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

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* 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**
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

Conventional

2007 Saturn Vue FWD

- 19 City
- 21 Combined
- 25 Hwy

HEV

2007 Saturn Vue Hybrid

- 23 City
- 26 Combined
- 29 Hwy

2009 Model

- 22 Combined
- 26 Hwy

2009 Model

- 28 Combined
- 32 Hwy

Could Ucaps provide similar fuel economy benefit? – YES!

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

## Project Approach

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<th>Project Phase</th>
<th>Related Activities</th>
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<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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<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>
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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>
</tr>
</tbody>
</table>
Temperature Performance Summary (25 C ambient)

No heating problems anticipated in application

Center Cell
(Max temp location)

Terminal Cells
(Min temp location)

100A Square Wave Cycle:
Aggressive upper bound

US06 Bench Cycle:
Anticipated usage
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

1Ucap Configuration Over Repeated Test Loop

Volt range: 38 - 47 V
(18 Wh for this 1Ucap config.)
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>2.8</td>
<td>30</td>
</tr>
<tr>
<td>2.66</td>
<td>29</td>
</tr>
<tr>
<td>2.52</td>
<td>28</td>
</tr>
<tr>
<td>2.38</td>
<td>27</td>
</tr>
<tr>
<td>2.24</td>
<td>26</td>
</tr>
<tr>
<td>2.1</td>
<td>25</td>
</tr>
<tr>
<td>1.96</td>
<td>24</td>
</tr>
<tr>
<td>1.82</td>
<td>23</td>
</tr>
<tr>
<td>1.68</td>
<td>22</td>
</tr>
<tr>
<td>1.54</td>
<td>21</td>
</tr>
</tbody>
</table>

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

Speed (mph), Power (kW) and SOC
NiMH vs. Ucap Voltage and Cumulative Energy Comparison
Shown for second (hot start) UDDS in FTP-75 test

NiMH Configuration

1Ucap Configuration

- Speed
- ESS Volts
- ESS Cumulative Wh Profile

Graph showing the comparison of NiMH and Ucap configurations.
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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