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:

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.

- **Sizeable fuel savings (≈half) with window ≤50 Wh**
- **Most additional savings with expansion out to ≈150 Wh**

![Graph showing fuel consumption vs. ESS Energy Window (Wh)]
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)

- In-use energy window for charge-sustaining tests: same range as simulation results
- Total “nominal” battery energy much larger, most of it used only occasionally
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
- **25** Hwy

**HEV**

**2007 Saturn Vue Hybrid**

- **26** Combined
- **29** Hwy

≈ +25% mpg*

**2010 Model**

**2010 Model**

- **22** Combined
- **26** Hwy

- **28** Combined
- **32** Hwy

Project shows Ucaps provide similar fuel economy benefit

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

* From the aforementioned DOE-sponsored testing at ANL

Driving Energy Analysis (UDDS cycle example)
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 ft³
  - 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.

<table>
<thead>
<tr>
<th>Module</th>
<th>Capacity [Ah]</th>
<th>Capacity [Wh]</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.047 ± 0.005</td>
<td>37.2 ± 0.2</td>
</tr>
<tr>
<td>2</td>
<td>1.042 ± 0.005</td>
<td>37.3 ± 0.2</td>
</tr>
<tr>
<td>3</td>
<td>1.035 ± 0.005</td>
<td>36.7 ± 0.2</td>
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</tbody>
</table>
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

1Ucap Configuration Over Repeated Test Loop

- Volt range: 38 - 47 V
  (18 Wh for this 1Ucap config.)

- BSE Capacitance (F)
- BSE Resistance (ohms)
- Speed (kph)
In-Vehicle Ucap Temperature and Cell Voltage Performance Consistent with Bench Observations

1Ucap Configuration Over Same Repeated Test Loop

<table>
<thead>
<tr>
<th>Volts (V)</th>
<th>Temp (C)</th>
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<tbody>
<tr>
<td>2.38</td>
<td></td>
</tr>
<tr>
<td>2.52</td>
<td></td>
</tr>
<tr>
<td>2.66</td>
<td></td>
</tr>
<tr>
<td>2.8</td>
<td></td>
</tr>
</tbody>
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Primary Ucap Cell Voltages (V)

Secondary Ucap Cell Voltages (V)

Primary Ucap Thermocouple Probes (C)

Secondary Ucap Thermocouple Probes (C)
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

Provided same in-vehicle mpg

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

NiMH Configuration

1Ucap Configuration

45 V = 2.50 V/cell
47 V = 2.61 V/cell
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

Caveat: Did not test NiMH with lowered temperature calibrations (may obtain same result)
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

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- **NREL**
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  - 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

<table>
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<tr>
<th>Project Phase</th>
<th>Related Activities</th>
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<tbody>
<tr>
<td>System Design</td>
<td>Ucap energy storage system design study</td>
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<tr>
<td>Hardware Bench-top Evaluation</td>
<td>Hardware acquisition and bench-top verification</td>
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<tr>
<td>Vehicle Conversion</td>
<td>Acquiring vehicle and integration of Ucap system into vehicle</td>
</tr>
<tr>
<td>Vehicle Test Results &amp; NiMH Comparison</td>
<td>Baseline testing; Ucap system in-vehicle performance testing; Modeling; Trade-off analysis of different system designs</td>
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</table>
NiMH vs. Ucap Voltage and Cumulative Energy Comparison
Shown for second (hot start) UDDS in FTP-75 test