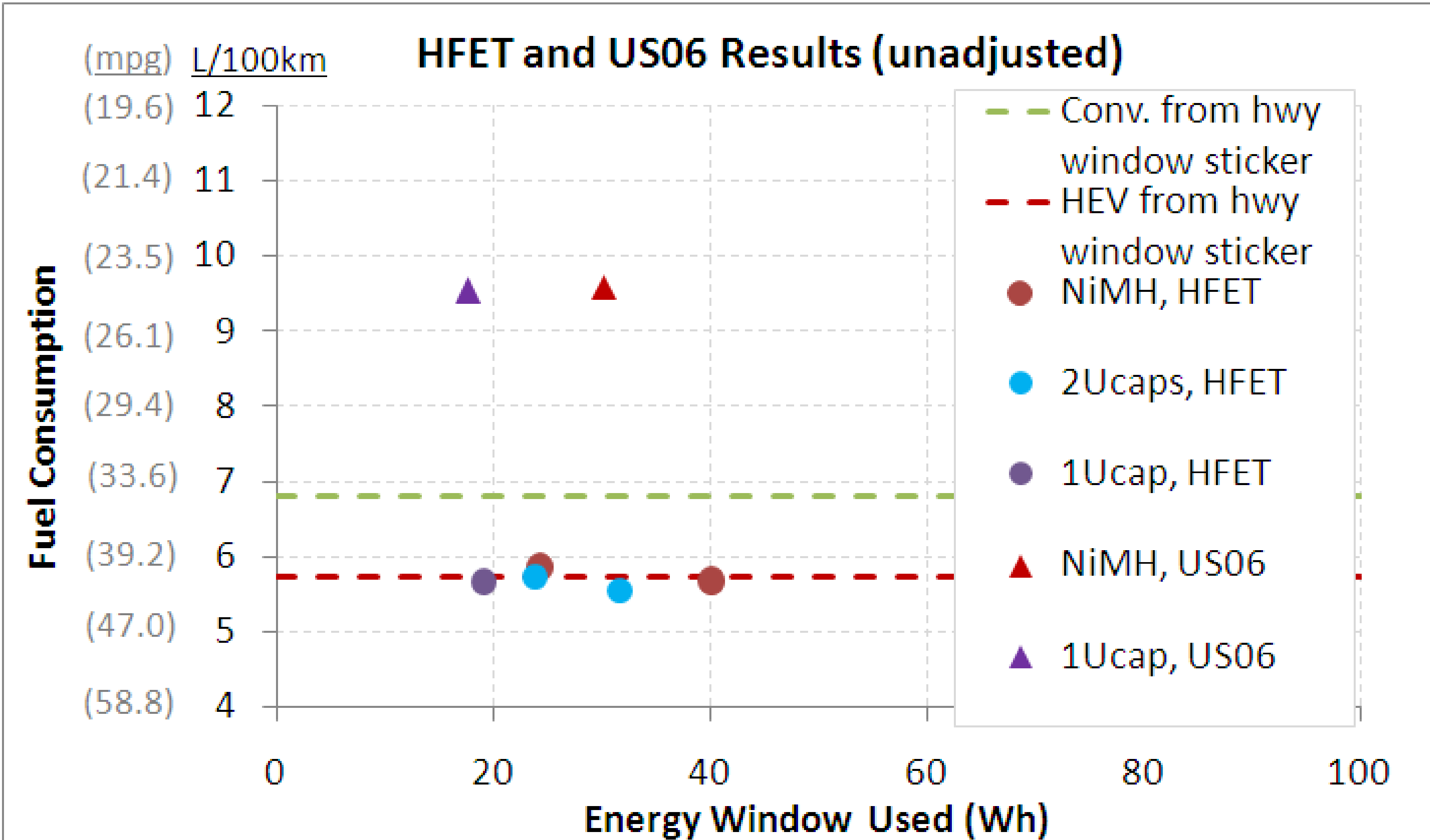
1Ucap Configuration



Dyno Testing Comparison for All Three Configurations, FTP Drive Cycle (24 C ambient)

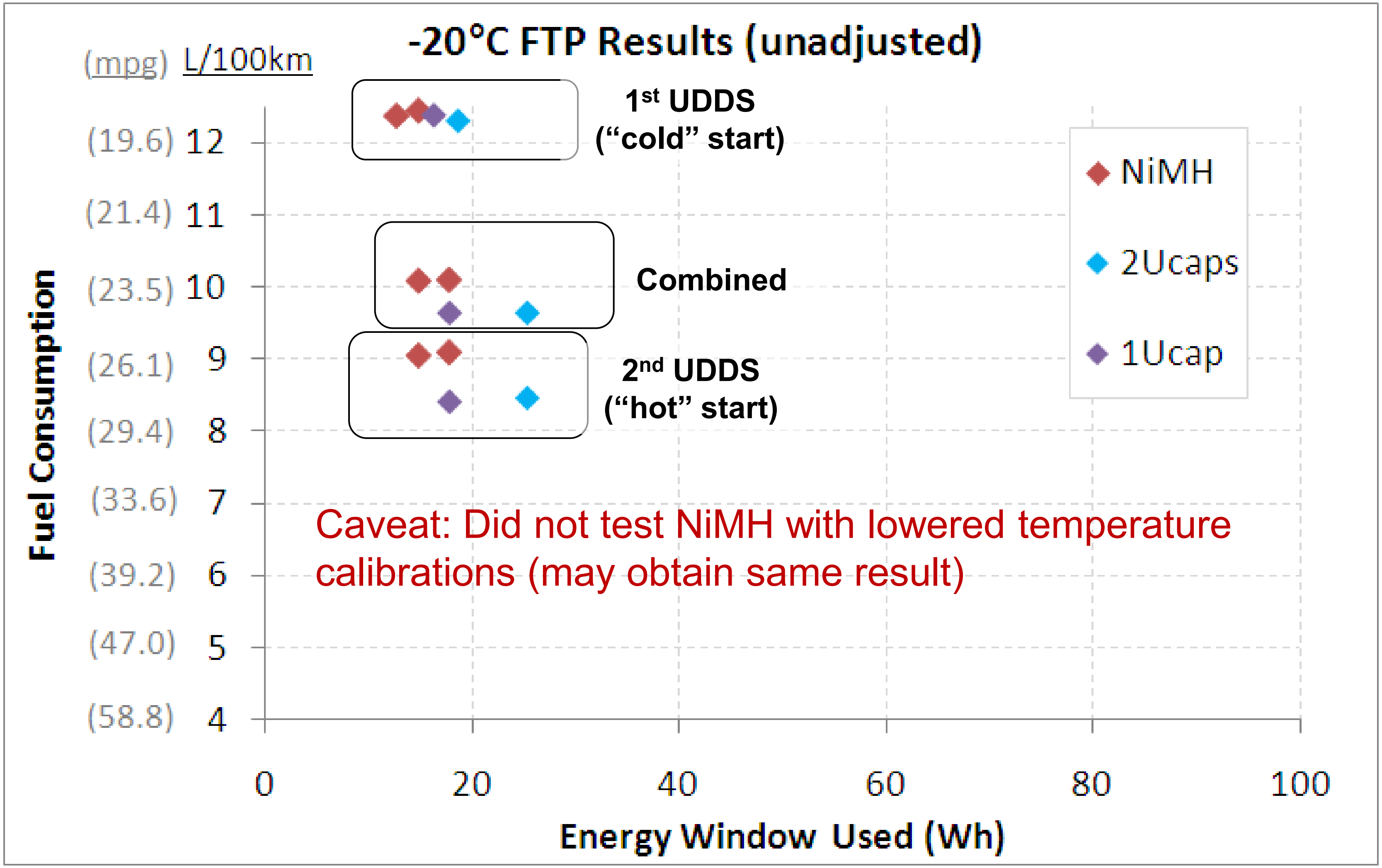


Dyno Testing Comparison for All Three Configurations Highway and US06 Drive Cycles (24 C ambient)

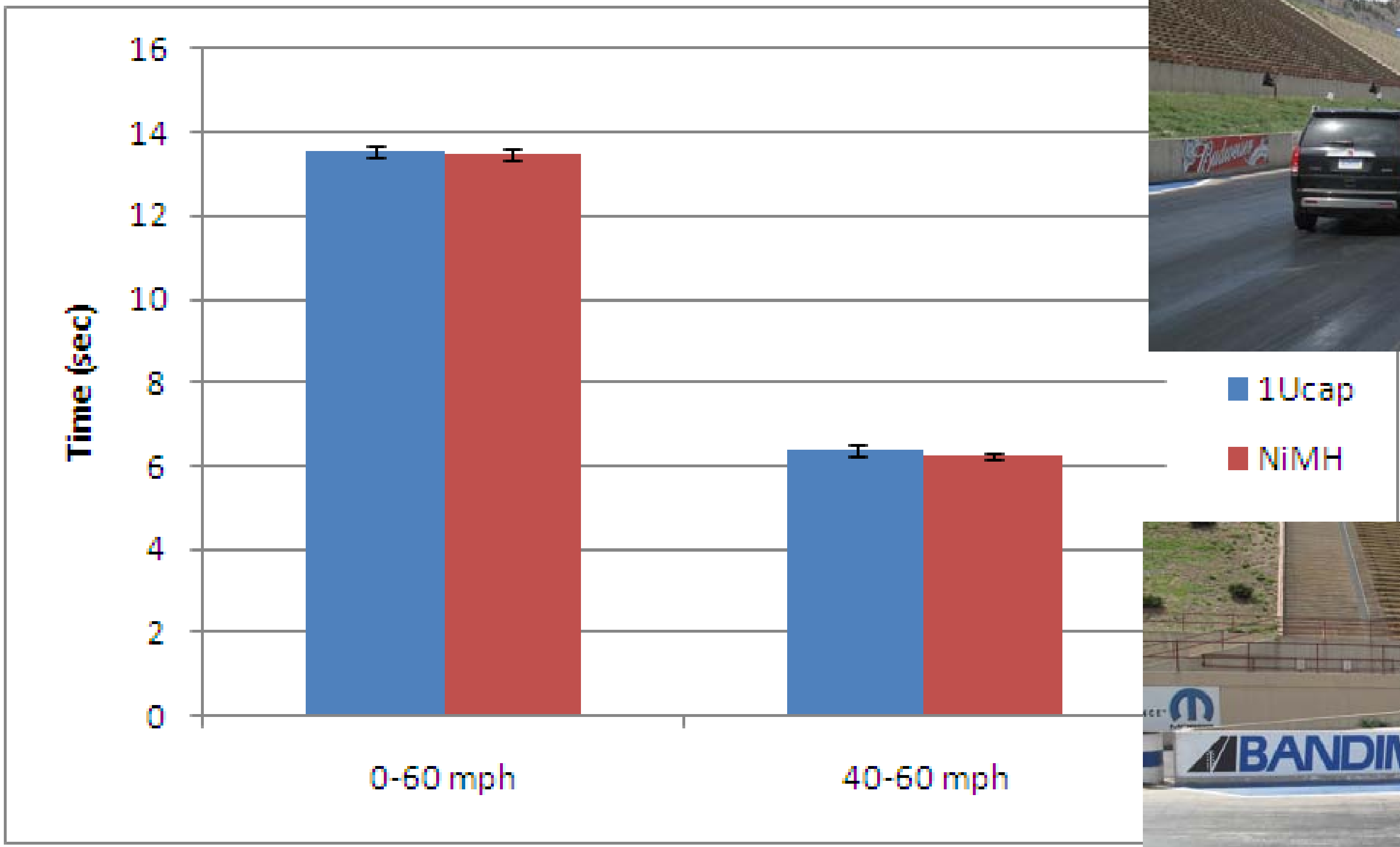


Very Cold Dyno Testing Comparison

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*)
- Designed a low-energy Ucap HEV conversion (no additional DC/DC)
- Performed bench hardware evaluation and verified module performance
- Implemented Saturn Vue BAS HEV conversion with ability 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 to optimize design
  - Controls tuning and motor sizing
  - Take advantage of cold temp capability

Ucap HEV performed equal or better than the stock Saturn Vue BAS battery HEV

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

Potential Next Steps

- Further experimentation with this test bed
  - Evaluate higher power motor
  - Examine air conditioning and/or mountain driving impacts
  - Test a smaller/custom Ucap module (decrease number of Ucap cells and/or F/cell)
  - Further optimize calibration settings
  - Artificially force a smaller Wh operating window (by modifying vehicle controls) and observe any fuel economy drop off
- Examine a different platform
- Expand platform-specific vehicle modeling to further explore the design space

Acknowledgements

- GM
  - Jim Yurgil, Damon Frisch
  - Mike Reynolds, Andrew Namou
  - Mark Verbrugge, Shawn Hawkins
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- 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)