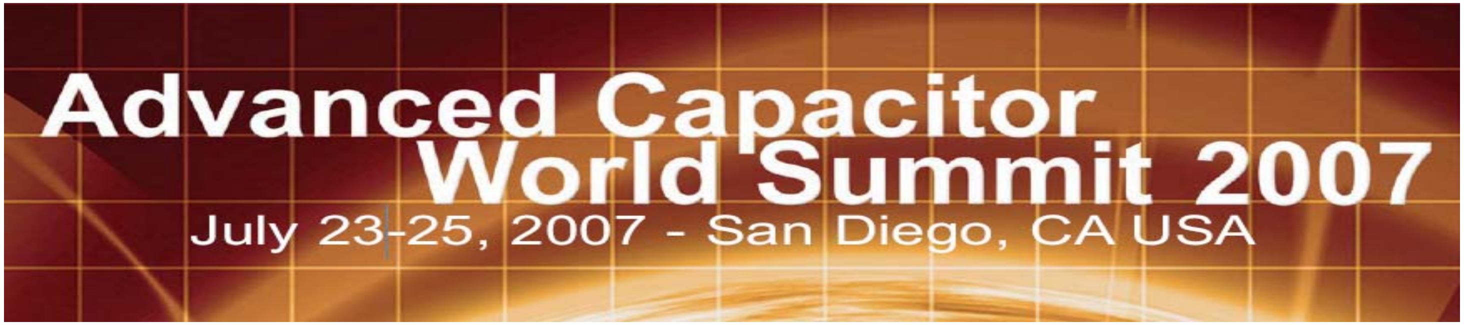
Factors & Conditions for Widespread Use of Ultracapacitors in Automotive Applications



Ahmad Pesaran
(ahmad_pesaran@nrel.gov)
With input from Jeff Gonder and Aaron Brooker
National Renewable Energy Laboratory

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FreedomCAR & Fuel Partnership

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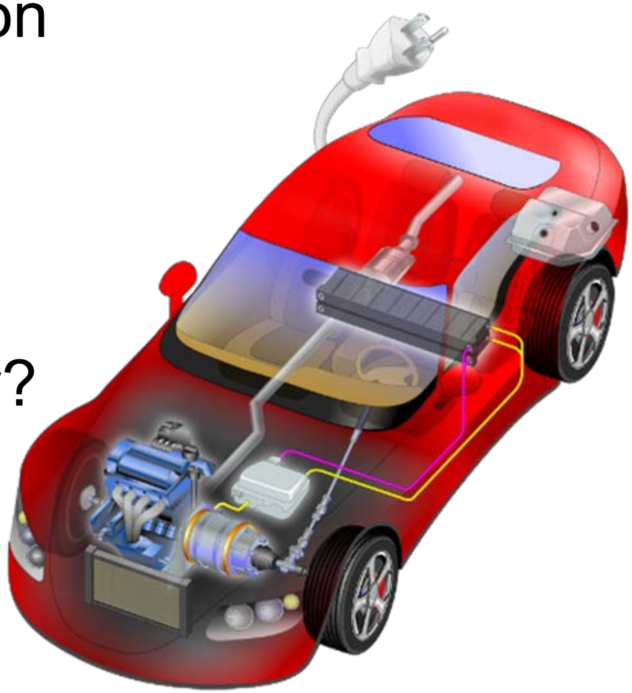
Content

- 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

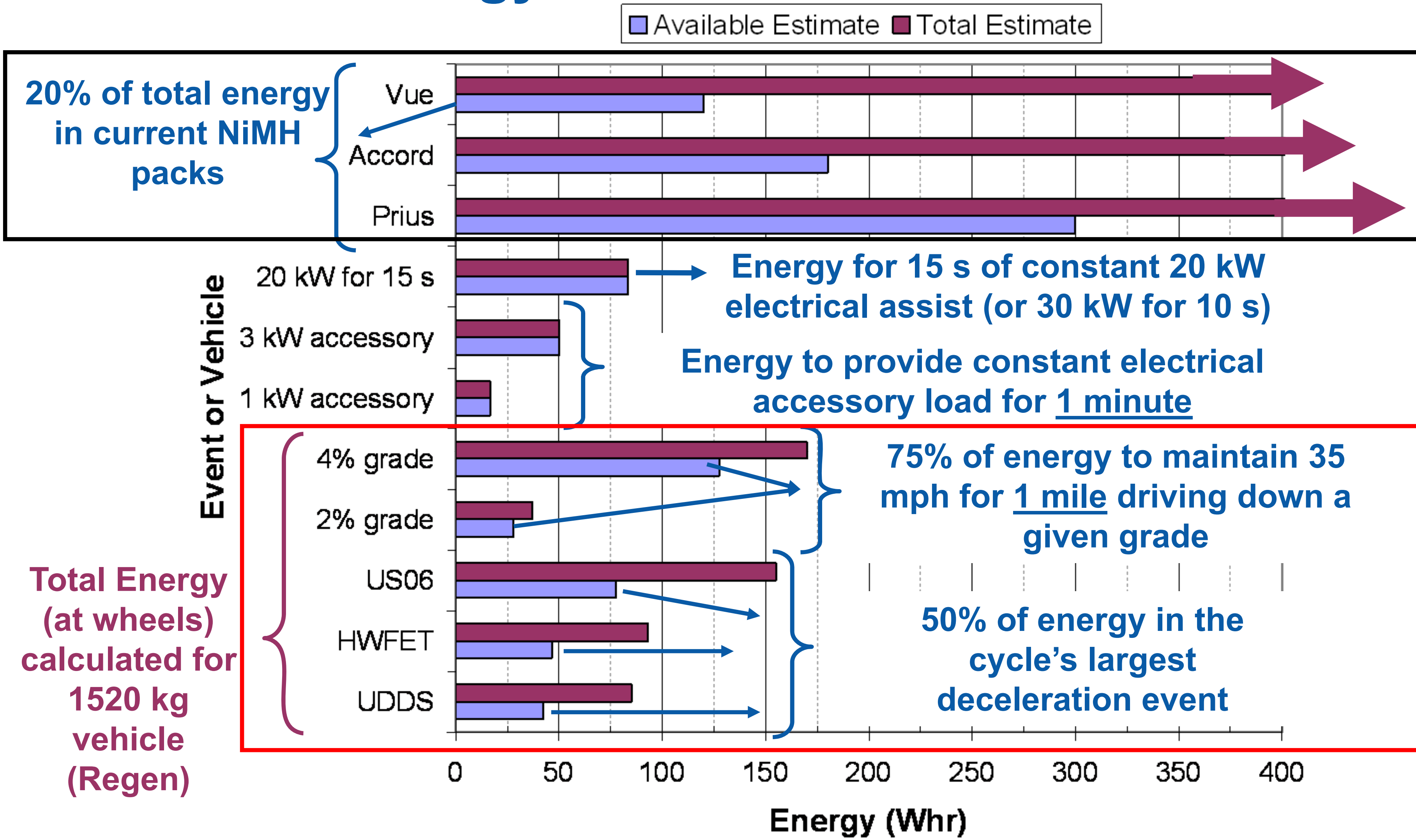
Rationale for Using Ucaps with Electric Drive

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

- \+ High specific power and efficiency → Engine assist
- \+ Efficient charge acceptance → Regen capture
- \+ Low resistance → Lower cooling needs
- \+ Quick response (short time constant) → Supporting engine transients
- \+ Long anticipated calendar and cycle lifes → Fewer replacements
- \+ High specific power at low temperatures (cold starts) → Smaller capacity
- – Low specific energy → Limited "durations" for power draw
- – High self discharge
  - Acceleration
  - Engine assist, specifically for grade
  - Running auxiliaries at idle
- ?? 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?



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

Deg. of Hybr. = 0.26

- H_2 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 H_2

BMW X3 Efficient Dynamics Mild Hybrid Concept

Deg. of Hybr. = 0.16

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

Supercaps (Asahi glass?)

Supercaps (EPCOS?)

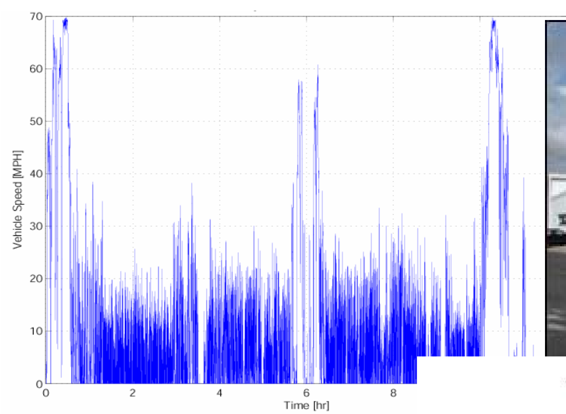
Background - Heavy Duty Hybrids with Ucaps

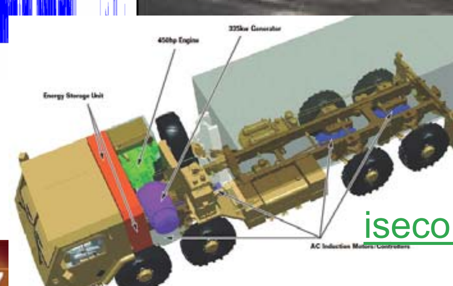
Oshkosh's Hybrid Refuse Hauler

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

greencarcongress.com/2006/11/oshkosh_truck_u.html)





ISE's Hybrid Transit Buses

ISE uses Two Ultracapacitor Packs

Spec of a Ucap Pack:

- **Total Energy Stored: 0.407kWh**
- **150 kW Power**
- **4 Wh/kg Energy Density**
- **1.5kW/kg Power Density**
- **Expected life 10-12 years**
- **System Cost : 100 $/kW**

isecorp.com/hybrid_information_center/pdf/ultracapacitors_001.pdf

FreedomCAR/USABC Ucap Requirements

USCAR.org

System Attributes	12V Start-Stop (TSS)		42V Start-Stop (FSS)		42V Transient Power Assist (TPA)	
Discharge Pulse	4.2 kW	2s	6 kW	2s	13 kW	2s
Regenerative Pulse	N/A		N/A		8 kW	2s
Cold Cranking Pulse @ -30°C	4.2 kW	7 V Min.	8 kW	21 V Min.	8 kW	21 V Min.
Available Energy (CP @1kW)	15 Wh		30 Wh		60 Wh	
Recharge Rate (kW)	0.4 kW		2.4 kW		2.6 kW	
Cycle Life / Equiv. Road Miles	750k / 150,000 miles		750k / 150,000 miles		750k / 150,000 miles	
Calendar Life (Yrs)	15		15		15	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Selling Price ($/system @ 100k/yr)	40		80		130	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Energy Density (Wh/lLiter)	3.25		3.25		3.25	
Specific Power (W/kg)	840		600		650	
Selling Price ($/Wh)	2.78		2.78		2.17	
Selling Price ($/kW)	9.6		10		10	

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, 8cyl, 5.3L
- **Real fuel economy improvement with idle off**
  - — 5% to 10%

Source: Pesaran, et.al., "Ultracapacitors and Batteries in Hybrid Vehicles," Proceedings of the Advanced Capacitor Summit, 2005

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

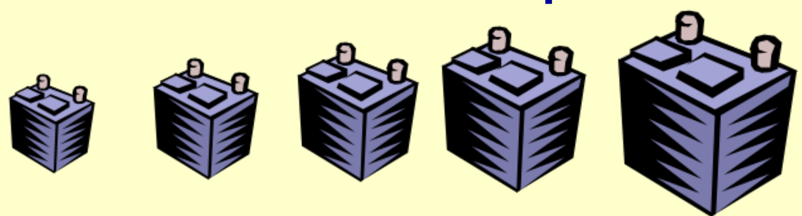
Midsize Car Assumptions

FA = 2.27 m^2
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

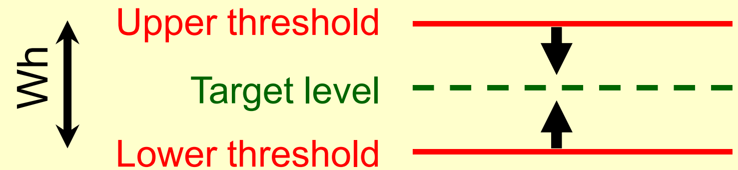
Simulated different ES energy content cases with the otherwise constant platform values

Smallest ES energy



Largest ES energy

Constant 30 kW power → changing P/E ratio

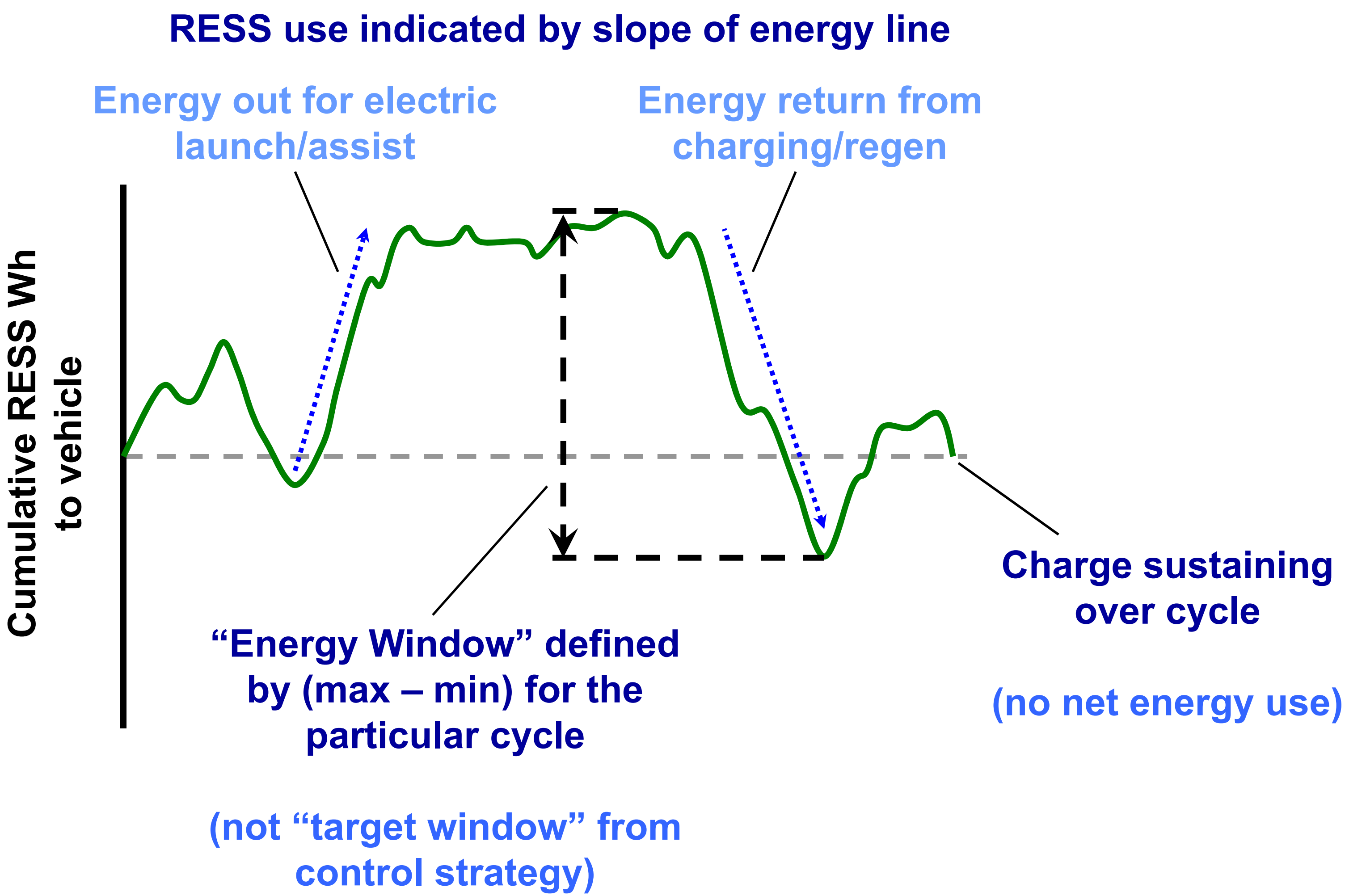


Constant SOC-based controls (charge sustaining)

↓

Changing Wh control window tolerance

Definition of ES Energy Window Use (for a drive cycle or event)

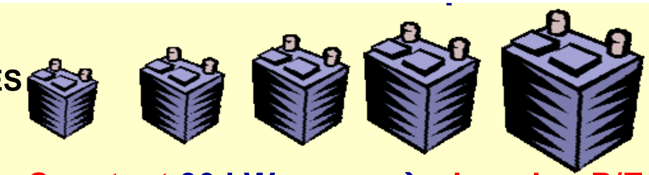


Energy Window Used ≤ Available Energy

Source: J. Gonder, Presentation to USABC, July 19, 2007

Three cycles simulated to observe energy window and fuel use (for each ES case)

Smallest ES energy



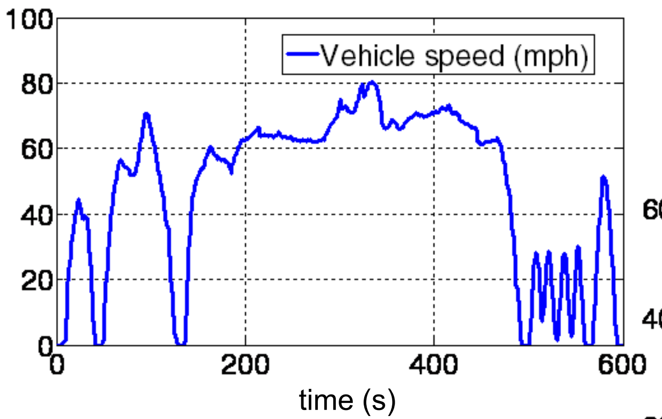
Largest ES energy

Constant 30 kW power → changing P/E ratio

Aggressive driving

US06 Cycle

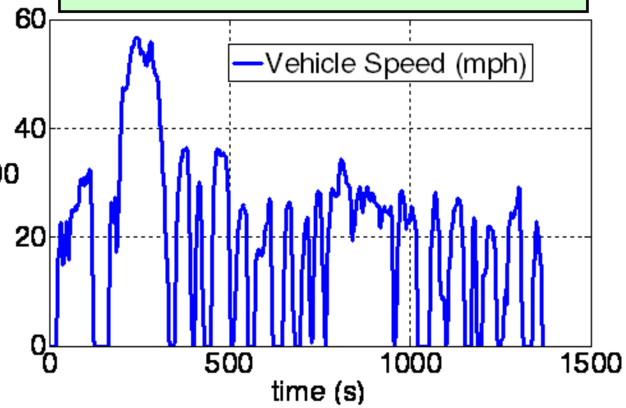
- Mean power during:
  - Propulsion = **21 kW**
  - Deceleration = **-17 kW**
- No grade



Mild urban driving

UDDS Cycle

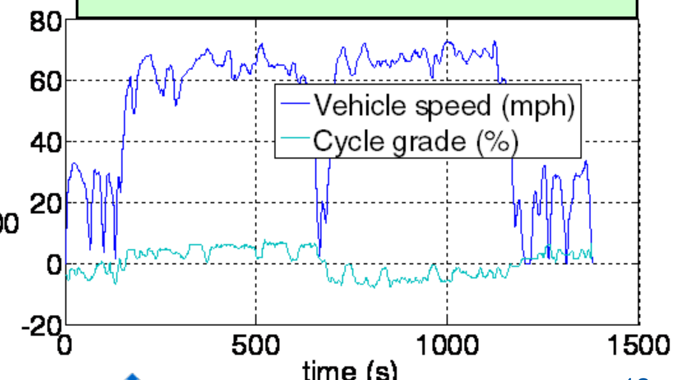
- Mean power during:
  - Propulsion = **7 kW**
  - Deceleration = **-5 kW**
- No grade



Up and down, foothills driving

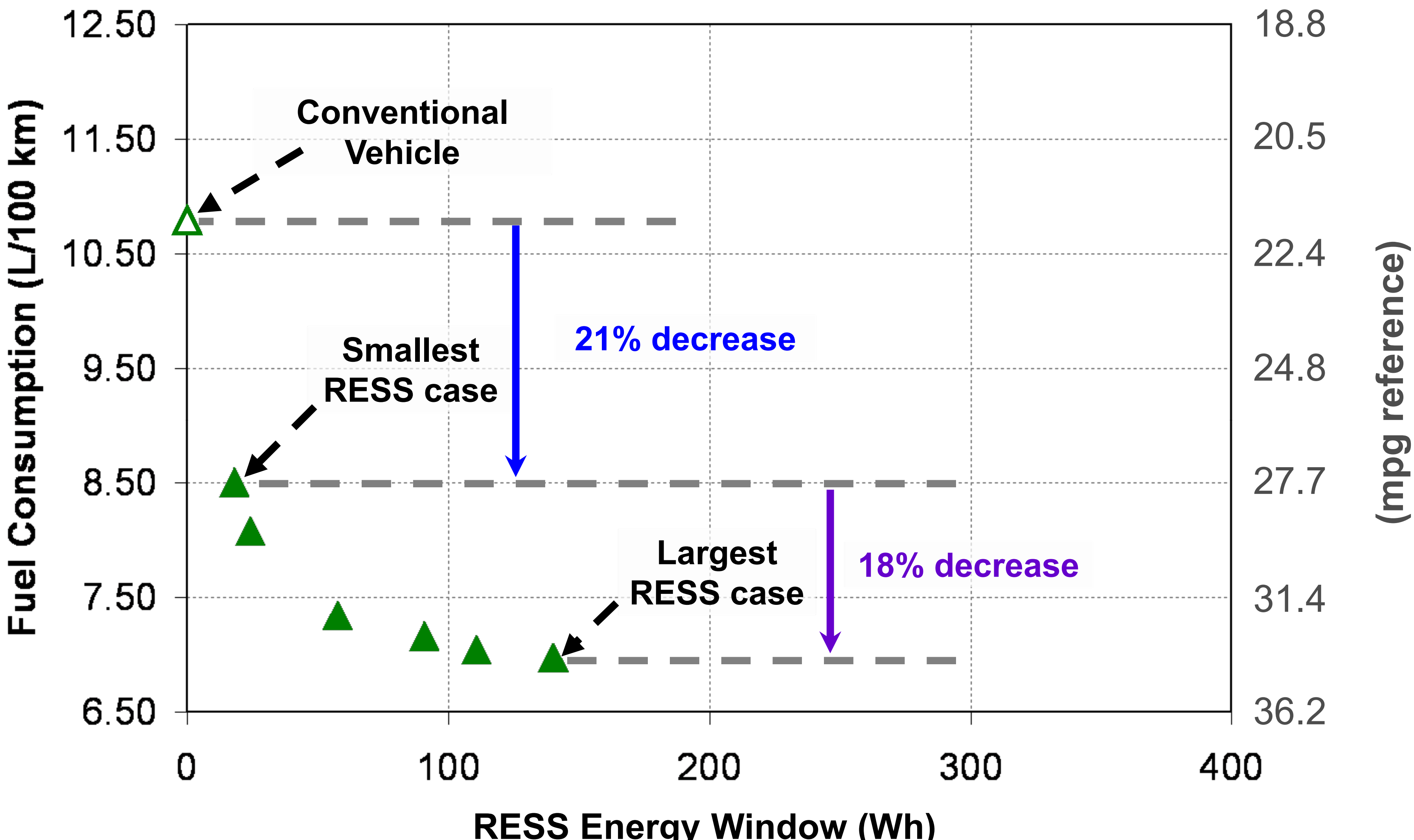
"NREL to Genesee, CO Cycle"

- Mean power during:
  - Propulsion = **23 kW**
  - Deceleration = **-12 kW**
- Considerable grade



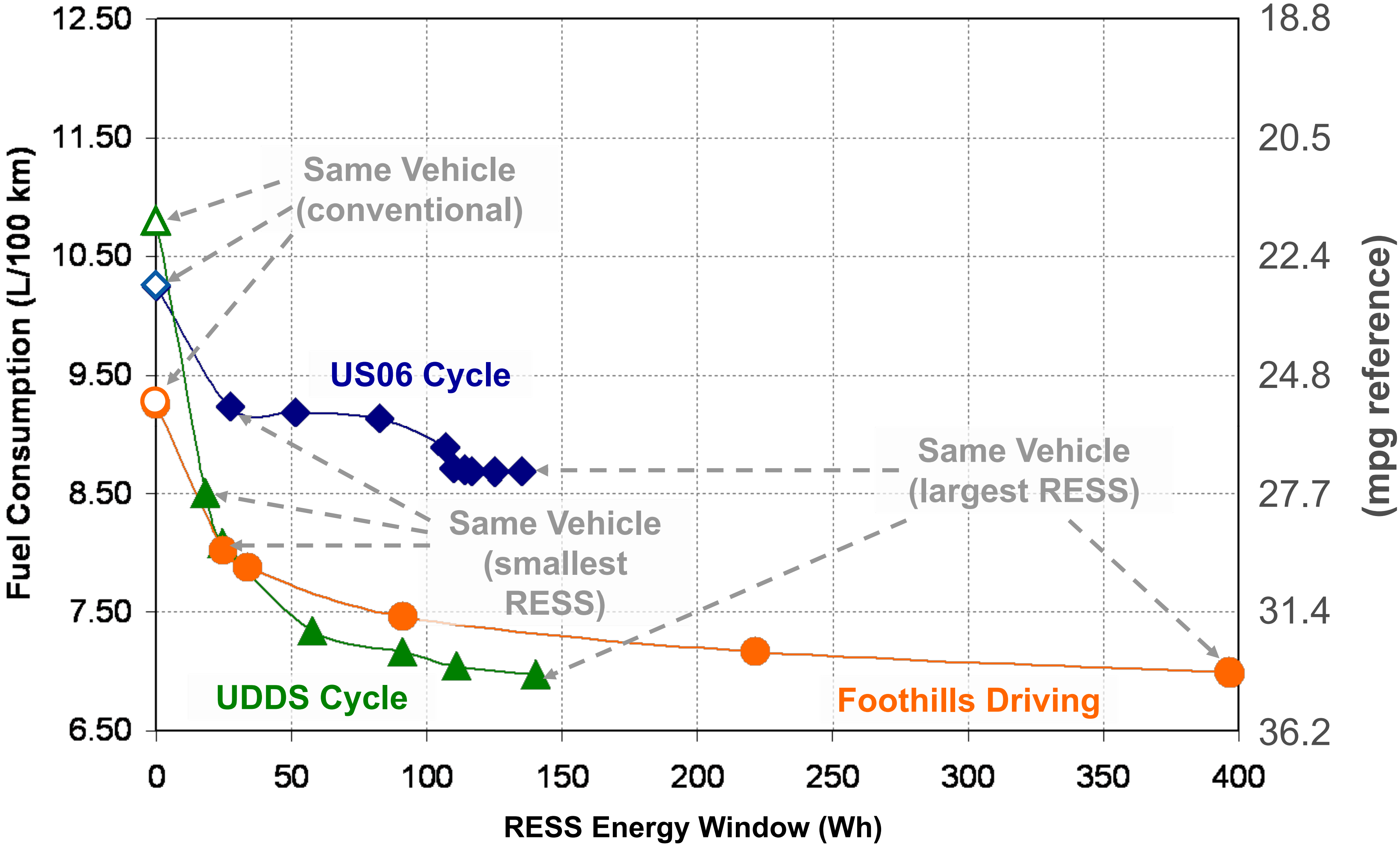
Source: J. Gonder, Presentation to USABC, July 19, 2007

On UDDS, large fuel savings from hybridization and from energy window expansion



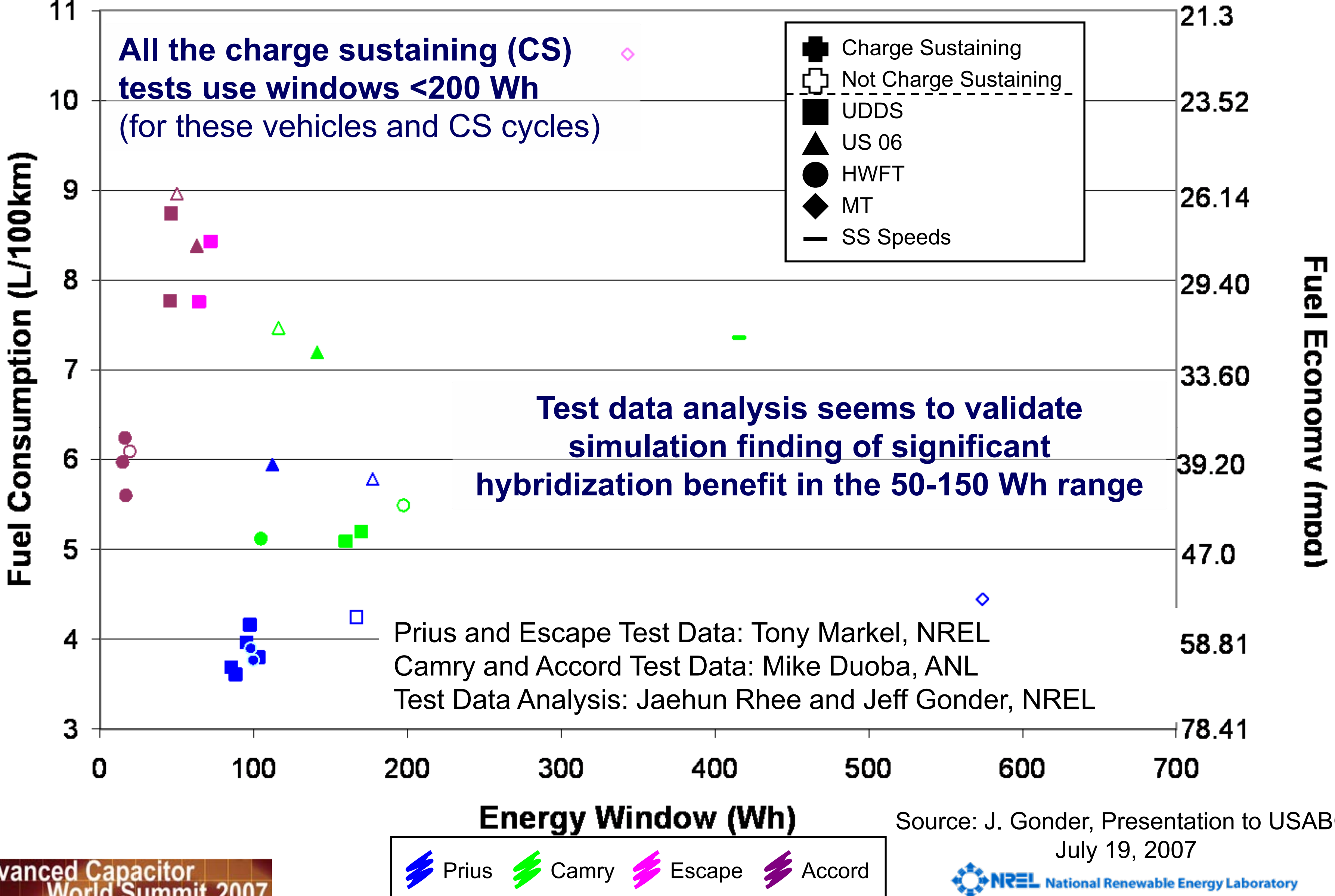
Source: J. Gonder, Presentation to USABC, July 19, 2007

Summary Results of ES Energy Window and Fuel Economy Simulations



Source: J. Gonder, Presentation to USABC, July 19, 2007

Vehicle Test Results: Battery Energy Window for Today's HEVs under Various Drive Cycles



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?

10-S pulse power: 25- 50 kW

Available energy: 4 -12 kWh

Number of HEV cycles: 300,000

Calendar life: 15 years

Cost: $200-$350/kWh$_{total}$

$30-$70/kW

USCAR.org

USABC Goals for Energy Storage in PHEV's

Requirements of End of Life Energy Storage Systems for PHEVs

Characteristics at EOL (End of Life)		High Power/Energy Ratio Battery	High Energy/Power Ratio Battery
Reference Equivalent Electric Range	miles	10	40
Peak Pulse Discharge Power - 2 Sec / 10 Sec	kW	50 / 45	46 / 38
Peak Regen Pulse Power (10 sec)	kW	30	25
Available Energy for CD (Charge Depleting) Mode, 10 kW Rate	kWh	3.4	11.6
Available Energy for CS (Charge Sustaining) Mode	kWh	0.5	0.3
Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	90	90
Cold cranking power at -30°C, 2 sec - 3 Pulses	kW	7	7
CD Life / Discharge Throughput	Cycles/MWh	5,000 / 17	5,000 / 58
CS HEV Cycle Life, 50 Wh Profile	Cycles	300,000	300,000
Calendar Life, 35°C	year	15	15
Maximum System Weight	kg	60	120
Maximum System Volume	Liter	40	80
Maximum Operating Voltage	Vdc	400	400
Minimum Operating Voltage	Vdc	>0.55 x Vmax	>0.55 x Vmax
Maximum Self-discharge	Wh/day	50	50
System Recharge Rate at 30°C	kW	1.4 (120V/15A)	1.4 (120V/15A)
Unassisted Operating & Charging Temperature Range	°C	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66
Maximum System Production Price @ 100k units/yr	$	$1,700	$3,400

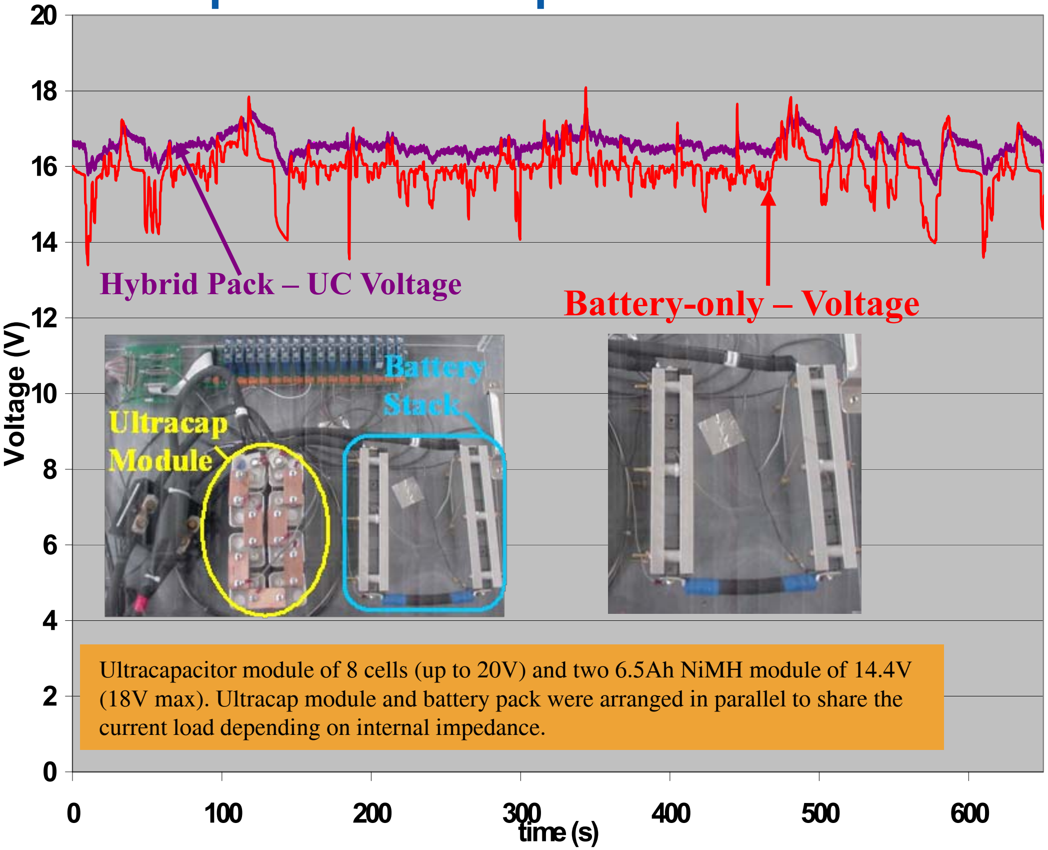
Common ultracapacitors do not have the energy for "charge depleting" operation of a PHEV, but their ability to cycle at high power rates many times and long calendar life provide the opportunity to be combined with high energy batteries.

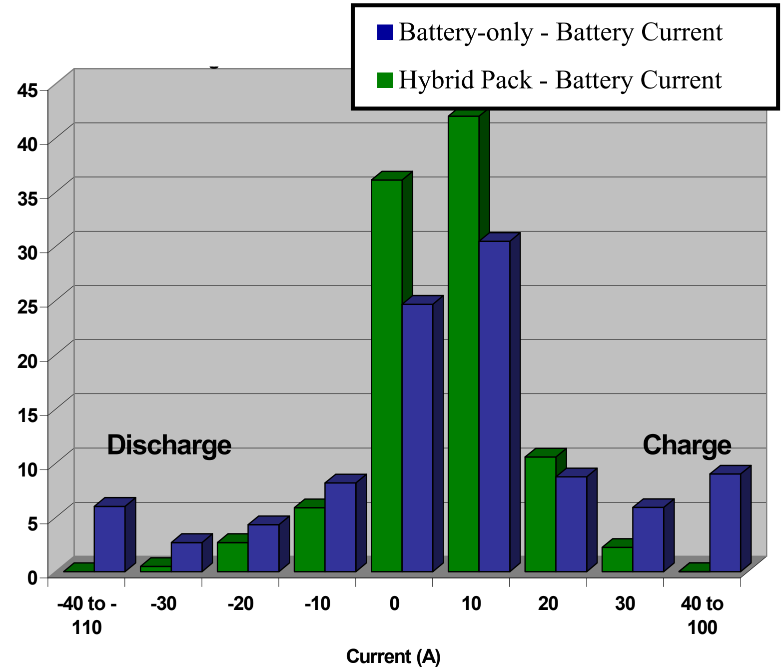
NREL Tests Show that Combining Ultracapacitors with Batteries Could Filter High Voltage Transients

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

Parallel connection; no DC/DC converter

Not practical to implement in vehicles



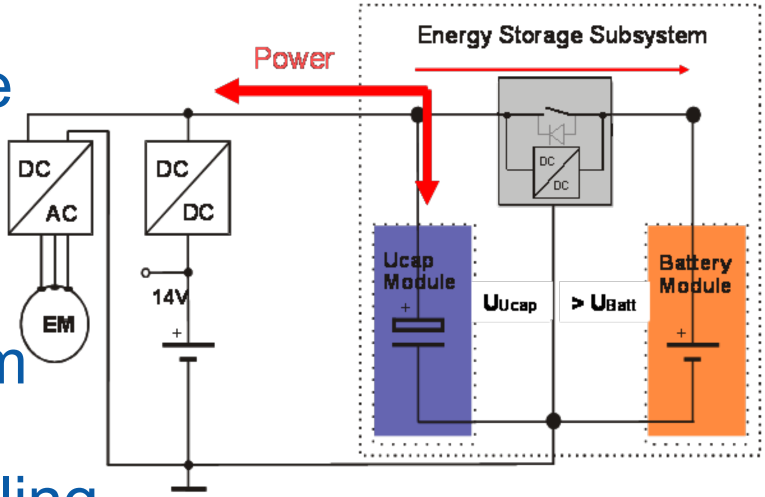


- Overall, the batteries in the hybrid pack experienced no currents larger than ±40A, while the batteries in the traditional pack saw currents up to 110A.
- Up to 33% narrower battery SOC cycling range was observed; has the potential to increase battery life.

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

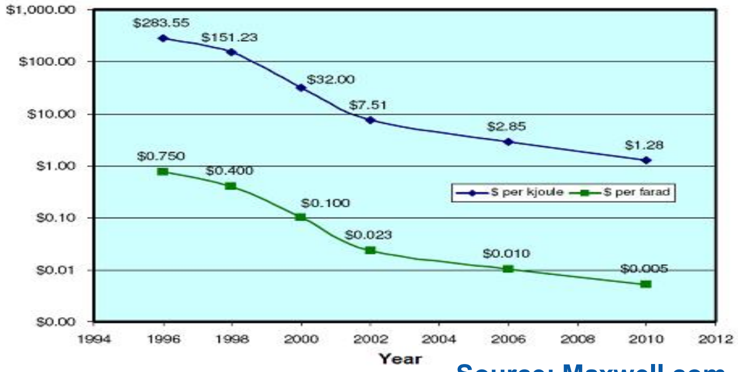


Source: Continental ISAD, “New Energy Storage Concept,” Proceedings of AABC-04

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?



Source: Maxwell.com

- 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?*

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?

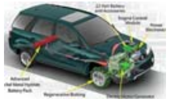
- **The need for more fuel efficient and green vehicles**
  - Continued higher gasoline demand and prices
  - Environmental and global warming concern (green movement)
  - Hybridization becomes common
- **Energy security (lower petroleum imports)**
- **Government regulations**
  - Higher CAFE (fuel economy regulation)
    - » 27.5 mpg for cars, now
    - » 22.5 mpg for light trucks, now

    → To combined 35 mpg in 2019*

    *Proposed bill S. 357 in the 110th Congress
  - Adoption of CO_2 regulation/tax
  - Tax incentives
  - Idle-off from heavy to light vehicles??

- 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

Micro Hybrids - (12V-42V: Start-Stop, Launch Assist) 	VRLA: Yes NiMH and Li-Ion: Yes, Likely **Ucap: Likely** **Ucap + VRLA: Possible** **Min energy needed** **15-20 Wh**
Mild Hybrids - (42V-150V: Micro HEV Function + Regen)  	VRLA: Yes (42V) NiMH and Li-ion: Yes, Likely **Ucaps: Likely if engine is not downsized** **Ucaps + VRLA: Possible** **20-60 Wh**
Full Hybrids - (150V-350V: Power Assist HEV)  	VRLA: Not Likely NiMH and Li-Ion: Yes, Likely **Ucaps: Possible** **Ucaps + (NiMH or Li-Ion): Possible** **60-120 Wh**
Fuel Cell Hybrids  	VRLA: Not Likely NiMH and Li-ion: Yes, Likely **Ucaps: Likely if Fuel Cell is not downsized** **Ucaps + (NiMH or Li-Ion): Possible** **60-120 Wh**
Plug-in HEV (some EV range) 	VRLA: Not Likely NiMH and Li-ion: Yes, Likely **Ucaps or (Ucap + VRLA): Not Likely** **Ucaps + Li-ion or NiMH : Possible** **80-100 Wh***

Simple Market Analysis

Example

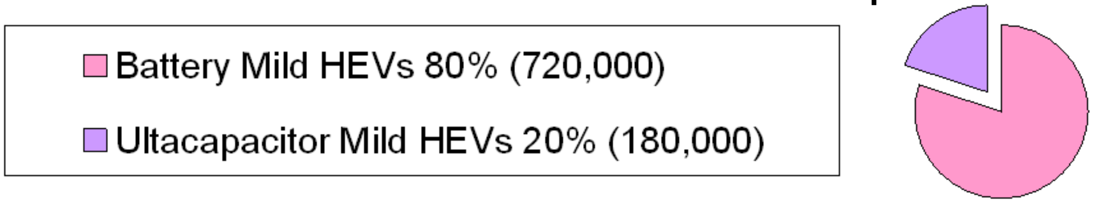
- What are the overall size of automotive markets?
    - — Light duty vehicles vs. heavy duty vehicles

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?



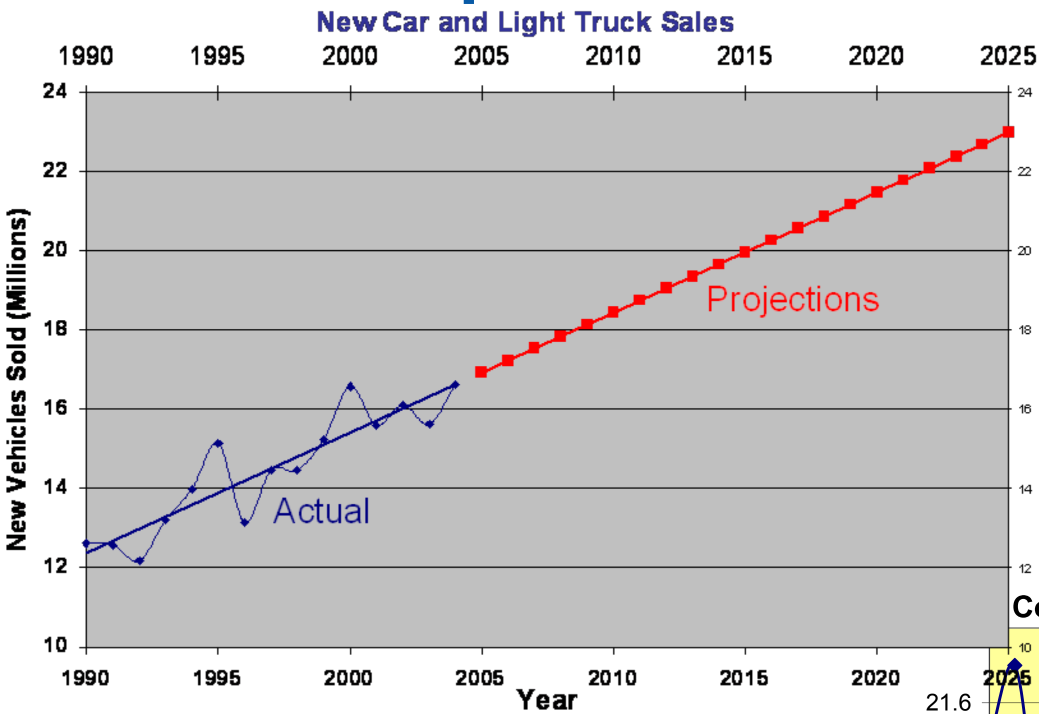
- What ultracapacitor size is required in that vehicle market?

Available energy needed for Mild Hybrids: 80 Wh

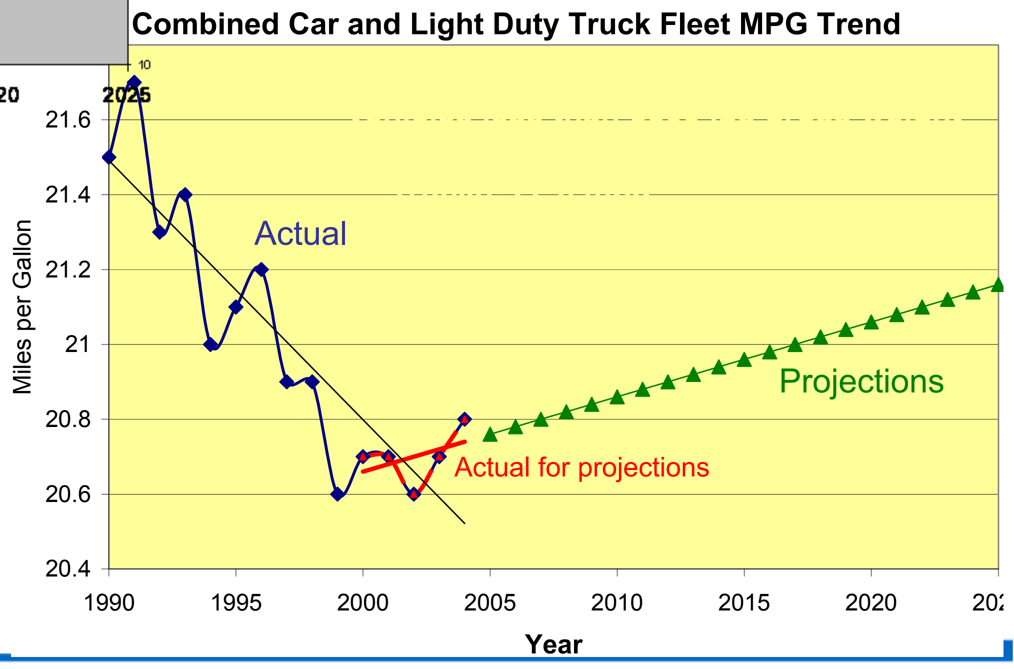
- What would be the total size of that particular market?

Market size: 14 MWh; 6.8 Million cells (at 2.1 Wh/cell); $72 Million (at $5/Wh, $10.5/cell)

Light Duty Vehicle Market and Gasoline Consumption Considerations- Rough Estimates



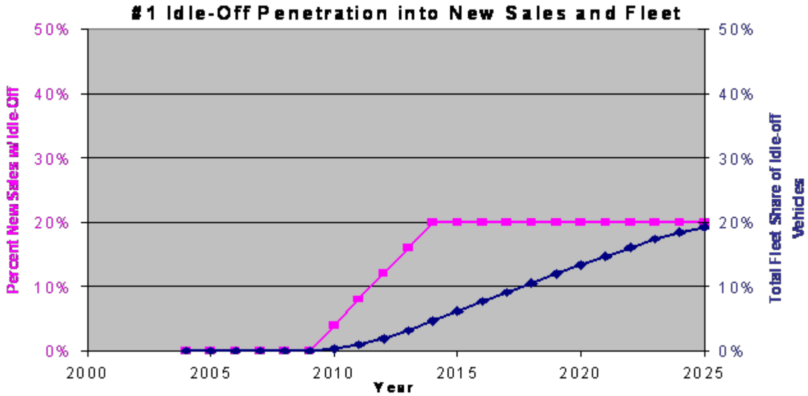
• Currently the annual new cars and light trucks sale in US is about 16 million.



- 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

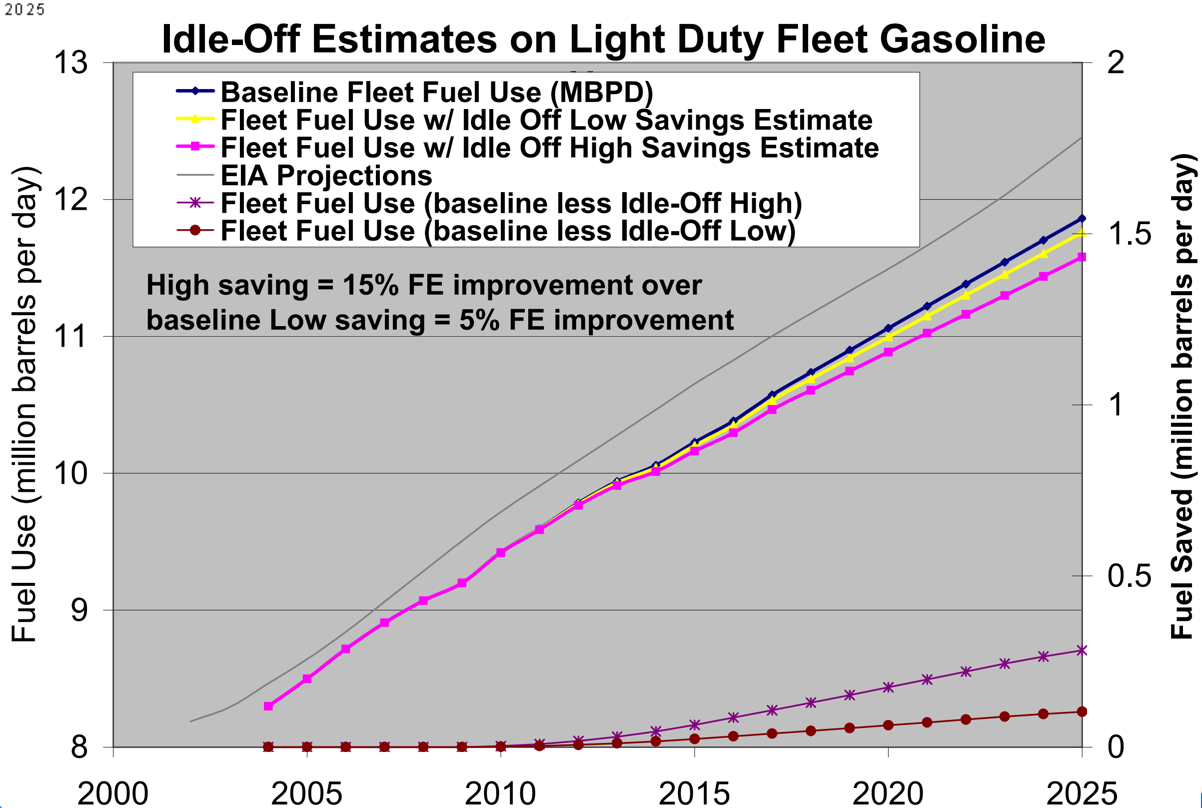


- **Market penetration: 4%/year until 20% saturation**
- **Total number of vehicles in passenger fleet is now about 200 millions (in USA).**
- **Average vehicle turn-over: 14 years**
- **It takes a long time to turn over the entire fleet.**

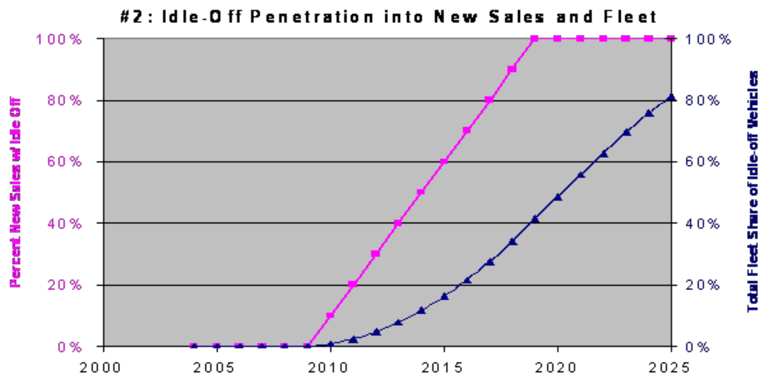
Annual Vehicle Miles Traveled:
13,000

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



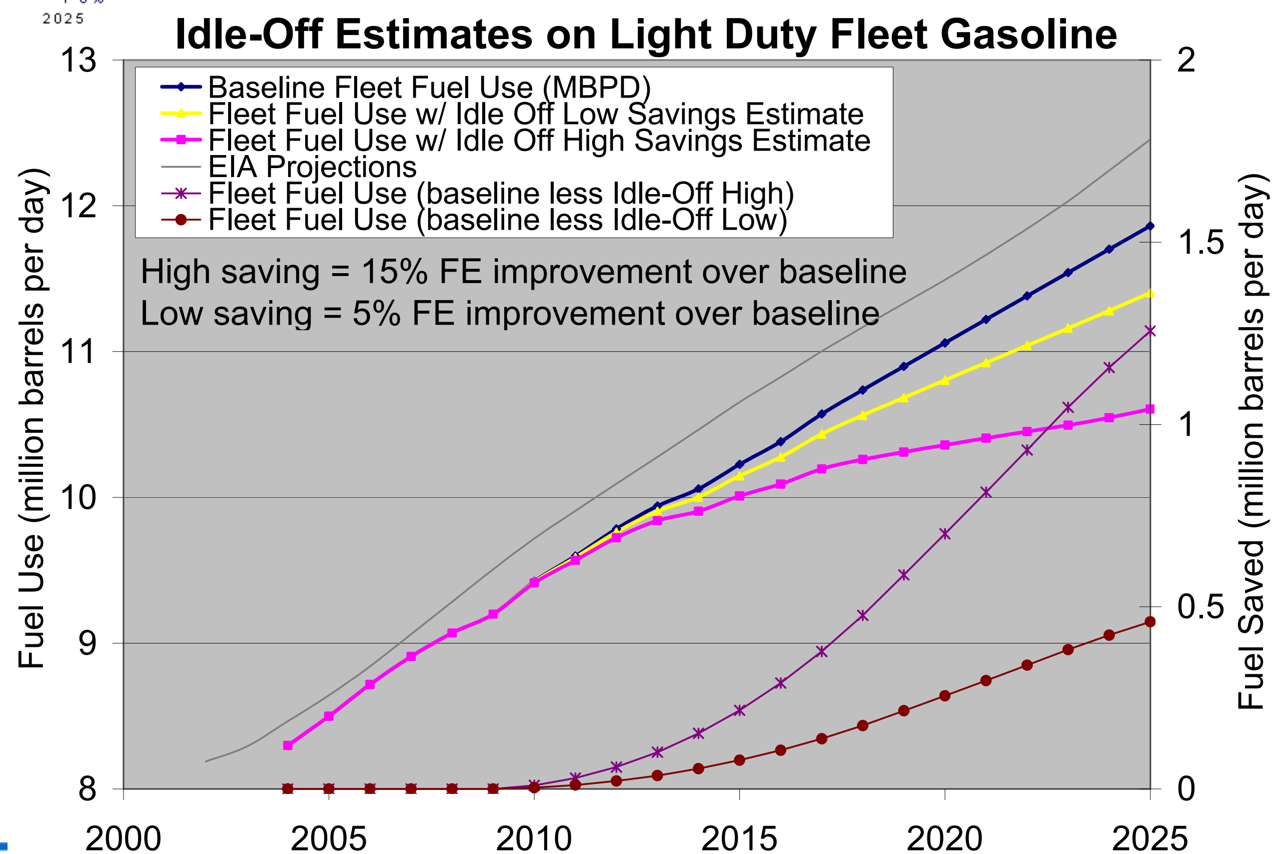
- **Market penetration: 10%/year until 100% saturation**

- **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

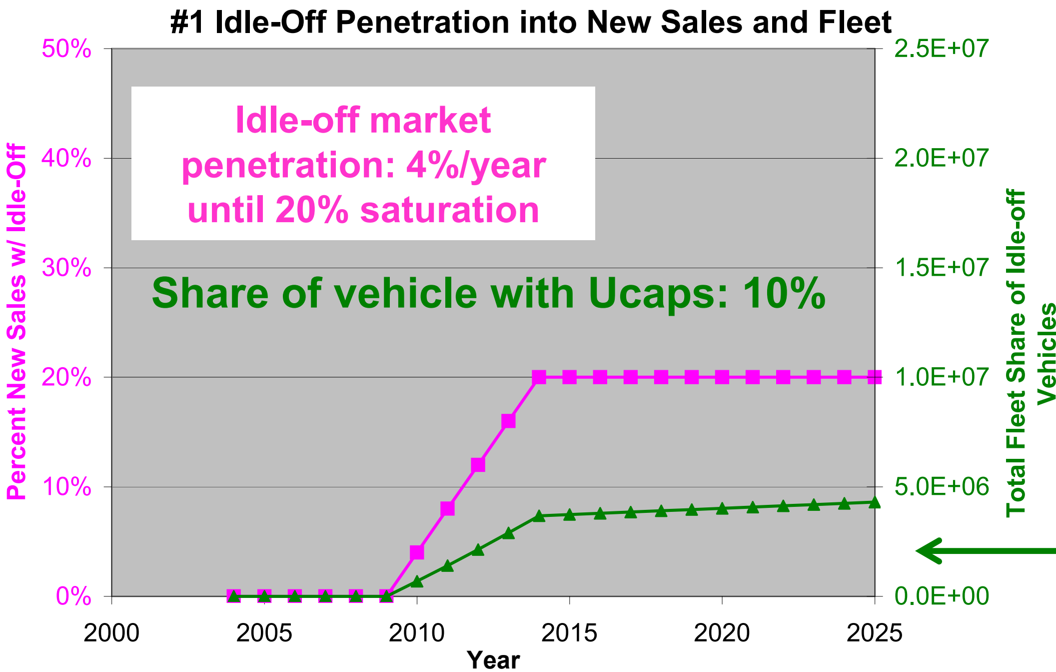
Base fuel consumption:
8.9 million barrel per day in 2007
11.9 million barrels per day in 2025

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



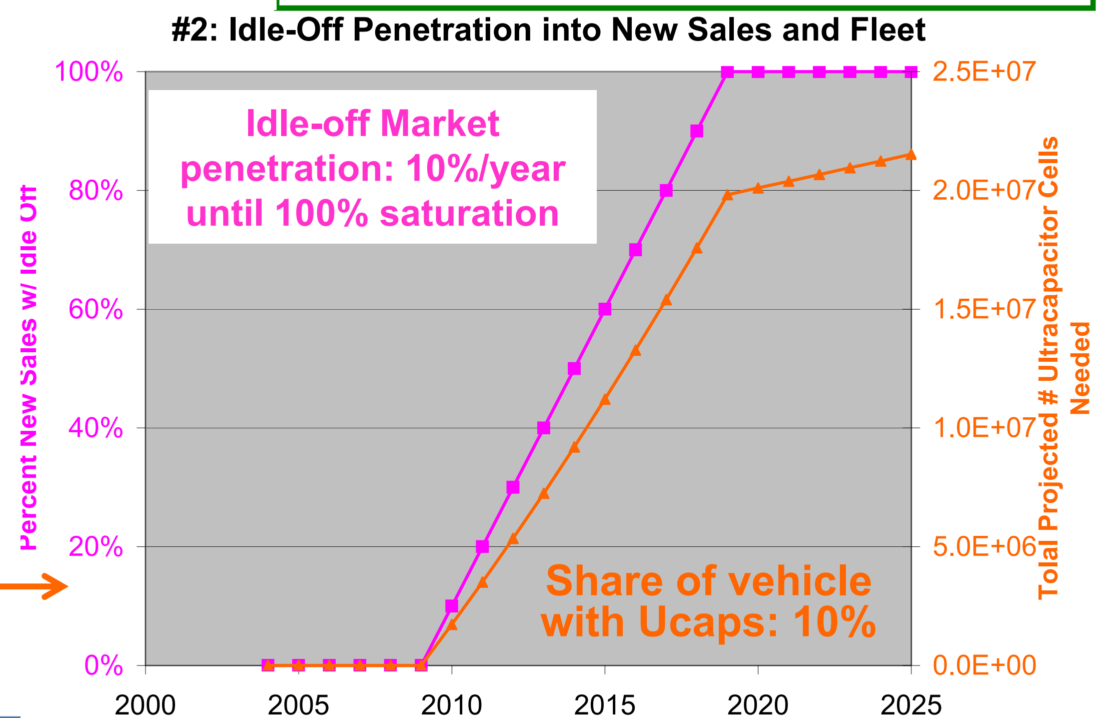
3.7 million cells in 2015
4.0 million cells in 2020

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

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



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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