Factors & Conditions for Widespread Use of Ultracapacitors in Automotive Applications

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• Background
  — Potential ultracapacitor (Ucaps) functions in vehicles
  — Energy and power requirements of various HEVs
  — Hybrids with Ucaps
  — Start-stop vehicle fuel economy
• Simulations – Impact of energy window on fuel economy of power assist hybrids
• Ucaps and Plug-in HEVs
• Suitability of Ucaps for different hybrid vehicles
• What would make the Ucap market grow?
• Fuel consumption considerations
• Concluding remarks
Background - Summary of Previous Work

- Rational for using Ucaps with electric drive
- How much energy is needed for various vehicle events/functions?
- Examples of prototype vehicles with Ucaps
Rationale for Using Ucaps with Electric Drive

Taking advantage of ultracapacitor’s strengths (+) while minimizing impact of its weaknesses (-) if the COST was comparable to batteries

+ High specific power and efficiency
+ Efficient charge acceptance
+ Low resistance
+ Quick response (short time constant)
+ Long anticipated calendar and cycle lifes
+ High specific power at low temperatures (cold starts)

– Low specific energy
– High self discharge

?? Cost (initial versus life-cycle cost)

The best use for Ucaps are strategies that make engines operate more efficiently (idle off, load leveling), recapturing regen energy, and start-stop.
Ucap is Energy Limited

How Much Energy Is Needed for Various Events?

- 20% of total energy in current NiMH packs
- 20 kW for 15 s
- 3 kW accessory
- 1 kW accessory
- 4% grade
- 2% grade
- US06
- HWFET
- UDDS

Total Energy (at wheels) calculated for 1520 kg vehicle (Regen)

Energy for 15 s of constant 20 kW electrical assist (or 30 kW for 10 s)

Energy to provide constant electrical accessory load for 1 minute

75% of energy to maintain 35 mph for 1 mile driving down a given grade

50% of energy in the cycle’s largest deceleration event

Cold-start capability is expected to dictate the size of batteries, but not for Ucaps.
Background - Light Duty Hybrids with Ucaps

Honda Fuel Cell hybrid Vehicle (FCX-V4) Prototype

- H₂ Fuel Cell 78 kW
- Motor/Ucap Power 28 kW
- Ucap functionality
  - Improve fuel cell/vehicle’s response
  - Recapturing regenerative braking
  - Energy for startup of the fuel cell
- Ucap available energy 80 Wh
- City/highway FE 62/51 miles per kg of H₂

Deg. of Hybr. = 0.26

BMW X3 Efficient Dynamics Mild Hybrid Concept

- 6-cyl engine 190kW
- Motor 30kW (peak power 60kW)
- Start/Stop and regen functionality
- Ucap available energy 53 Wh
- Estimated 20% fuel economy increase

Deg. of Hybr. = 0.16

Supercaps (Asahi glass?)

Supercaps (EPCOS?)
Demanding vehicle requirements

- 8 to 12 hours of continuous stop-and-go duty cycle
- Much higher traction / regen power
- Durability and reliability are musts
- 0.4 kWh and 200 kW ultracapacitors

ISE uses Two Ultracapacitor Packs
Spec of a Ucap Pack:
- Total Energy Stored: 0.407 kWh
- 150 kW Power
- 4 Wh/kg Energy Density
- 1.5 kW/kg Power Density
- Expected life 10-12 years
- System Cost: 100 $/kW
<table>
<thead>
<tr>
<th>System Attributes</th>
<th>12V Start-Stop (TSS)</th>
<th>42V Start-Stop (FSS)</th>
<th>42V Transient Power Assist (TPA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge Pulse</td>
<td>4.2 kW 2s</td>
<td>6 kW 2s</td>
<td>13 kW 2s</td>
</tr>
<tr>
<td>Regenerative Pulse</td>
<td>N/A</td>
<td>N/A</td>
<td>8 kW 2s</td>
</tr>
<tr>
<td>Cold Cranking Pulse @ -30°C</td>
<td>4.2 kW 7 V Min.</td>
<td>8 kW 21 V Min.</td>
<td>8 kW 21 V Min.</td>
</tr>
<tr>
<td>Available Energy (CP @1kW)</td>
<td>15 Wh</td>
<td>30 Wh</td>
<td>60 Wh</td>
</tr>
<tr>
<td>Recharge Rate (kW)</td>
<td>0.4 kW</td>
<td>2.4 kW</td>
<td>2.6 kW</td>
</tr>
<tr>
<td>Cycle Life / Equiv. Road Miles</td>
<td>750k / 150,000 miles</td>
<td>750k / 150,000 miles</td>
<td>750k / 150,000 miles</td>
</tr>
<tr>
<td>Calendar Life (Yrs)</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Self Discharge (72hr from Max. V)</td>
<td>&lt;4%</td>
<td>&lt;4%</td>
<td>&lt;4%</td>
</tr>
<tr>
<td>Selling Price ($/system @ 100k/yr)</td>
<td>40</td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td>Maximum System Weight (kg)</td>
<td>5</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Maximum System Volume (Liters)</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Energy Density (Wh/Liter)</td>
<td>3.25</td>
<td>3.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Specific Power (W/kg)</td>
<td>840</td>
<td>600</td>
<td>650</td>
</tr>
<tr>
<td>Selling Price ($/Wh)</td>
<td>2.78</td>
<td>2.78</td>
<td>2.17</td>
</tr>
<tr>
<td>Selling Price ($/kW)</td>
<td>9.6</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Vehicle Fuel Economy With Stop-Start (Idle-Off) Function

- **Strongly depends on the fuel usage rate at idle**
  - 0.2 g/s for a compact car, 4 cyl, 2.5L
  - 0.4 g/s for a midsize car like 2005 Chevy Malibu, 6 cyl, 3.5L
  - 0.48 g/s for a midsize truck like 2005 GMC Sierra, 8 cyl, 5.3L

- **Strongly depends on the drive cycle**
  - City (a lot of stop and re-start)
  - Highway (little chance of stop)
  - US06 (some chance of stop)

- **Maximum FTP fuel economy improvement with idle-off**
  - 16% for 2005 Chevy Malibu, 6 cyl, 3.5 L
  - 14% for 2005 GMC Sierra, 8 cyl, 5.3L

- **Real fuel economy improvement with idle off**
  - 5% to 10%

Recent Analysis

Impact of Energy Window on Power-Assist HEVs

- **Motivation:** Investigate the relation between in-use energy window and fuel economy (a request from USABC/FreedomCAR)
- **Approach:** Simulate a midsize sedan with different component power levels and control settings for different drive cycles using PSAT analysis software

### Midsize Car Assumptions

- **FA =** 2.27 m²
- **CD =** 0.30
- **Crr1 =** 0.008
- **Crr2 =** 0.00012
- **Mass =** 1675 kg
- **Engine =** 90 kW
- **RESS/Motor =** 30 kW
- **Elec accessories =** 500 W
- **Mech accessories =** 230 W

### Simulated different ES energy content cases with the otherwise constant platform values

- **Smallest ES energy**
- **Largest ES energy**

**Constant 30 kW power → changing P/E ratio**

**Upper threshold**

**Target level**

**Lower threshold**

**Constant SOC-based controls (charge sustaining)**

**Changing Wh control window tolerance**

Source: J. Gonder, Presentation to USABC, July 19, 2007
Definition of ES Energy Window Use (for a drive cycle or event)

RESS use indicated by slope of energy line

- Energy out for electric launch/assist
- Energy return from charging/regen

“Energy Window” defined by (max – min) for the particular cycle

Charge sustaining over cycle (no net energy use)

Energy Window Used ≤ Available Energy

Source: J. Gonder, Presentation to USABC, July 19, 2007
Three cycles simulated to observe energy window and fuel use (for each ES case)

**Aggressive driving**

**US06 Cycle**
- Mean power during:
  - Propulsion = 21 kW
  - Deceleration = -17 kW
- No grade

**Mild urban driving**

**UDDS Cycle**
- Mean power during:
  - Propulsion = 7 kW
  - Deceleration = -5 kW
- No grade

**Up and down, foothills driving**

“NREL to Genesee, CO Cycle”
- Mean power during:
  - Propulsion = 23 kW
  - Deceleration = -12 kW
- Considerable grade

Source: J. Gonder, Presentation to USABC, July 19, 2007
On UDDS, large fuel savings from hybridization and from energy window expansion

Source: J. Gonder, Presentation to USABC, July 19, 2007
Summary Results of ES Energy Window and Fuel Economy Simulations

Source: J. Gonder, Presentation to USABC, July 19, 2007
All the charge sustaining (CS) tests use windows <200 Wh (for these vehicles and CS cycles).

Test data analysis seems to validate simulation finding of significant hybridization benefit in the 50-150 Wh range.

Source: J. Gonder, Presentation to USABC, July 19, 2007
Summary/Observations from HEV Energy Window Simulations

• Relative to the conventional, about half of the hybrid fuel saving is realized with 25-50 Wh energy window usage
• Most fuel savings are realized with 125-150 Wh energy window usage
• For better acceleration and passing-grade performance, higher energy window is needed: 300-400 Wh
• For a given ES energy window, vehicle fuel consumption is lower with higher power capability
• It is possible to use ultracapacitors (with available energy of 50-150 Whr) in power-assist HEVs with modest fuel economy improvements, however, acceleration and passing on grade performance considerations could be limiting factors.
Do Plug-in Hybrid Vehicles Provide an Opportunity for Ultracapacitors?

USABC Goals for Energy Storage in PHEV's

<table>
<thead>
<tr>
<th>Characteristics at end of life</th>
<th>High Power/Energy Ratio Battery</th>
<th>High Energy/Power Ratio Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Equivalent Electric Range</td>
<td>Watts</td>
<td>10</td>
</tr>
<tr>
<td>Peak Pulse Discharge Power - 2 sec / 10 sec</td>
<td>kWe</td>
<td>50 / 45</td>
</tr>
<tr>
<td>Peak Regen Pulse Power (10 sec)</td>
<td>kWe</td>
<td>30</td>
</tr>
<tr>
<td>Available Energy for CD (Charge Depleting) Mode, 10 kWe Rate</td>
<td>kWh</td>
<td>.5</td>
</tr>
<tr>
<td>Available Energy for CS (Charge Sustaining) Mode</td>
<td>kWh</td>
<td>3.4</td>
</tr>
<tr>
<td>Minimum Round-trip Energy Efficiency (USABC HEV Cycle)</td>
<td>%</td>
<td>90</td>
</tr>
<tr>
<td>Cold cranking power at -30°C, 2 sec - 3 Pulses</td>
<td>kW</td>
<td>7</td>
</tr>
</tbody>
</table>

CD Life / Discharge Throughput Cycles / MWh 5,000 / 17 5,000 / 58

Common ultracapacitors do not have the energy for “charge depleting” operation of a PHEV, but their ability to cycle at high power rates many times and long calendar life provide the opportunity to be combined with high energy batteries.
NREL Tests Show that Combining Ultracapacitors with Batteries Could Filter High Voltage Transients

Source: M. Zolot (NREL Reports and 2003 Florida Capacitor Seminar)

- Overall, the batteries in the hybrid pack experienced no currents larger than ±40A, while the batteries in the traditional pack saw currents up to 110A.
- Up to 33% narrower battery SOC cycling range was observed; has the potential to increase battery life.

Parallel connection; no DC/DC converter
Not practical to implement in vehicles

Ultracapacitor module of 8 cells (up to 20V) and two 6.5Ah NiMH module of 14.4V (18V max). Ultracap module and battery pack were arranged in parallel to share the current load depending on internal impedance.
Advantages/Disadvantages of Hybridizing Energy Storage (Ucap + Battery)

Advantages
• Reduced battery currents
• Reduced battery cycling range
• Increased battery cycle/calendar life (to what extent?)
• Increased combined power and energy capabilities
• Lower cooling requirements
• Better low temperature performance

Disadvantages
• Complex control strategy
• Larger volume & mass
• Need for electronics for each system
• Increased energy storage cost
• Unknown side affects of direct coupling
• Any need for DC/DC converters adds even more cost and complexity

Summary - Technical Consideration

• Ucap applications match well to HEVs with Start-Stop strategies (small energy, high power)
  — Idle-off operation, potentially could increase standard EPA fuel economy of midsize truck by 14% and midsize car by 16%;
  — In real driving, idle-off strategy could improve fuel economy between 5% -10%

• Ucaps have potential in mild or full hybrids with some modest fuel economy improvements, but acceleration and passing-grade performance may be an issue

• Ucaps+batteries may have some applications in Mild HEVs, even full and plug-in hybrids
  — Increased cycle life of the battery by limiting high current excursions
  — Added cost and volume could be a major issue
  — If DC/DC needed cost increase may wash out battery life benefits
  — Other approaches?
What would **pull** ultracapacitors toward the market?

- **Lower Cost**
  - Larger volume productions
  - Lower materials cost
  - Improved energy and power performance

- Ultracapacitor companies need to deliver quality, performance, life, and cost per requirements

- Use of commonly accepted definitions, specifications, and standards by both car and ultracapacitor companies

- Ultracapacitors are attractive relative to batteries for specific applications
  - Cost/features

- Niche markets, so the industry begins to increase volume production to lower cost and improve performance
  - *Does the heavy hybrid vehicles provide the transitioning market?*

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For example:

9000 Trash Haulers are produced each year. Assuming 40% of them will be hybrids with 400Wh Ucap Systems then the Ucap market size will be 0.5 million large cells/year
What would push the market toward ultracapacitor?

• The need for more fuel efficient and green vehicles
  — Continued higher gasoline demand and prices
  — Environmental and global warming concern (green movement)
  — Hybridization becomes common
• Energy security (lower petroleum imports)
• Government regulations
  — Higher CAFE (fuel economy regulation)
    » 27.5 mpg for cars, now
    » 22.5 mpg for light trucks, now
  — Adoption of CO₂ regulation/tax
  — Tax incentives
  — Idle-off from heavy to light vehicles??

→ To combined 35 mpg in 2019*

*Proposed bill S. 357 in the 110th Congress

• But still, ultracapacitors must provide better value compared to Li-Ion batteries for some applications
# Potential High-Volume Applications of Ultracapacitors in Light-Duty HEVs

<table>
<thead>
<tr>
<th>Application</th>
<th>VRLA:</th>
<th>NiMH and Li-ion:</th>
<th>Ucap:</th>
<th>Ucap + VRLA:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Micro Hybrids</strong></td>
<td>Yes</td>
<td>Yes, Likely</td>
<td>Likely</td>
<td>Possible</td>
</tr>
<tr>
<td>(12V-42V: Start-Stop, Launch Assist)</td>
<td>Min energy needed 15-20 Wh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mild Hybrids</strong></td>
<td>Yes (42V)</td>
<td>Yes, Likely</td>
<td>Likely if engine is not downsized</td>
<td>Possible</td>
</tr>
<tr>
<td>(42V-150V: Micro HEV Function + Regen)</td>
<td>20-60 Wh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Full Hybrids</strong></td>
<td>Not Likely</td>
<td>Yes, Likely</td>
<td>Possible</td>
<td>Possible</td>
</tr>
<tr>
<td>(150V-350V: Power Assist HEV)</td>
<td>60-120 Wh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Cell Hybrids</strong></td>
<td>Not Likely</td>
<td>Yes, Likely</td>
<td>Likely if Fuel Cell is not downsized</td>
<td>Possible</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60-120 Wh</td>
</tr>
<tr>
<td><strong>Plug-in HEV</strong></td>
<td>Not Likely</td>
<td>Yes, Likely</td>
<td>Not Likely</td>
<td>Possible</td>
</tr>
<tr>
<td>(some EV range)</td>
<td></td>
<td></td>
<td></td>
<td>80-100 Wh*</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Simple Market Analysis

Example

• What are the overall size of automotive markets?
  — Light duty vehicles vs. heavy duty vehicles

  **Total # of LD vehicles sold in US in 2012: 18,000,000**

• What is the potential market size for a particular application?

  **Mild hybrid market potential in 2012: 5% or 900,000**

• What portion of that market could use ultracapacitors?

  - Battery Mild HEVs 80% (720,000)
  - Ultracapacitor Mild HEVs 20% (180,000)

• What ultracapacitor size is required in that vehicle market?

  **Available energy needed for Mild Hybrids: 80 Wh**

• What would be the total size of that particular market?

  **Market size: 14 MWh; 6.8 Million cells (at 2.1 Wh/cell); $72 Million (at $5/Wh, $10.5/cell)**
• Currently the annual new cars and light trucks sale in US is about 16 million.

• Fuel economy of **cars** has improved steadily in the last 15 years, but sales have gone down

• Sale of less fuel efficient **trucks** has increased steadily in the last 10 years
Potential Impact of Penetration of Fuel Efficient Hybrid Vehicles – Scenario 1: Idle-off, market

- Market penetration: 4%/year until 20% saturation
- Total number of vehicles in passenger fleet is now about 200 millions (in USA).
- Average vehicle turn-over: 14 years
- It takes a long time to turn over the entire fleet.

Annual Vehicle Miles Traveled: 13,000

Base fuel consumption:
8.9 million barrel per day in 2007
11.9 million barrels per day in 2025

Amount of daily fuel saved in 2025:
5% FE: 0.10 million barrels
15% FE: 0.28 million barrels
Potential Impact of Penetration of Fuel Efficient Hybrid Vehicles – Scenario 2: Idle-off, regulation

- Market penetration: 10%/year until 100% saturation
- Total number of vehicles in passenger fleet is now about 200 millions (in USA).
- Average vehicle turn-over: 14 years
- It takes a long time to turn over the entire fleet.

Annual Vehicle Miles Traveled: 13,000

Base fuel consumption:
- 8.9 million barrel per day in 2007
- 11.9 million barrels per day in 2025

Amount of daily fuel saved in 2025:
- 5% FE: 0.46 million barrels
- 15% FE: 1.26 million barrels
Idle-Off Ucap Market?

Assumptions:
~ 25 Wh/Vehicle
~ 2.67 Wh/(3000 F) Cells

3.7 million cells in 2015
4.0 million cells in 2020

Amount of daily fuel saved in 2025:
5% FE: 0.46 million barrels
15% FE: 1.26 million barrels

#1 Idle-Off Penetration into New Sales and Fleet
Idle-off market penetration: 4%/year until 20% saturation
Share of vehicle with Ucaps: 10%

Heavy Hybrid Trash Haulers:
9000 vehicles per year
40% with 400 Wh energy
0.5 million cells/year

11 million cells in 2015
20 million cells in 2020

Amount of daily fuel saved in 2025:
5% FE: 0.10 million barrels
15% FE: 0.28 million barrels

#2: Idle-Off Penetration into New Sales and Fleet
Idle-off market penetration: 10%/year until 100% saturation
Share of vehicle with Ucaps: 10%
Concluding Remarks

• Ultracapacitors provide opportunity for modest fuel savings in hybrid cars
  — Idle-off: 5%-10% FE improvement and most likely to be implemented
  — Mild and full hybrid: 15%-25% FE improvement, possible
  — Plug-in hybrids: possible Ucap combined with batteries, cost??

• Competition from Li-Ion is strong and ultracapacitors should provide added value to compete
  — Low temp performance
  — Longer cycle and calendar life

• Lower cost is the key for increased automotive market growth
  — Large volume production will reduce cost

• Idle-off provides the biggest opportunity for Ucaps in the short term, especially if it is accelerated by CAFÉ standard increases being considered by Congress
  — Large number of idle-off vehicles require high volume production resulting in lower Upcap cost
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nrel.gov/vehiclesandfuels/energystorage/publications.html