# Recent Analysis of UCAPs in Mild Hybrids

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# Outline

- Background and objectives
- Review of ucap-mild HEV analysis
- NREL’s results with mild HEV with simple strategy
- Ucap roles in hybrid vehicles
- Energy requirements for various functions
- What applications could make ucaps attractive?
- Summary
- Proposed future analysis and testing

# Background

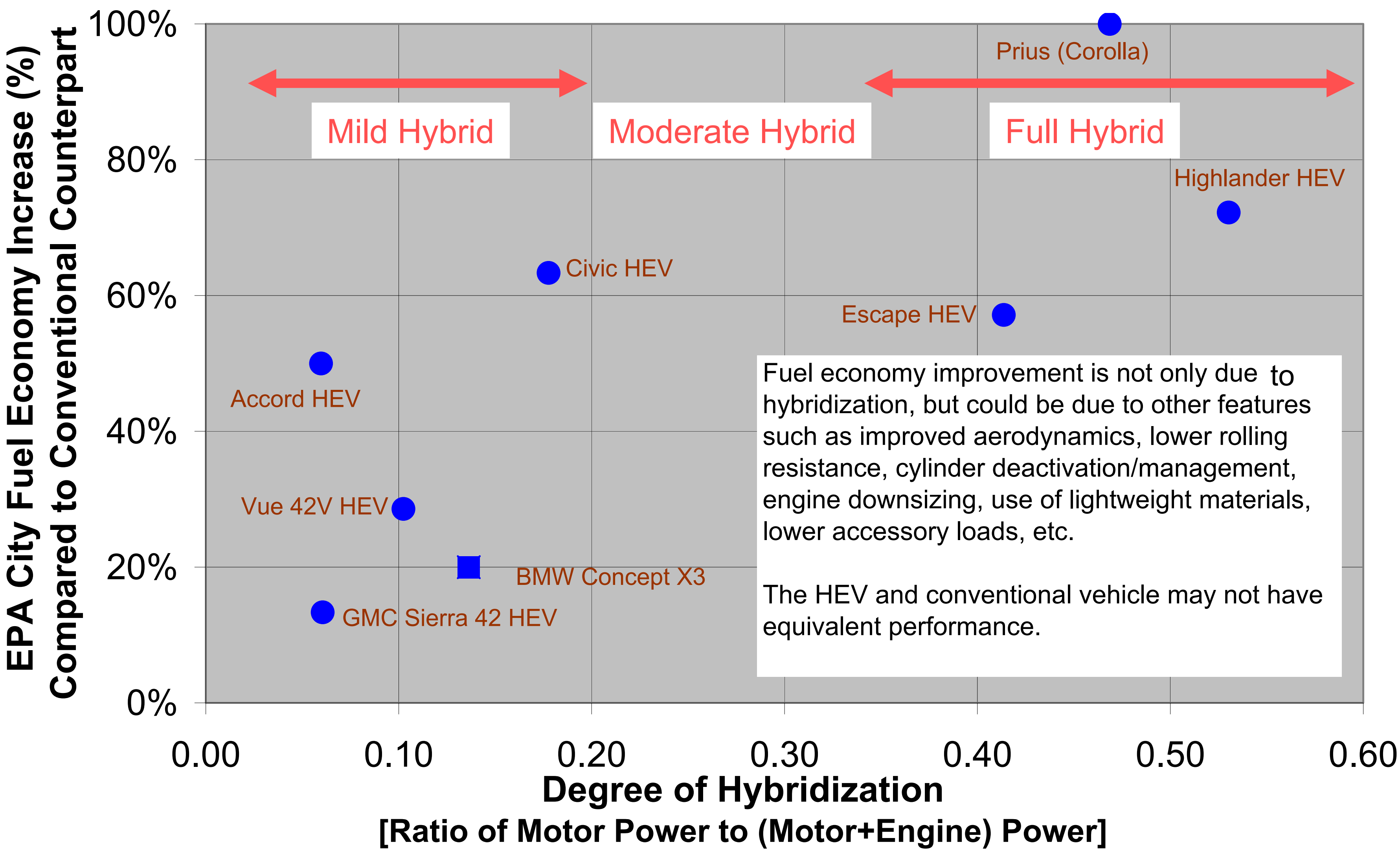
- Last year's analysis by Burke (AABC-05) suggested that using a relatively small high-voltage, ultracapacitor pack in a midsize car, without any engine downsizing, could increase the city fuel economy improvement by:
  - 60% over conventional vehicle, and
  - 20% over the same hybrid using NiMH batteries.
- This created interest in evaluating high-voltage ultracapacitors for mild/moderate hybrid applications.
- Analysis and discussions were initiated among interested stakeholders.
  - We performed analysis using the assumptions in the previous study.
  - A recently proposed "sawtooth" control strategy with ucaps indicates up to 72% (city) and up to 24% (highway) fuel economy improvement over the conventional vehicle the same engine size (UCAP-06).
- The potential roles of ultracapacitors in meeting different requirements of hybrid vehicles were revisited.

# Objectives

- Review the fuel economy improvement trends of today's HEVs with respect to degree of hybridization.
- Perform analysis to see the extent of fuel economy improvement possible with various strategies in mild/moderate HEVs, with no engine downsizing, using either batteries or ultracapacitors.
- Identify energy requirements of various driving events/functions – what matches a limited ucap's energy?
- Discuss potential roles for high-voltage ultracapacitors in HEVs, if any.

# Background

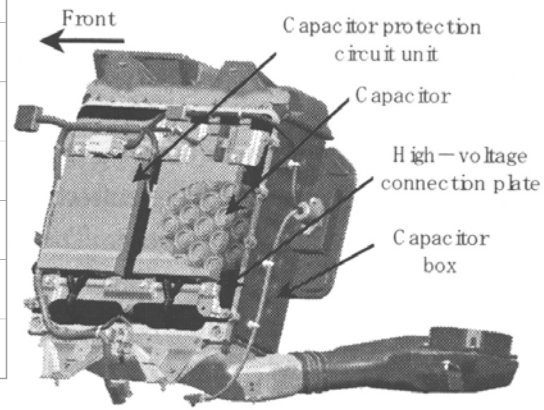
## Today's Commercial or Concept Hybrid Vehicles



# Background

## One Example of Ucap Use in a Mild Fuel Cell Hybrid

| Item | Specification | Note |
|---|---|---|
| Volume (L) | 36.8 | |
| Weight (kg) | 34.3 | |
| Max. voltage (V) | 216 | |
| Max. power (kW) | **28** | |
| Energy (Wh) | **80** | 216-→ 108V |
| Number | 80 | |



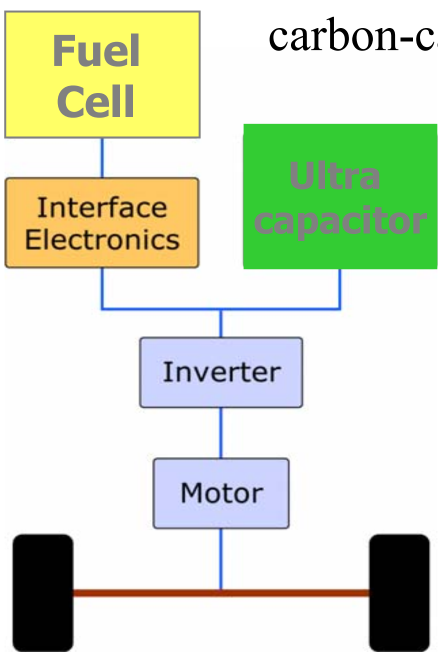

Honda Fuel Cell Vehicle (FCX-V4)


Vehicle Mass = 1680 kg

Fuel Cell Power = 78 kW

Ucap Power = 28 kW

Deg. of Hybr. = 0.26




carbon-carbon with propylene carbonate electrolyte

EPA city/highway FE 62/51 miles per kg of hydrogen

Sources: AABC-03 and 2004 SAE Congress

Utility of Ucaps:

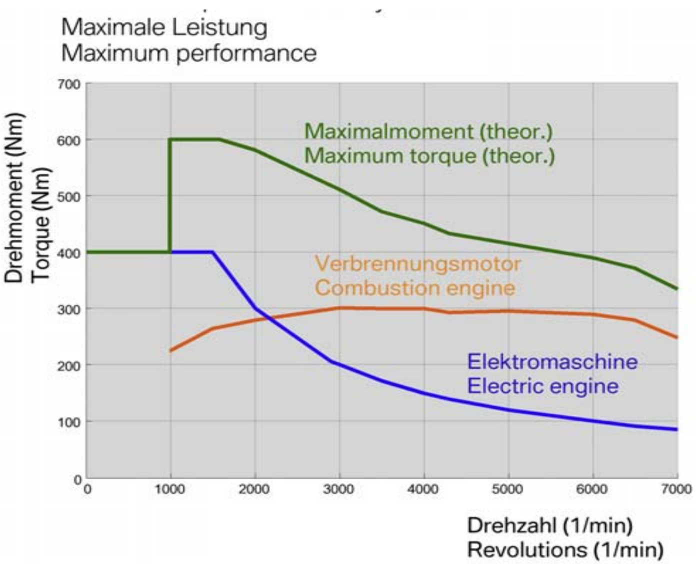
- Improve fuel cell/ vehicle's response
- Recapturing regenerative braking for better fuel economy
- Energy for startup of the fuel cell

# BMW X3 Efficient Dynamics Mild Hybrid Concept

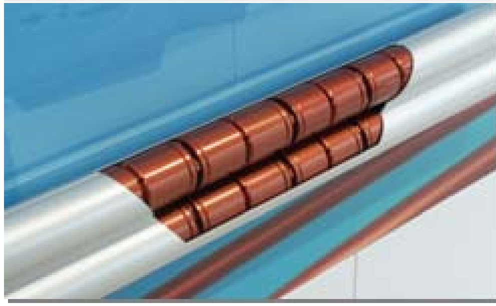
- 6-cyl engine 190kW
- Motor 30kW (peak power 60kW)

Deg. of Hybr. = 0.16

- Max. 600 Nm torque, 400 Nm from electric motor
- Start/Stop and regen functionality
- Ucap capacity 53 Wh
- Estimated acceleration 0-60 mph in 6.7 S
- Estimated 20% fuel economy increase





Supercaps (EPCOS?)

# Ucap-Mild HEV Analysis

## Results of Analysis by Burke (AABC-05)*

Conventional and Hybrid Vehicle Assumptions:

Mass = ~1500 kg; Engine = 120 kW peak; Motor =15 kW continuous/27 kW peak

Ultracapacitor = 7 kg, ~35 Wh "available"; previous gen. NiMH Battery = 20 kg, ~200 Wh "available"

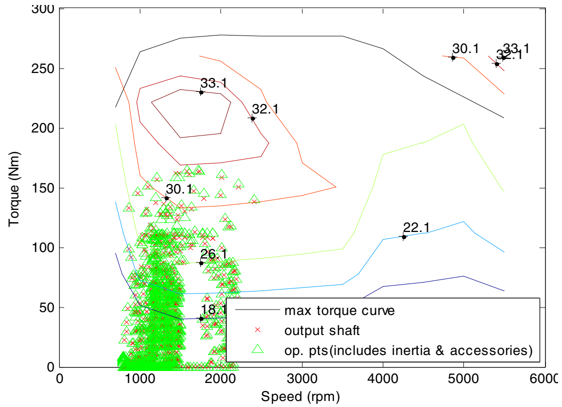
**Control Strategy:** **Typical control parameters for full assist hybrids**

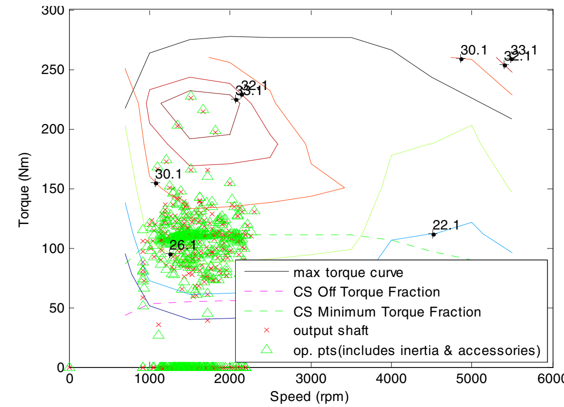
| Configuration | ESS Technology | ESS kg | Unadjusted mpg* (% mpg improvement) | |
|---|---|---|---|---|
| | | | UDDS | US06 |
| Conv. CVT 120 kW | N/A | N/A | 21.7 | 23.8 |
| HEV CVT (120 + 15/27) kW | NiMH (previous generation) | 20 | 32.9 (52%) | 24.9 (5%) |
| HEV CVT (120 + 15/27) kW | Ultracap (advanced generation) | 7 | 36.1 (66%) | 26.3 (11%) |

* Andrew Burke – "The Present and Projected Performance and Cost of Double-Layer and Pseudo-Capacitive Ultracapacitors for Hybrid Vehicle Applications," AABC, Honolulu, Hawaii, June 2005, and other papers.

# Engine Efficiency and Engine/Motor Power Distribution

## Based on our simulations similar to Burke's 2005 analysis



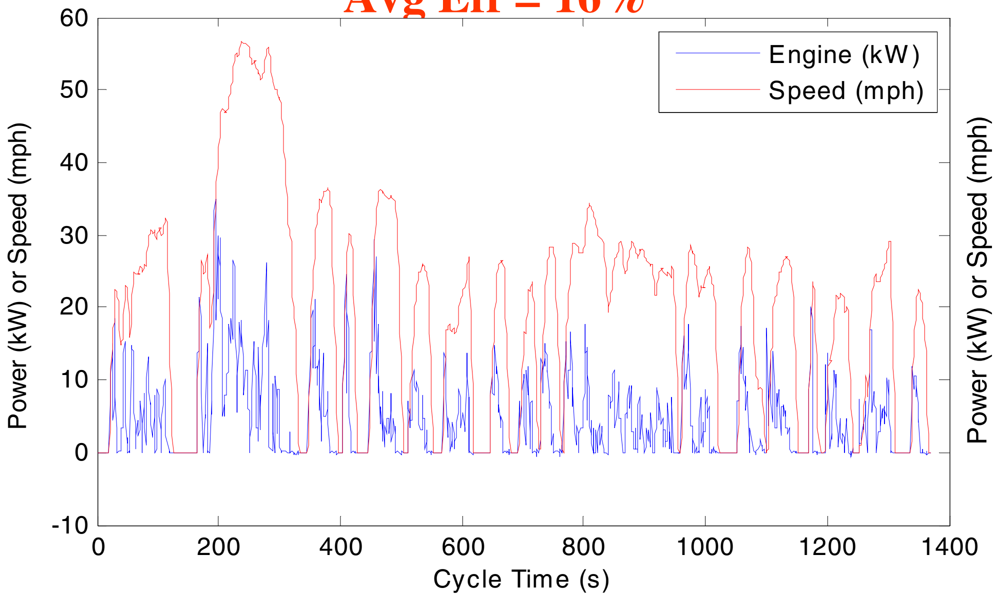



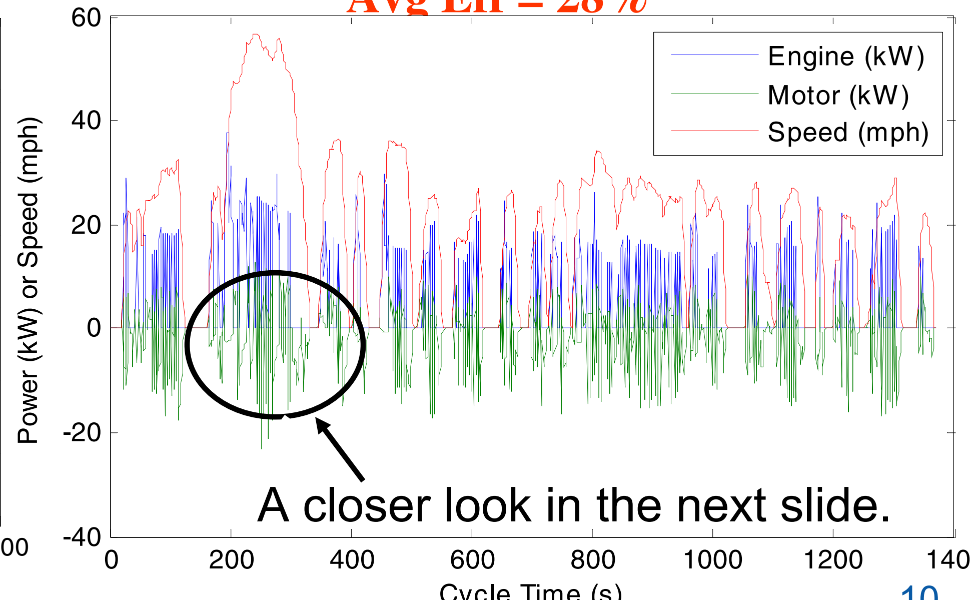

Conventional Vehicle - 21.7 mpg (city)

**Avg Eff = 16%**

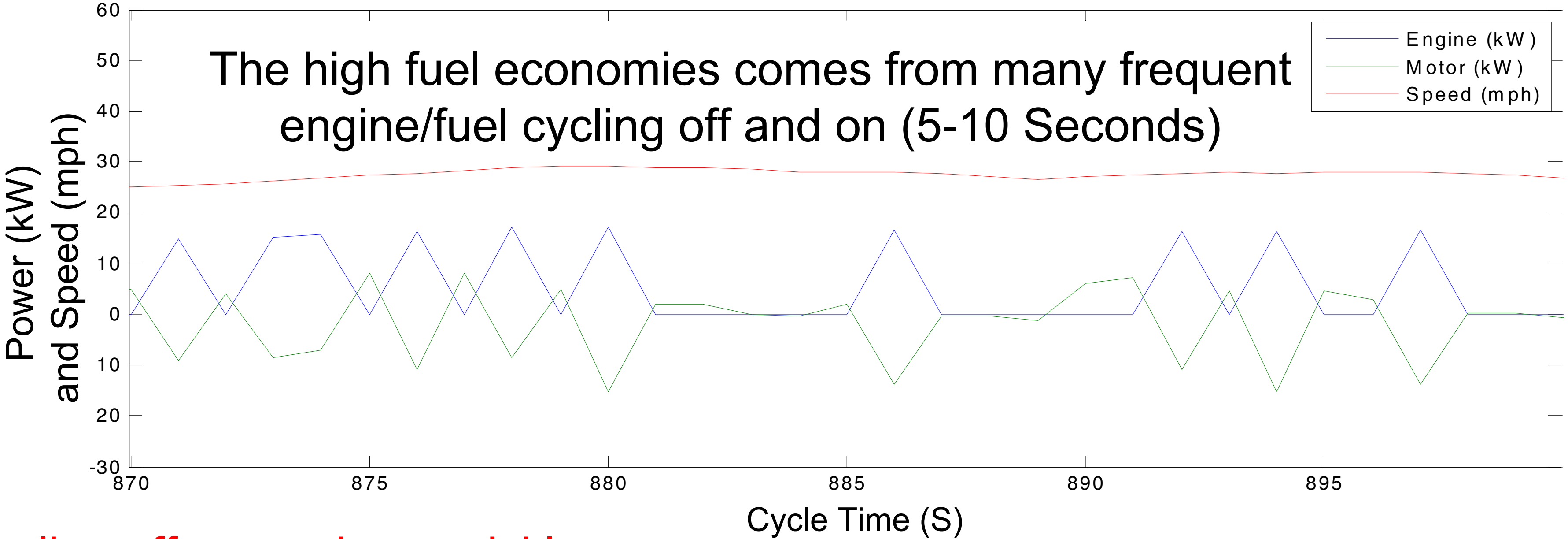
Ultracapacitor Mild Hybrid Vehicle - 36.1 mpg (city)

**Avg Eff = 28%**

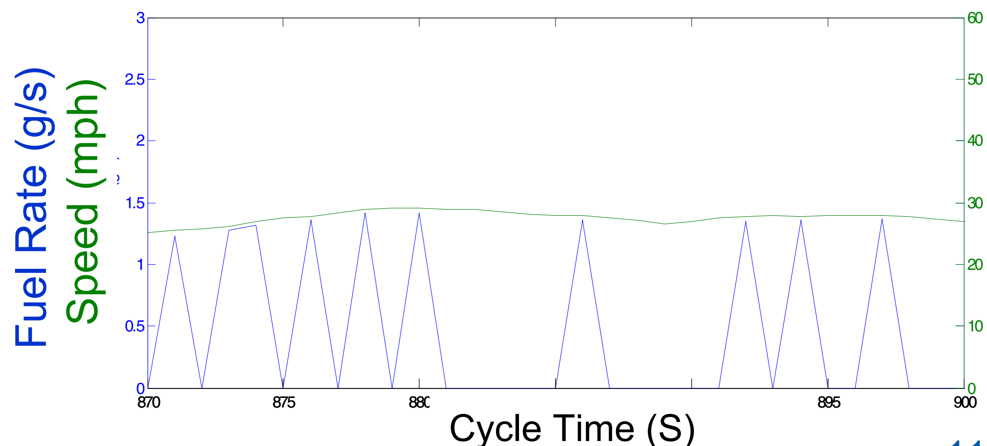


# Closer Look at 2005 Analysis Showed Rapid Engine On/Off Oscillation for Ucap Hybrid




Cycling off-on engines quickly may not be practical from operating, noise, durability, and drivability perspectives so stated high fuel economy predictions would not be achievable.



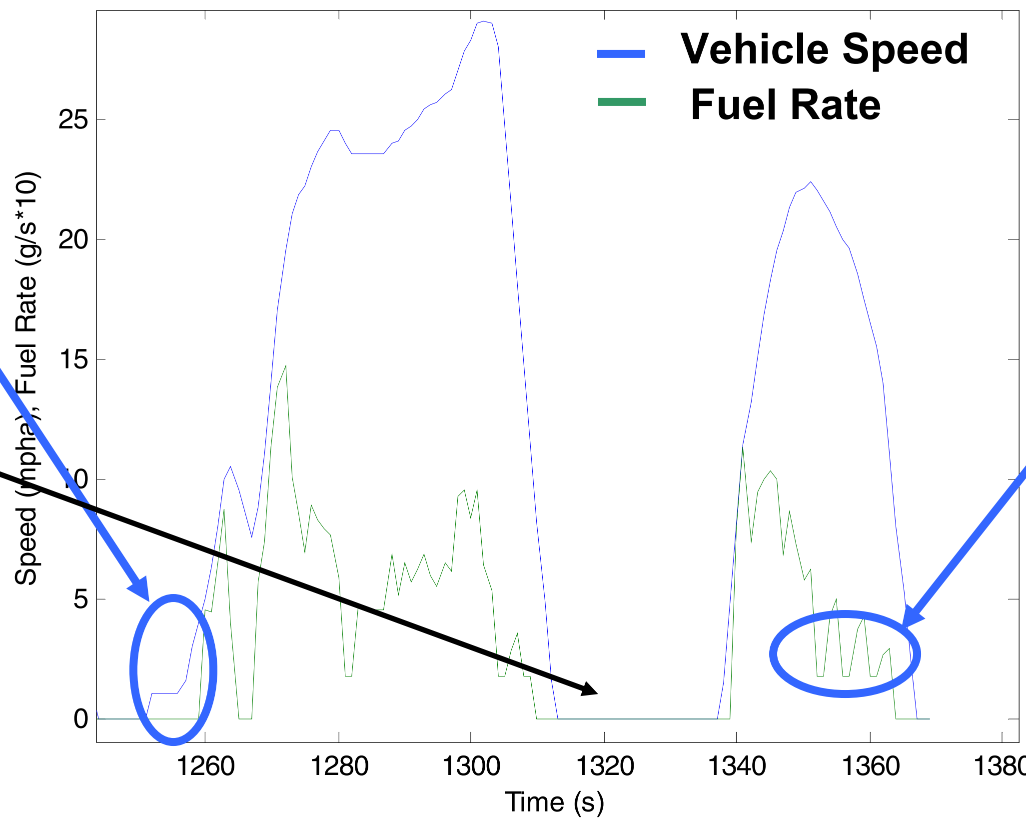
# How Much Fuel Economy Is Possible with Ucaps?

## Relatively Aggressive *Mild Hybrid* Strategy Assumptions

Engine is OFF when vehicle has stopped, ON above electric launch speed, and OFF during decel below electric decel speed. Regen energy is captured. No extensive fuel cycling during higher speed driving.

**No fuel consumed during electric launch (up to ~4.5 mph)**

**or idle stop**




**Idle above electric decel speed of ~11 mph**

***Idealized Low-Speed Engine Off Assumption*: no added driveline friction when fuel off.**

# NREL Simulation Results – Mild Hybrid Strategy

Strategy: Practical engine OFF/ON and Regen Capture. Component sizing similar to Burke's study except using 5 speed manual transmission: no downsizing of engine for a midsize car. Assumed that all runs are with hot engine, ignoring cold start losses.

| Configuration | ESS | ESS kg | Unadjusted mpg | | |
|---|---|---|---|---|---|
| | | | UDDS | US06 | HWFET |
| Conv. 5-spd<br>120 kW | N/A | N/A | 26.0 | 27.8 | 38.4 |
| HEV 5-spd<br>(120 + 15/27) kW | Advanced NiMH | 20 | 31.8 | 31.3 | 39.6 |
| HEV 5-spd<br>(120 + 15/27) kW | Current Li-Ion | 20 | 32.1 | 31.7 | 39.8 |
| HEV 5-spd<br>(120 + 15/27) kW | Ultracap | 7 | 32.2 | 31.3 | 39.7 |

Fuel economy comparison with conventional

- Gains: 23% on UDDS, 13% on US06, 3% on HWFET
- More in line with hybridization benefits from commercial mild hybrids

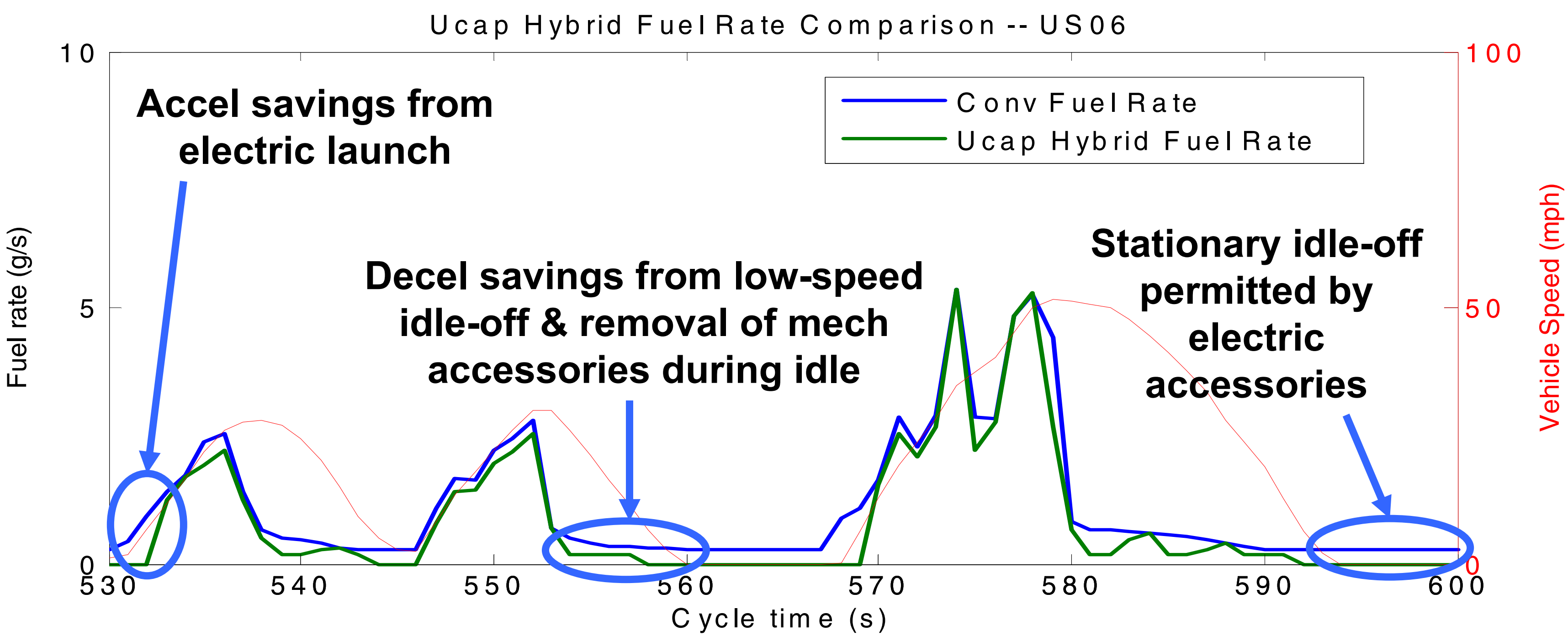
Fuel economy comparison between hybrids

- No appreciable difference between ucap and battery hybrids in this configuration.

# Categorization of Mild Hybrid Fuel Savings

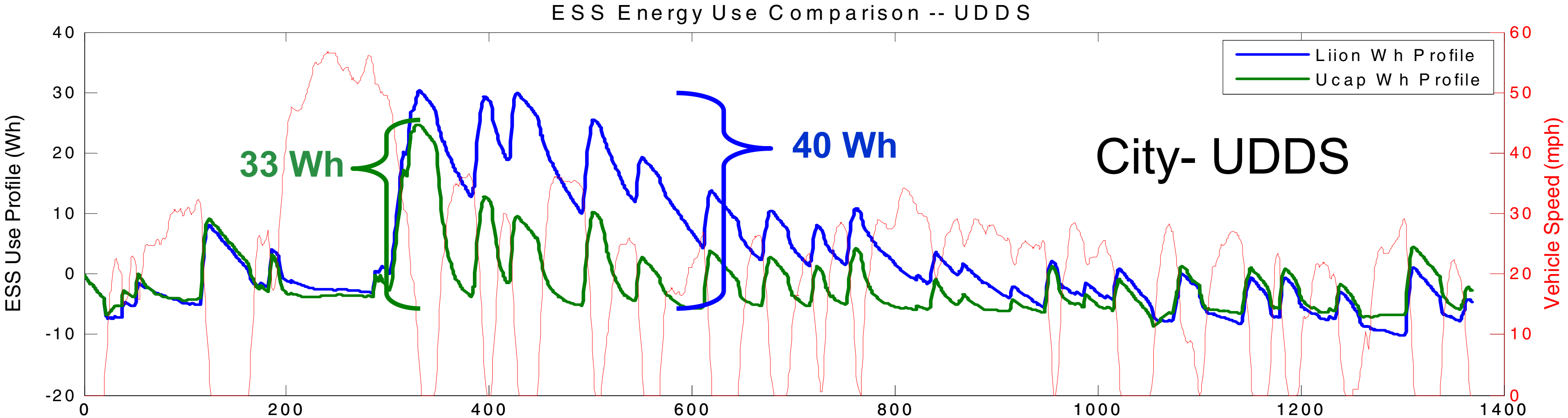
## (no significant mpg difference between Li-Ion and Ucap hybrids)

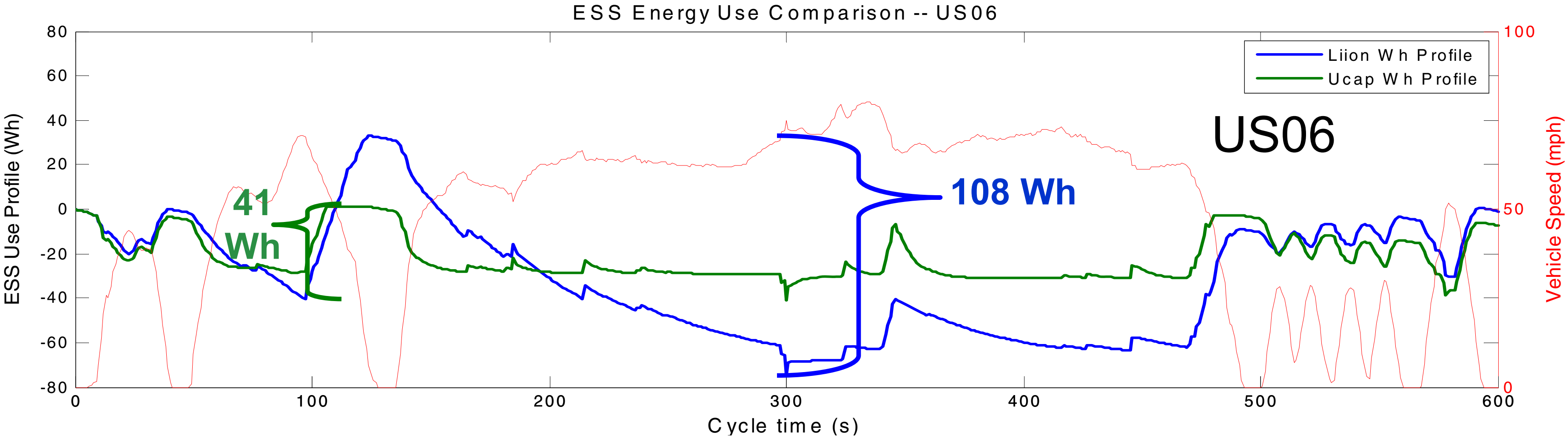
| Driving Condition Category | UDDS | | HWFET | | US06 | |
|---|---|---|---|---|---|---|
| | Ucap | Li-ion | Ucap | Li-ion | Ucap | Li-ion |
| Stationary - Stop | 47% | 48% | 8% | 7% | 14% | 13% |
| Decelerating | 42% | 44% | 77% | 82% | 53% | 52% |
| Accelerating | 10% | 9% | 15% | 10% | 33% | 36% |
| *(Cycle mpg gain)* | *(~23% over conv.)* | | *(~13% over conv.)* | | *(~3% over conv.)* | |



# Ucap & Battery Energy Use Comparison

## (Drive-cycle characteristics dictate the amount of energy needed.)



# Comments on Results with Simple Mild-Hybrid Strategy and No Engine Downsizing

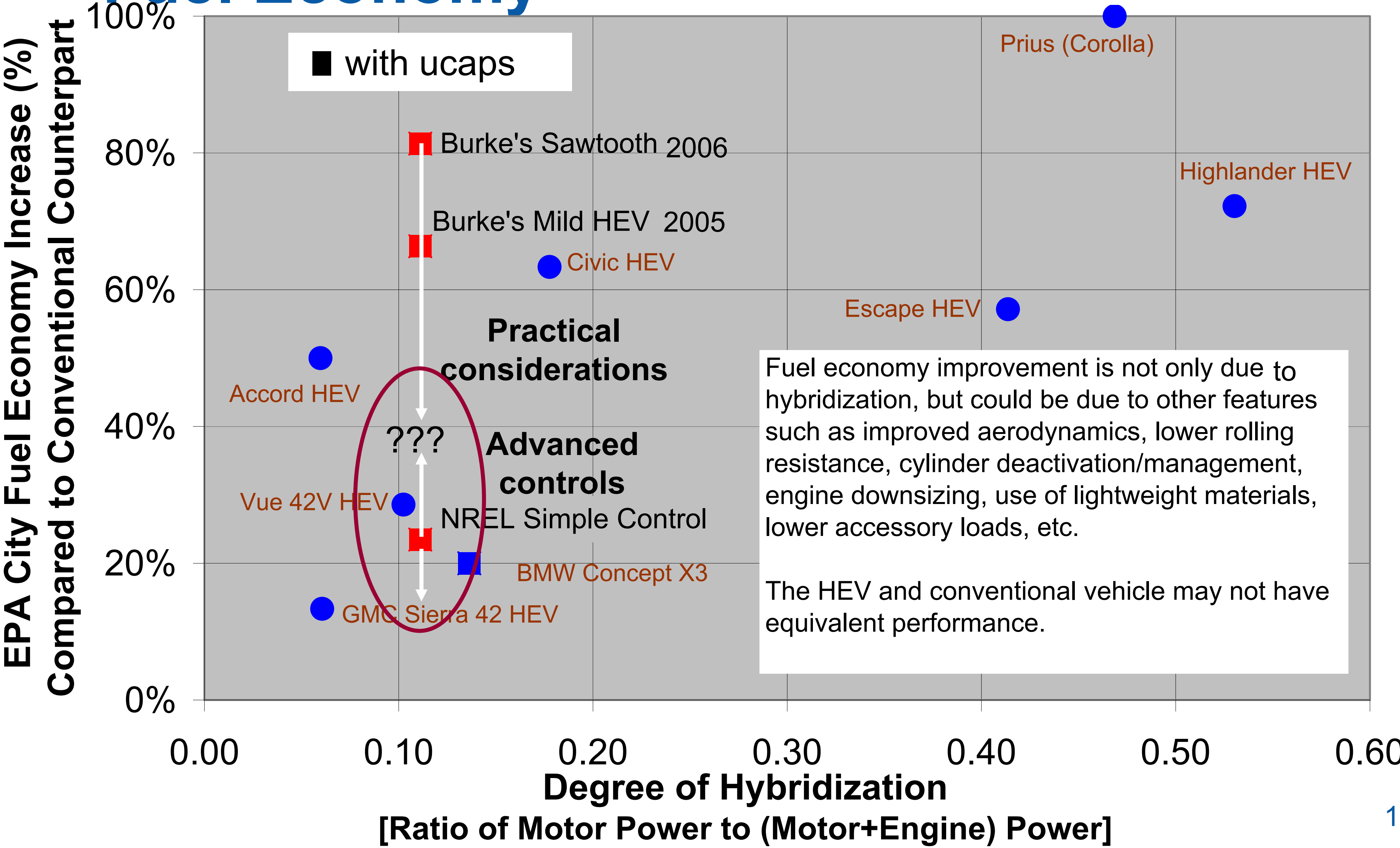
- Differences Between the Drive Cycles
  - Larger number and duration of stops on UDDS → larger mpg improvement from idle-off
- Comparing Hybrids' Performance
  - Efficiency gains of Ucap hybrid is offset by restricted regen capture from 100% SOC ceiling (limited energy)
  - Mild hybrid control strategy with no engine downsizing
    - → Small power flow through ESS relative to engine
    - → Diluted fuel economy impacts of ESS changes
  - Modeled batteries larger than needed – used <50% of available energy window for given control strategy and drive cycles.
    - Can this energy be used better if engine is downsized ?
  - Fuel economy improvements (23% for city and 13% for US06) may be on the high end due to idealized low-speed engine off assumption (neglecting any fuel penalty or added driveline friction)
  - No significant difference in fuel economy between Ucap and Li-ion hybrids

# Comments on Recent Sawtooth Control Strategy for Mild HEVs*

- Fuel economy of baseline conventional vehicle seems too low – may contribute to high mpg improvement (74% in city with no engine losses).
- Many engine/fuel on/off cycles (e.g. – engine alternately ON for 30 seconds then OFF for 30 seconds over ~1/2 hour of highway driving).
  - Critical to properly model how this engine operation could be implemented.
  - Drivability and emissions must be considered.
- If not de-clutching the engine, repeatedly blending torque ON and OFF the driveline requires either idling the engine or accounting for a resistive torque/friction on the driveline when powering the wheels electrically.
  - Underestimating the engine idle or restart fuel requirement or driveline impact will result in over prediction of the fuel savings.
- Such outside-the-box HEV control strategies (pairing novel engine management with frequent but shallow cycling of the ESS) could create a natural application for Ucaps to provide significant FE improvements.
  - Requires practical treatment of drivability, noise, engine wear, emissions, etc.
  - Will compete with advanced engine strategies not as reliant upon energy storage (e.g. – cylinder deactivation/variable displacement) that provide high efficiency at the power requested, rather than alternately providing excess power at high efficiency and then switching the engine off.

* Burke (UCAP 2006)

# Potential of Mild Hybrids with Ucaps for Fuel Economy



# Rationale for Using Ultracapacitors with Electric Drive

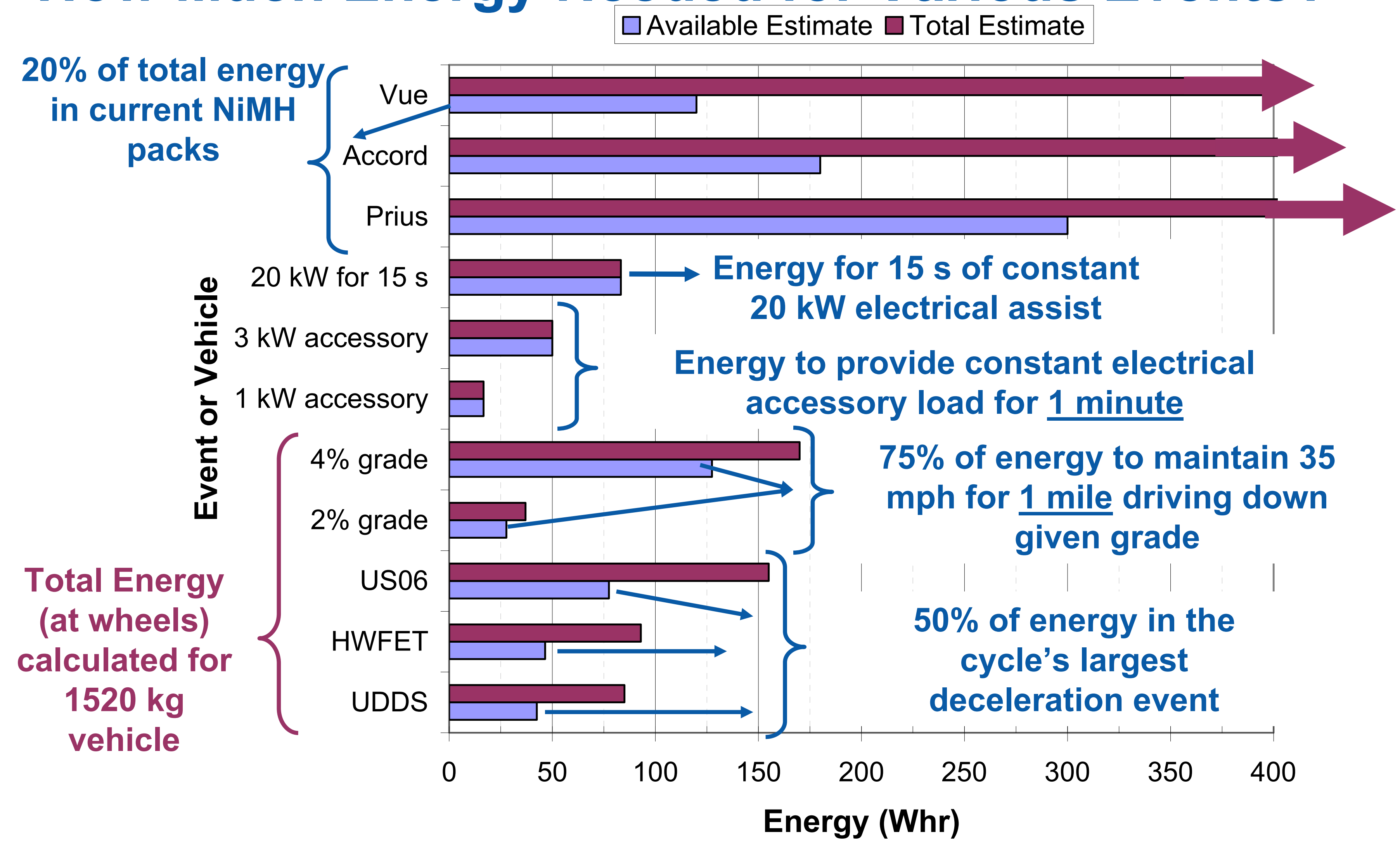
Taking advantage of ultracapacitor's strengths (+) while minimizing impact of its weaknesses (-) if the COST was comparable to batteries

+ High specific power → Engine assist
+ Efficient charge acceptance → Regen capture
+ Low resistance → Low cooling needs
+ Quick response (short time constant) → Supporting engine transients
+ Long anticipated calendar and cycle lifes
+ High specific power at low temperatures (cold starts) → Small energy storage

– Low specific energy → Limited power draw durations for
  - Acceleration
  - Engine assist, specifically for grade
  - Running auxiliaries at idle

The best use for ucaps are strategies that make engine to operate more efficiently (idle off, load leveling), and recapturing regen energy.

# Ucap is Energy Limited. How Much Energy Needed for Various Events?




Cold-start capability is expected to dictate the size of batteries, but not Ucap.

# Summary - 1

- The high fuel economies reported last year (AABC-05) with use of relatively small, high-voltage ultracapacitor pack in mild hybrids are high and could not be achieved in practice.
- For Ucaps used with a simple mild hybrid control strategy utilizing idle-off and regen capture (and no engine downsizing) in a midsize vehicle, we found:
  - The fuel economy improvement could be at best ~20% for city driving.
  - There is little fuel economy difference with a hybrid using Li-Ion batteries.
  - If cost is the same, and without taking advantage of extra energy from Li-Ion, the superior life and low-temperature performance of Ucaps make them more attractive.

# Summary - 2

- Ucaps provide opportunity for applications with low energy and quick response needs.
- Many of the functions required from an energy storage device in mild hybrids could be met with less than 100 Wh for a midsize car.
- Practical engine management and control strategies are “key” in enabling Ucaps (or batteries) to achieve fuel economy improvements much higher than 20% with novel mild hybrid approaches.
- Some advanced engine and control strategy development may match especially well with particular Ucap attributes such as quick response, high power, and high efficiency.

# Future Work for High-Voltage Ucap HEVs

- Need to go beyond “no downsized” engine mild hybrid applications.
- Evaluate different component sizes (engine, motor, and ESS) and control parameter values over a realistic range to find the optimum vehicle design for a set of drive cycles.
- Apply constraints to define what is “optimum” (e.g., hold performance constant and maximize fuel economy; find best mpg/$-increment vehicle; maximize combined equation for performance, cost and fuel economy; consider cold start, life, etc.).
- Study could also output relationship between ESS usable energy and fuel economy improvement (given by optimized control parameters at each Wh size increment).
- Evaluate concepts by perform experiments using advanced, but practical control and engine management strategies.

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