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.

- Sizeable fuel savings (≈half) with window \( \leq 50 \text{ Wh} \)
- Most additional savings with expansion out to \( \approx 150 \text{ Wh} \)
Background:
Results consistent with production HEV dyno test data*

- Data analysis confirmed **in-use energy window <200 Wh** 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

Could Ucaps provide similar fuel economy benefit? – YES!

# Project Approach

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<th>Project Phase</th>
<th>Related Activities</th>
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<tr>
<td>System Design</td>
<td>Ucap Energy Storage System Design Study</td>
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<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>
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<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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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 ft³
  - 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

<table>
<thead>
<tr>
<th>Module</th>
<th>Capacity [Ah]</th>
<th>Capacity [Wh]</th>
</tr>
</thead>
<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>
</tr>
</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
  - 0-60 mph
  - 40-60 mph
On-road Shakedown Testing and Calibration Setting
Good performance achieved

<table>
<thead>
<tr>
<th>Speed (kph)</th>
<th>Volts (V)</th>
<th>BSE R (ohms)</th>
<th>BSE C (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.001</td>
<td>200</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>0.002</td>
<td>150</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0.003</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>0.004</td>
<td>90</td>
</tr>
<tr>
<td>40</td>
<td>20</td>
<td>0.005</td>
<td>80</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>0.006</td>
<td>70</td>
</tr>
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<td>90</td>
<td>45</td>
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<tr>
<td>100</td>
<td>50</td>
<td>0.011</td>
<td>20</td>
</tr>
<tr>
<td>110</td>
<td>55</td>
<td>0.012</td>
<td>10</td>
</tr>
<tr>
<td>120</td>
<td>60</td>
<td>0.013</td>
<td>0</td>
</tr>
</tbody>
</table>

BSE Capacitance (F)
BSE Resistance (ohms)
Speed (kph)

Volts range: 38 - 47 V
(18 Wh for this 1Ucap config.)
In-Vehicle Ucap Temperature and Cell Voltage Performance Consistent with Bench Observations

<table>
<thead>
<tr>
<th>Volts (V)</th>
<th>Temp (°C)</th>
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1Ucap Configuration Over Same Repeated Test Loop

- **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
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

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*)
- 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
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