NREL National Renewable Energy Laboratory
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Office of Energy Efficiency & Renewable Energy
Innovation for Our Energy Future

Ultracapacitors and Batteries in Hybrid Vehicles

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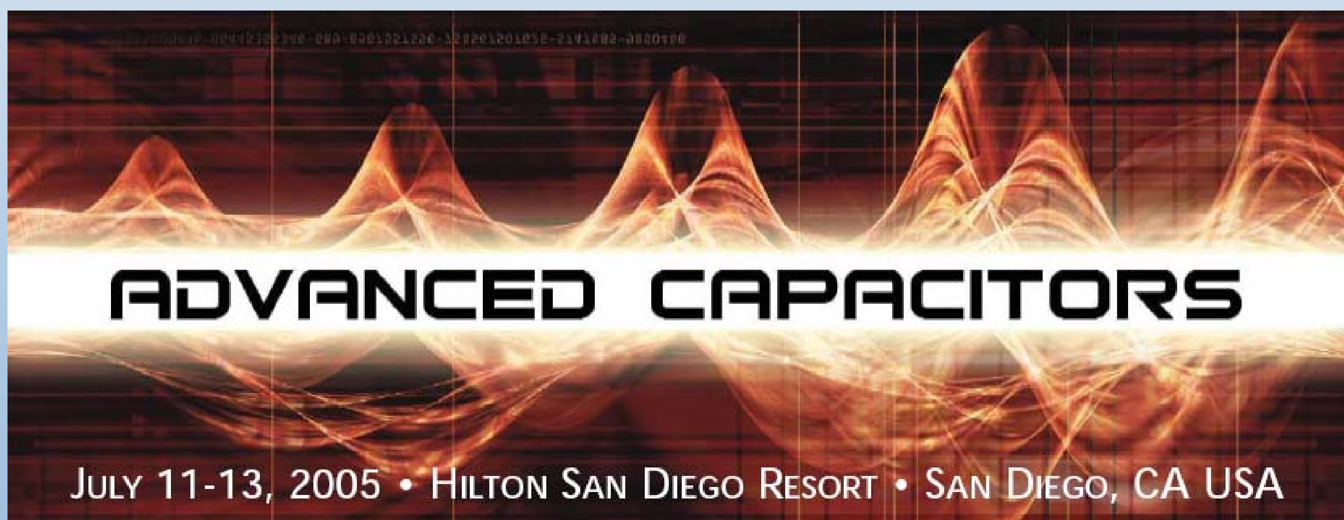

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Outline

- Hybrid Vehicle (HEV) Configurations/Categories
- HEV Energy Storage Requirements and Targets
- Ultracapacitor and Battery Characteristics
- Dual Energy Storage (Batt/Ucap) Solutions
  - Performance and life benefits
  - Cost, volume, and weight disadvantages
- Applications in Start-Stop and 42V Mild Hybrids
  - Drive Cycle Analysis (FTP and CA Real World)
  - Impact of Auxiliary Loads
  - Fuel Use from Idle-Restart
  - Fuel Economy
- Summary

Hybrid Vehicle Categories

Micro Hybrids (12V-42V: Start-Stop, Launch Assist)	
Mild Hybrids (42V Start/Stop, M-HEV, PA-HEV)	
Full Hybrids Power Assist HEV	
Fuel Cell Hybrids	
Plug-in HEV (low-mid EV range)	

Different energy storage requirements in vehicles with different strategies

FreedomCAR-USABC Energy Storage Requirements/Targets

Hybrids with Different Strategies		42-Volt			HEV (Power-Assist)		Fuel Cell Hybrid
Characteristics	**Unit**	**Stop Start**	**M-HEV**	**P-HEV**	**Low Power**	**High Power**	**Low Power***
Discharge Power	kW	6 for 2 sec	13 for 2 sec	18 for 10 sec	25 for 10 sec	40 for 10 sec	25 for 10 sec
Specific Power-Dischg 80% DOD/10 sec	W/kg						
Regen Pulse	kW	N/A	8 for 2 sec	18 for 2 sec	20 for 10 sec	35 for 10 sec	20 for 5 sec
Specific Power-Regen 20% DOD/10 sec	W/kg						
Engine-off Accessory Load	kW	3 for 5 min					
Recharge Rate	kW	2.4	2.6	4.5			
Power Density	W/l						
Available Energy (at 3 kW)	Wh	250	300	700	300	500	250
Specific Energy - C/3 Discharge Rate	Wh/kg						
Energy Density - C/3 Discharge Rate	Wh/l						
Specific Power/Specific Energy Ratio	h^{-1}						
Total Energy	kWh						
Energy Efficiency on Load Profile	%	90			90		90
Cycle Life profiles (engine starts)	cycle	450k			300k		TBD
Calendar Life	year	15			15		15
Cold cranking power at -30°C	kW	8 at 21V minimum for 2 sec			5 for 2 sec	7	5 for TBD min
Maximum System Weight	kg	10	25	35	40	60	40
Maximum System Volume	liter	9	20	28	32	45	32
Selling Price at 100k units/year	$	150	260	360	500	800	500
Maximum Operating Voltage	Vdc	48			400		440
Minimum Operating Voltage	Vdc	27			>0.55 x Vmax		>0.55 x Vmax
Maximum Self-discharge	Wh/d	20			50		50
Operating Temperature Range	°C	-30 to +52			-30 to +52		-30 to +52
Survival Temperature Range	°C	-46 to +66			-46 to +66		-46 to +66

Source: FreedomCAR and USABC websites (* Draft, under development)

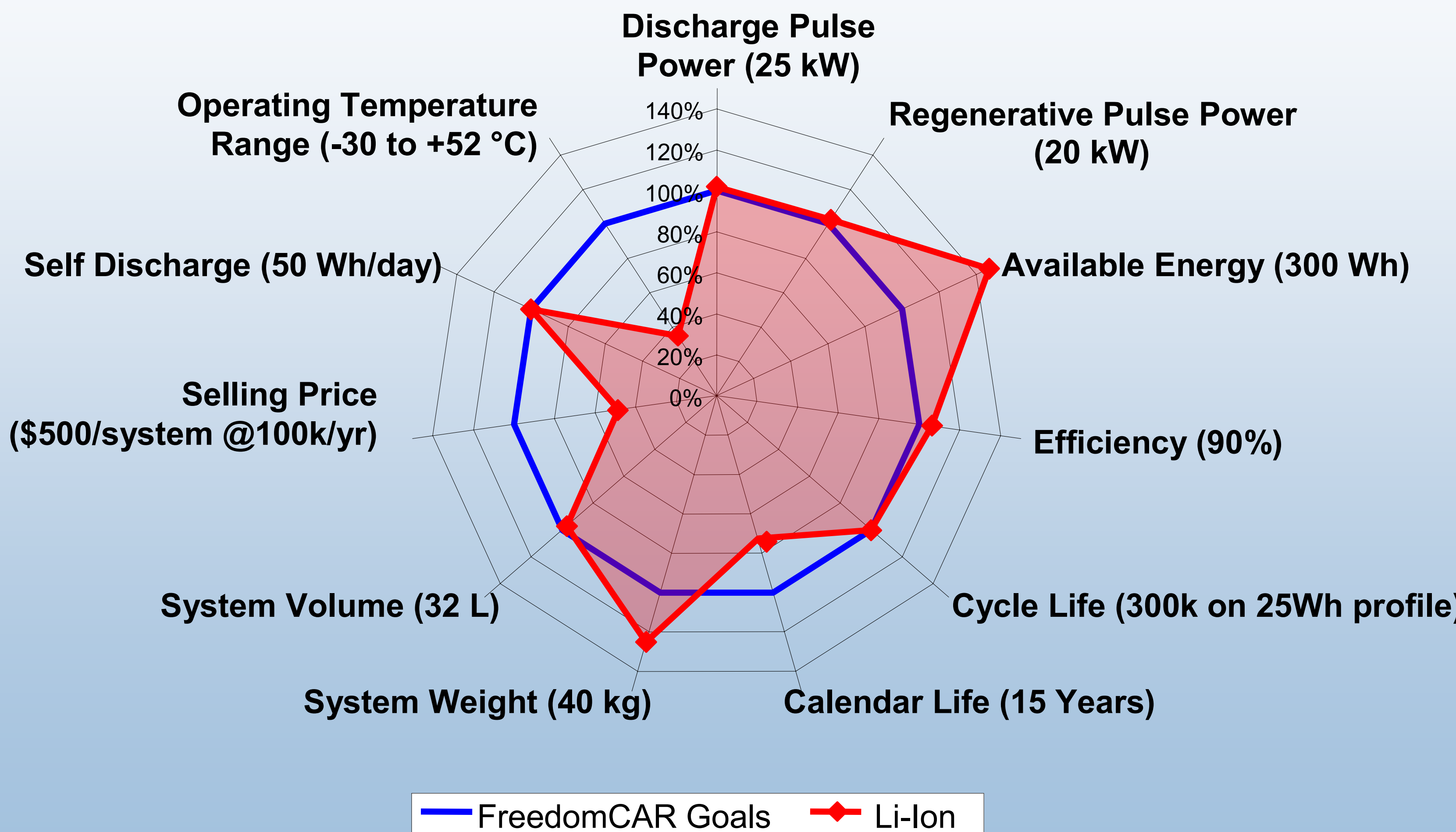
FreedomCAR-USABC Ultracapacitors Requirements/Targets

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	
Cycle Life and Efficiency Load Profile	UC10		UC10		UC10	
Calendar Life (Yrs)	15		15		15	
Energy Efficiency on UC10 Load Profile (%)	95		95%		95%	
Self Discharge (72hr from Max. V)	<4%		<4%		<4%	
Maximum Operating Voltage (Vdc)	17		48		48	
Minimum Operating Voltage (Vdc)	9		27		27	
Operating Temperature Range (°C)	-30 to +52		-30 to +52		-30 to +52	
Survival Temperature Range (°C)	-46 to +66		-46 to +66		-46 to +66	
Maximum System Weight (kg)	5		10		20	
Maximum System Volume (Liters)	4		8		16	
Selling Price ($/system @ 100k/yr)	40		80		130	

Source: FreedomCAR and USABC websites

Li-Ion Status of versus Targets

Power-Assist HEV (Low Power)



Source: FreedomCAR Energy Storage R&D Plan

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Qualitative Comparison of Energy Storage Technologies for HEVS

Source: K. Konecky (AABC-04)

Parameter	*Lead-Acid*	*UC*	*NiMH*	*LiIon*
Weight	Red	Yellow	Green	Yellow
Volume	Red	Yellow	Green	Yellow
Regen Power	Yellow	Green	Green	Yellow
Discharge Power	Green	Green	Green	Green
Cold-Cranking Power	Green	Green	Yellow	Green
Capacity/Energy	Green	Yellow	Green	Green
Life	Yellow/Red	Yellow	Green	Yellow/TBD
Maturity - Technology	Green	Yellow	Green	Red
Maturity - Manfg	Green	Red	Green	Red
Cost	Yellow	TBD	Yellow ↑	TBD
Overall	Red	Yellow	Green ↓	Yellow ↑
Safety	Green	Yellow	Green	Yellow

Battery and Ultracapacitor Characteristics

Source: M. Anderman (AABC-04 Tutorial)

Parameter	VRLA	NiMH	Li Ion	Ultracap
Cell configuration	Parallel plates; spirally wound cylindrical	Spirally wound cylindrical; parallel plates	Spirally wound cylindrical & elliptic	Spirally wound cylindrical & elliptic
Nominal cell voltage (V)	2	1.2	3.6	1.8
Battery electrolyte	Acid	Alkaline	Organic	Organic
Specific energy, Wh/kg	25	40	60 to 80	5
Battery/Module specific power, 10 sec, W/kg				
23ºC, 50% SOC	400	1300	3000	>3000
-20ºC, 50% SOC	250	250	400	>500
Charge acceptance, 10 sec. W/kg				
23ºC, 50% SOC	200	1200	2000	>3000
2010 Projected Cost >100,000 per year				
$/kWh, Module	100.00	500.00	700.00	20,000.00
$/kWh, Full pack	140	600	1100	25000
$/kW, pack	9.00	18.00	22.00	40.00
Energy efficiency	Good	Moderate	Good	Very Good
Thermal managements requirements	Moderate	High	Moderate	Light
Electrical control	Light	Light	Tight	Tight

Potential Applications of Batteries and 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: Possibly
Mild Hybrids (42V Start/Stop, M-HEV, PA-HEV)	VRLA: Yes NiMH and Li-ion: Yes, Likely Ucaps: Likely if engine not downsized (??) Ucaps + VRLA: Possibly
Full Hybrids Power Assist HEV	VRLA: Not Likely NiMH and Li-ion: Yes, Likely Ucaps: Not Likely if engine not downsized (??) Ucaps + VRLA: Not Likely
Fuel Cell Hybrids	VRLA: Not Likely NiMH and Li-ion: Yes, Likely Ucaps: Likely if Fuel Cell is not downsized Ucaps + VRLA: Not Likely
Plug-in HEV (low-mid EV range)	VRLA: Not Likely NiMH and Li-ion: Yes, Likely Ucaps or Ucap + VRLA: Not Likely

Most Likely Applications for Ultracapacitors In Light-Duty Vehicles

- Micro HEVs with Start-Stop (w or w/o regen) capabilities
  - Low temperature power capability desirable.
  - Low energy is a concern to support auxiliaries during idling.
  - Biggest opportunity if idle-stop becomes a common-place.
- Mild HEVs if engine is not downsized
  - Need to investigate potential benefits for full HEVs
- Fuel Cell hybrids if FC is not downsized
  - Similar to Honda FCX, regen capture.
  - Potential for load leveling.
- Micro and Mild HEVs if combined with VRLA or other batteries
  - Could add cost, volume, weight, and complexity.
  - Could extend the power capability and life.

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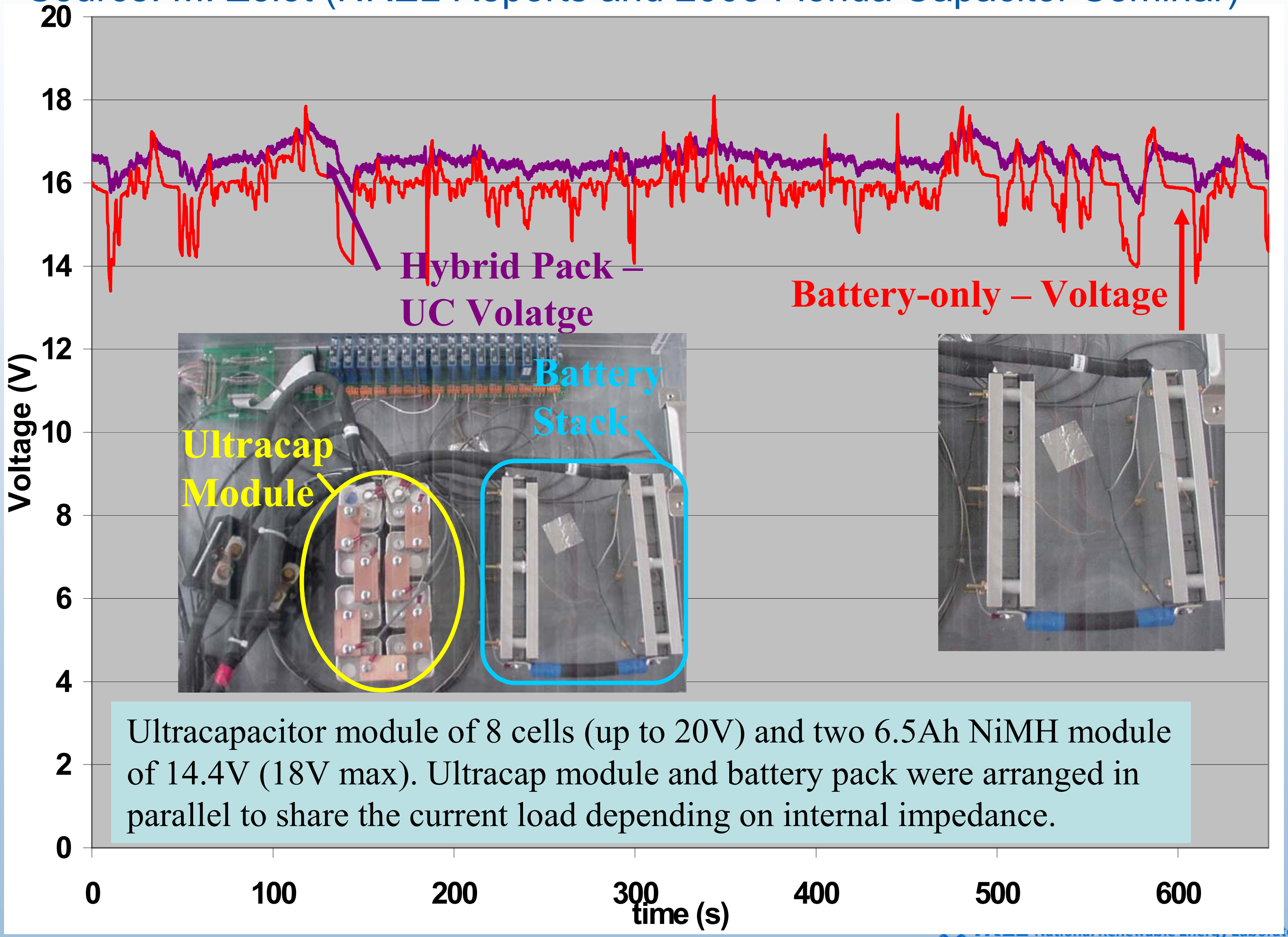
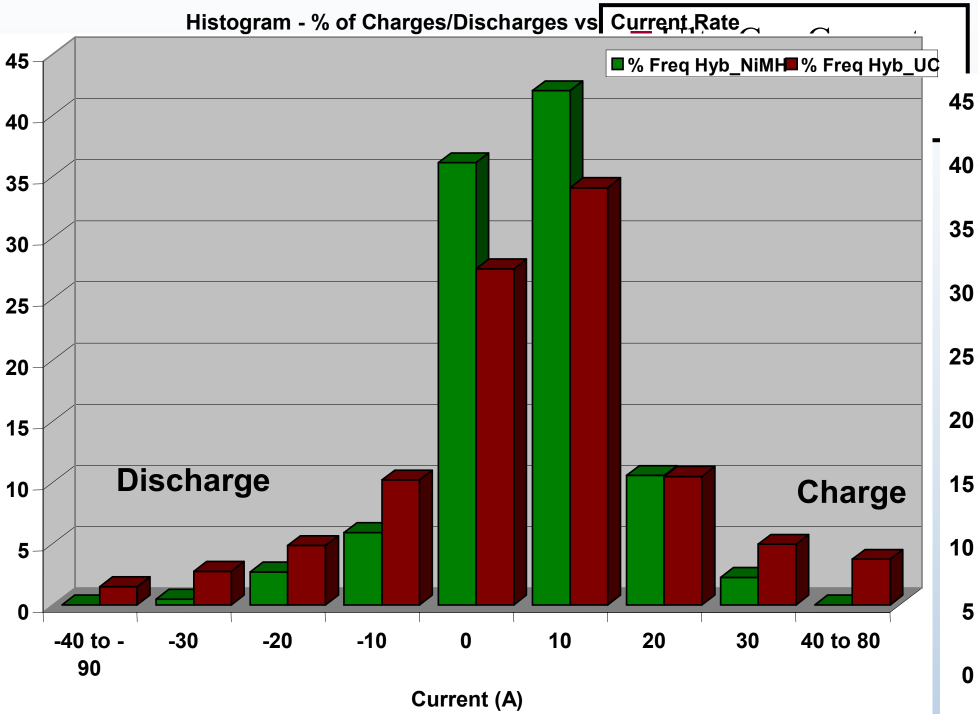
Experiments Show that Combining Ultracapacitors with Batteries Could Filter High Voltage Transients

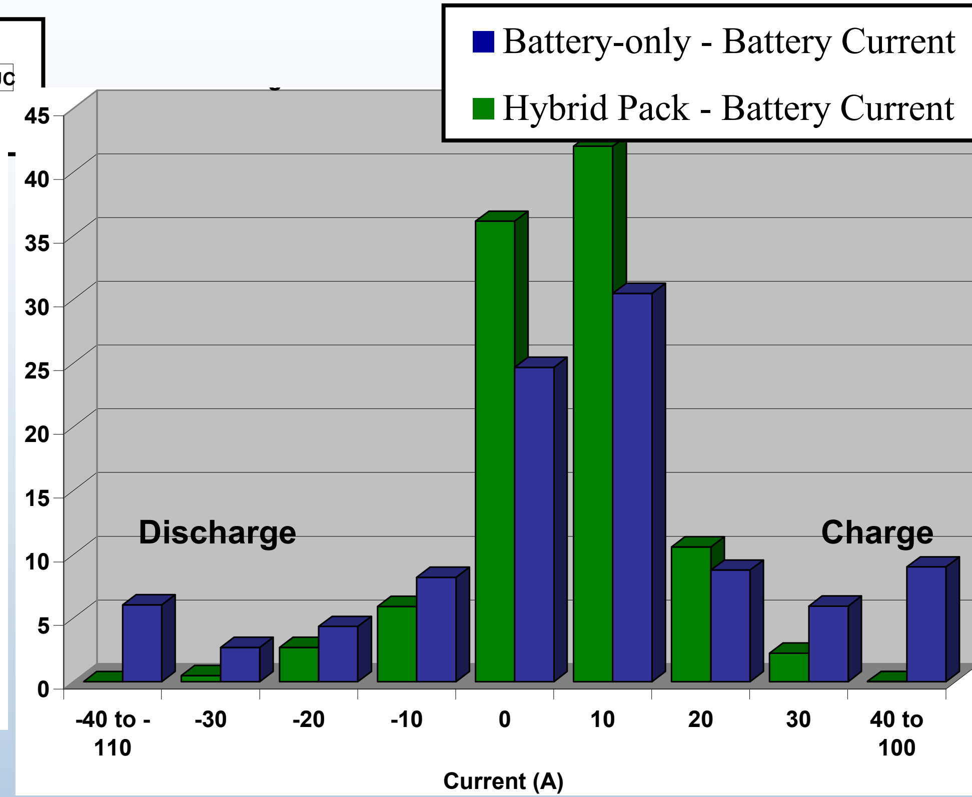
Source: M. Zolot (NREL Reports and 2003 Florida Capacitor Seminar)



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.

Current Histogram in the Battery-Only and Battery+Ucap Pack during US06 Cycle



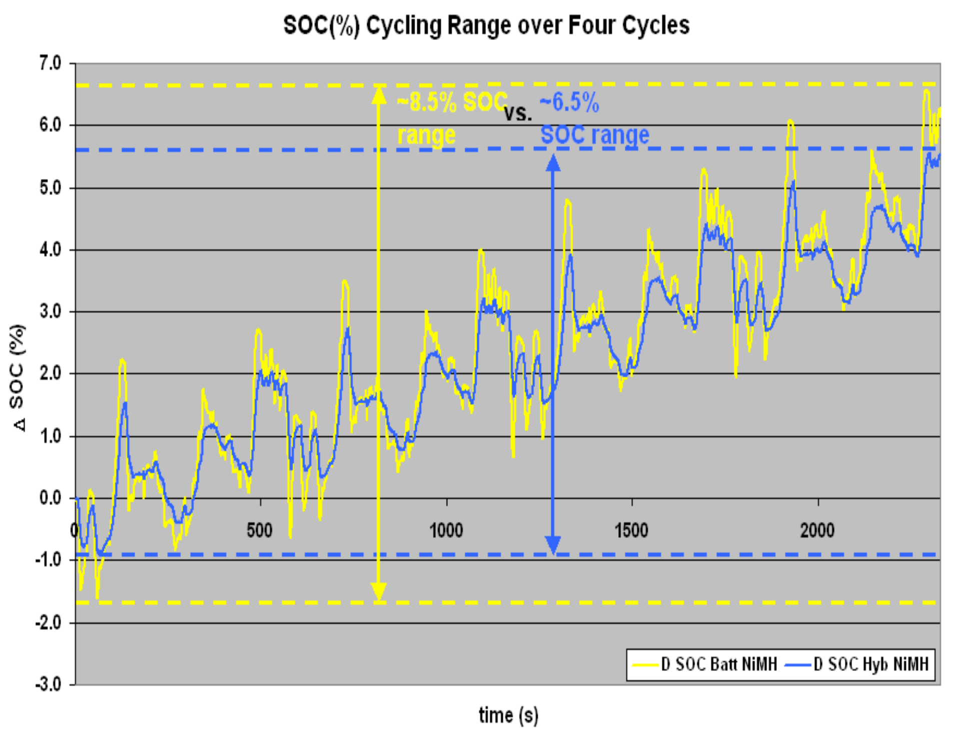


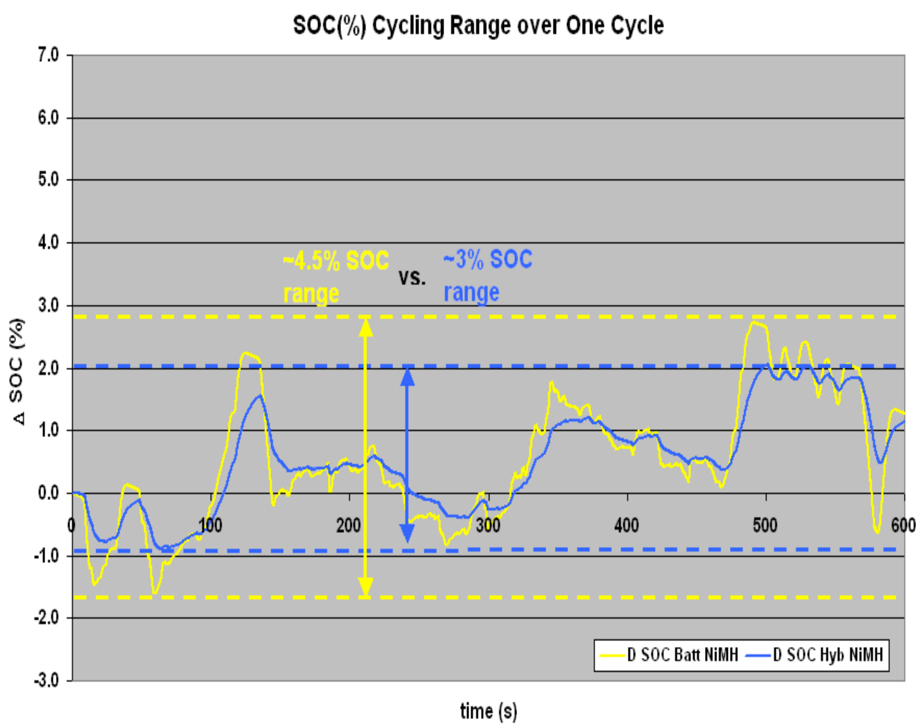
Lower impedance UC provides all currents larger than ±40A, while the battery absorbs/supplies additional low level currents from/to the UC to correct for voltage (Ah Capacity) inequalities.

Overall, the batteries in the hybrid pack “see” no currents larger than ±40A, while the batteries in the traditional pack see all the currents, from –110A to 100A.

Narrower Battery SOC Range in Battery+Ucap Could Extend Battery Life

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





24% narrower battery cycling range (over 40 minutes) has the potential to increase battery life.

33% narrower battery cycling range (over 10 minutes) has the potential to increase battery life.

Advantages/Disadvantages of Hybridizing Energy Storage (Ucap + Battery)

Advantages

- Reduced battery currents
- Reduced battery cycling range
- Positive affect on cycle life (to what extent?)
- Increased combined power and energy capabilities
- Better low temperature performance

Disadvantages

- Large volume & mass
- Increased energy storage cost
- Unknown side affects of direct coupling
- If not directly coupled then need to have DC/DC converters between the Ucaps and engine/FC adding more cost

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NREL's Previous Dual Source ESS Sizing Study

- 42 V ESS systems (PbA, UC, Li, NiMH, PbA+UC) were analyzed for Start-Stop, M-HEV and P-HEV specifications.

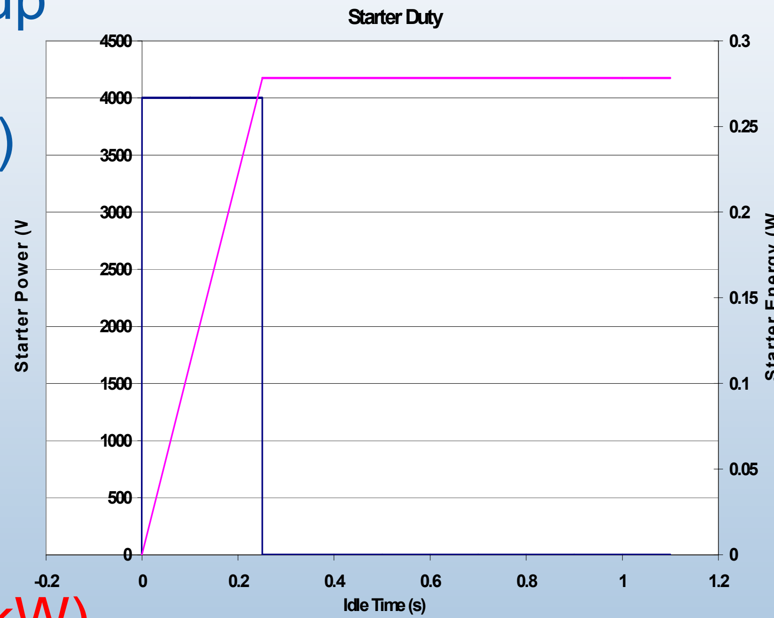
This table shows various EES specifications meeting the 42V Start-Stop minimum requirements

Description	Number of Modules	Parallel Strings	Nom. Voltage	10s Power	2s Power	Usable Energy	Mass	Cost	Volume
	--	--	V	kW	kW	Wh	kg	$	L
PbA only	3	1	37.89	7.8	7.85	256.7	33.0	330	11.6
UC only (2600F)	20	1	39.5	14	54	35.0	14.2	600	21.7
Li-ion (6Ah)	22	2	40.93	12.1	12.1	156.7	8.3	440	6.6
NiMH (6.5Ah)	10	2	39.78	7	7.8	125.0	10.0	400	8.8
3 PbA + 7 UC (PbA@HV)	(3+7)	n/a	37.89	12.5	27	271.7	46.4	847	22.0

- Based on NREL's previous results, auxiliary power requirements (P_{aux}) could be met by any of the ESS systems.
- We carried-over the Start-Stop results into fuel economy and an auxiliary load study.

What is the Impact of Auxiliary Loads on Ucap sizing in Start-Stop HEVs?

- ESS needs to support auxiliary loads only during idle-off (engine-off), no electric traction.
- Engine only turns off after it is warmed-up due to emission reduction strategies.
- Restarts are with motors (4 kW, 250 ms)
- Just before the ESS energy becomes insufficient, ESS restarts the ICE.
  - ICE idles to meet the auxiliary load and recharges ESS.
- $SOC_{mid} < ESS_{SOC} < SOC_{Top}$ (regen. just collected) at idle-stop
- Idle Fuel Rate Consumption: 0.4 g/s (6 kW) (If this is too high for a midsize car, then the fuel economy increase would be over-estimated.)



Auxiliary Load Assumptions

- Idle-off Auxiliary Loads:
  - Valvetrain = 0
  - Oil Pump = 0
  - Water Pump = 0 (except in winter)
  - ECM (Control Module) "sleep" Load = 10%
- Two Auxiliary Loading Cases:
  - Summer(+AC), Wipers, Turn Sigs, Lights-on
    - A/C compressor (D=0.9, T=30s [0.033 Hz])
    - Radiator Cooling Fan (D=0.5, T=15s [0.067 Hz])
    - HVAC fans on (D=1)
    - Wipers (D=50%, T=2s [0.5 Hz])
    - Turn Signal (D=50%, T=2s [0.5 Hz])
    - Radio + Misc + Brake-Light + Ext. Lights
  - Summer(-AC)
    - Same as Summer+AC, but without any A/C compressor load

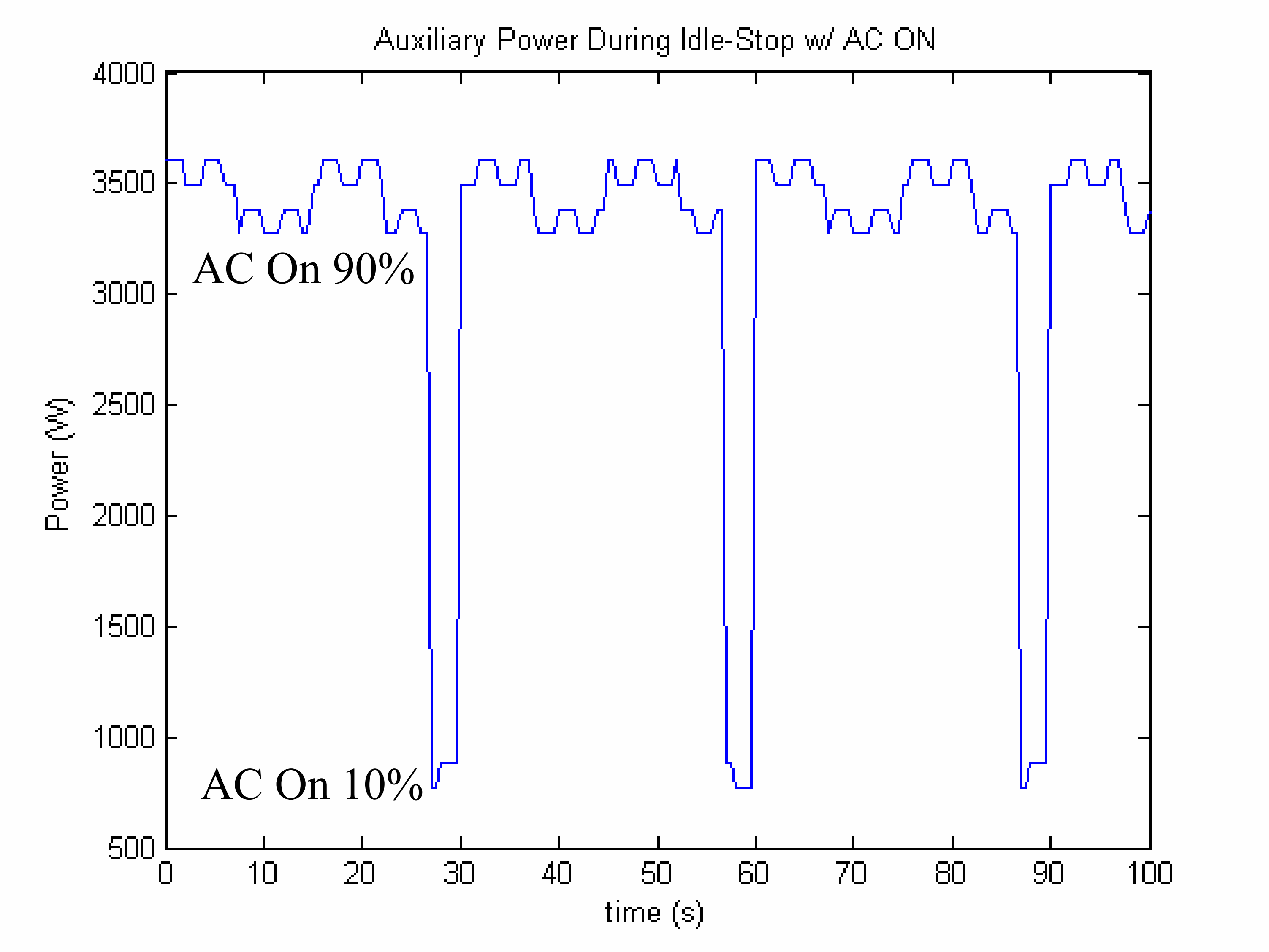
Load Power (W)		Mid-size
Radio	☑	28
Rear Wipers		-
Front Wipers	☑	34
Misc	☑	45
Turn Signals	☑	77
Brake Lights	☑	84
Heated Seats		145
Starter (1 s)	☑	1500
Engine Controller	☑	193
Rear HVAC Fans		-
External Lights	☑	263
Rear Defrost		260
Radiator Cooling Fan	☑	221
Front HVAC Fans	☑	328
Oil Pump		450
Water Pump		450
Valvetrain		1000
Catalyst Heater		2000
AC Compressor	☑	2500
Total		**9578**

❖ Enhancement of R-134a Automotive Air Conditioning System, M Bhatti, Delphi Harrison Thermal Systems - SAE Congress 1999-01-0870

❖ Interaction of Temp., Humidity, Drive Preferences, and Refrigerant Type on Air Conditioning Compressor Usage, Journal of the Air & Waste Management Associate, October 2000

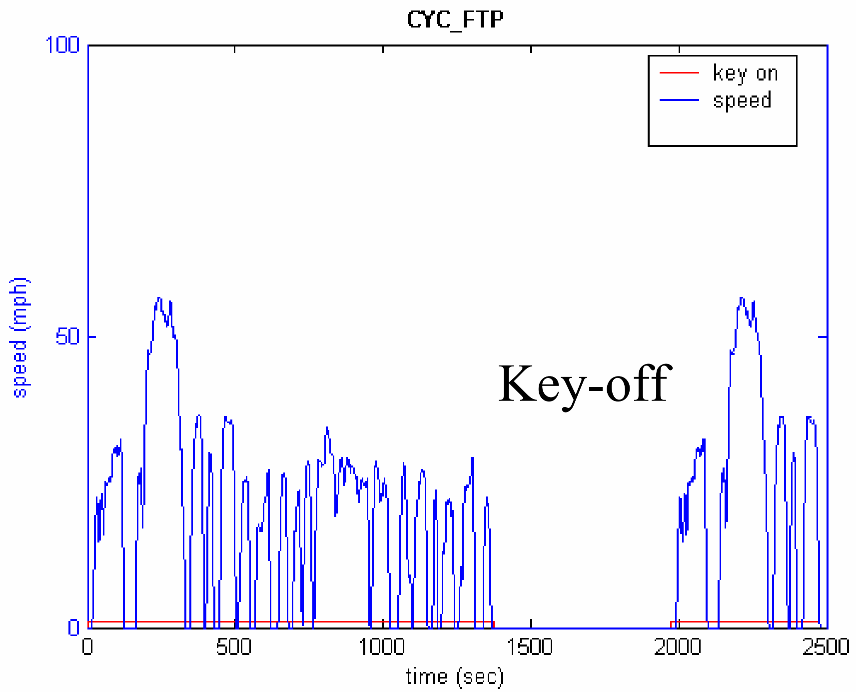
Auxiliaries and AC Power Profile for Case 1

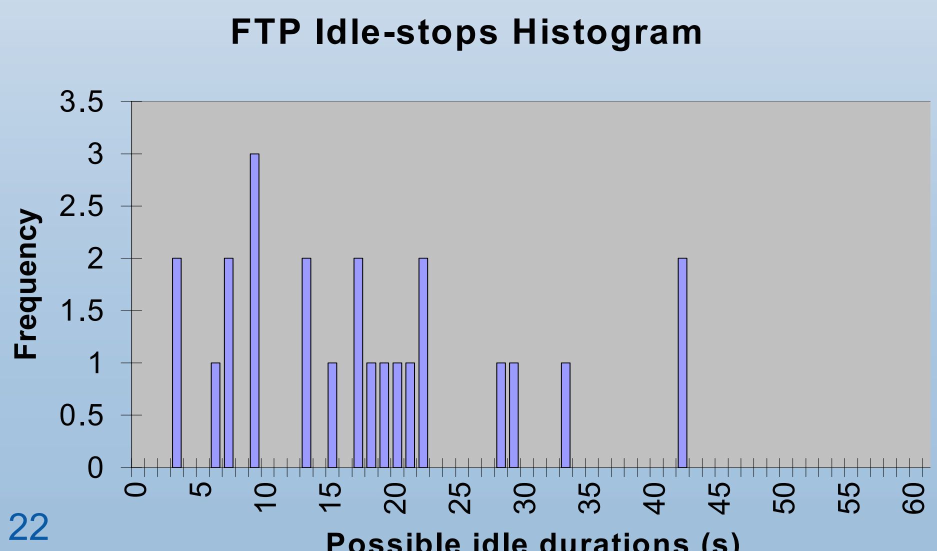
ESS Power Dissipation with AC on Could be Met (during longer idle-times), but Energy?



Laboratory

FTP Cycle Statistics





EPA FTP cycle

- Distance: 11 miles
- Max Speed: 56.7 mph
- Ave Speed: 20 mph
- Number of stops: 23

Cycle Statistics:

- Idle time: 424 s
- No. of idle-cut-outs: 24
- Key-off: 1 (~600s)
- Idling time: 18% of total
- Average duration of idle-off: 17.7s
- Maximum idle duration: 42 S

Assumptions:

- Engine cut-out below 10mph when decelerating
- Restarts above 0 mph and accelerating

California Real-World Cycle Statistics

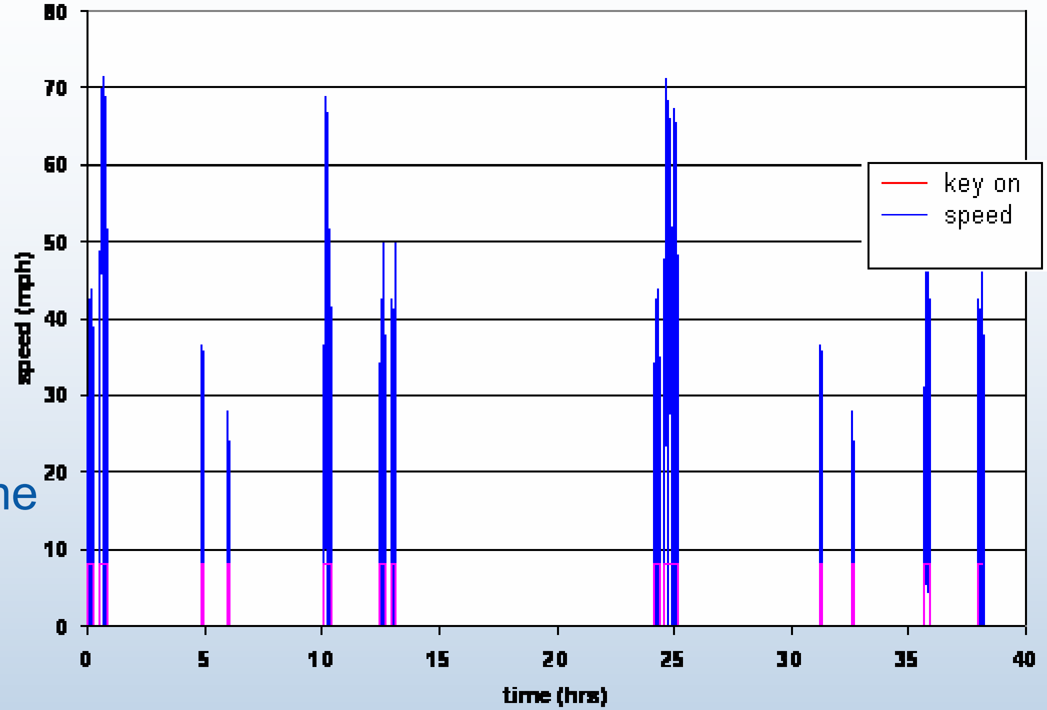
- Real-World Driving in CA
- Max Speed: 71.4 mph

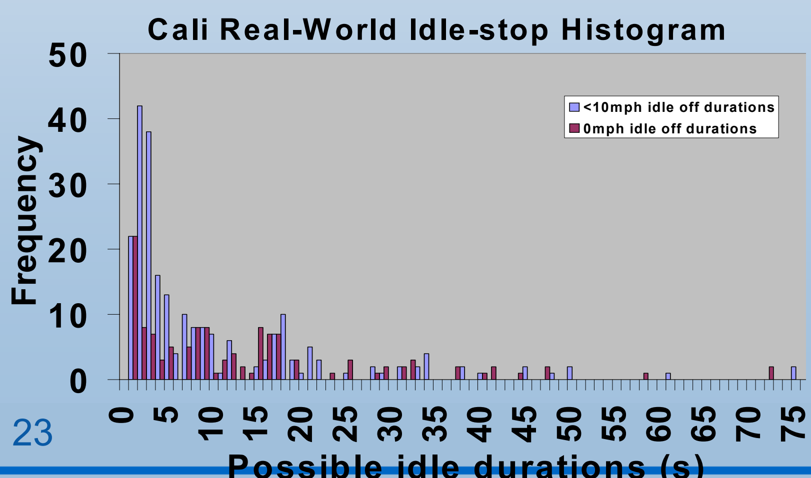
Assumptions:

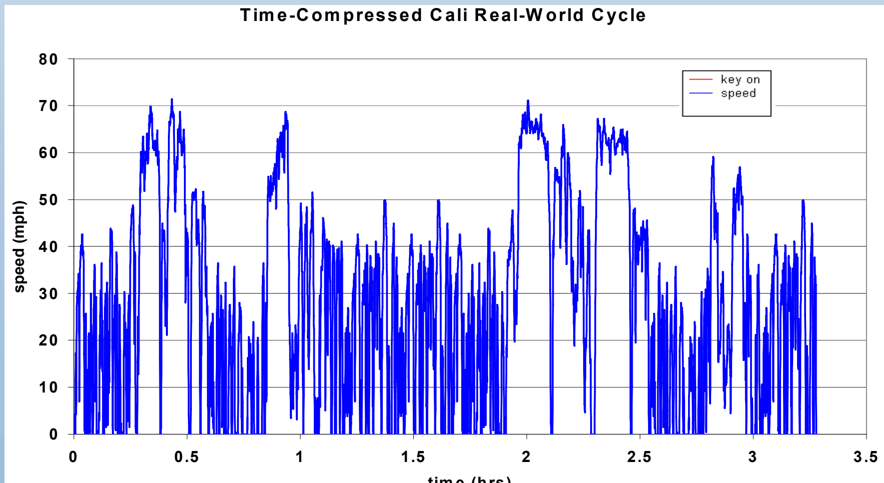
- Engine cut-out below 10mph
- Restarts above 0 mph / accel

Cycle Statistics:

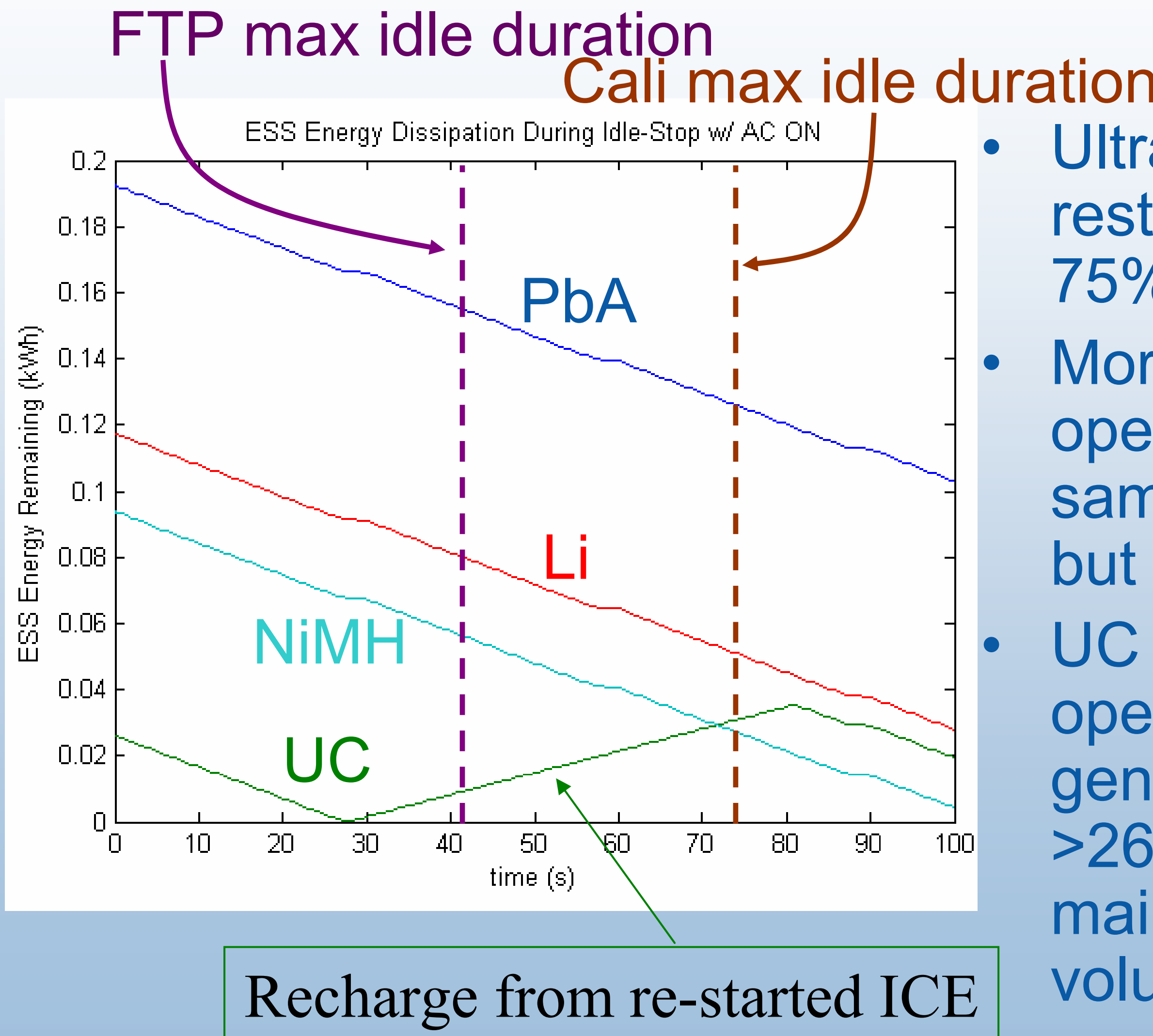
- Idle time: 2296 s (~38 mins)
  Out of: 11804 s (3.3hrs) drive time
- No. of idle-cut-outs: 232
- Key-offs: 13
- Average duration of idle-off: 10s





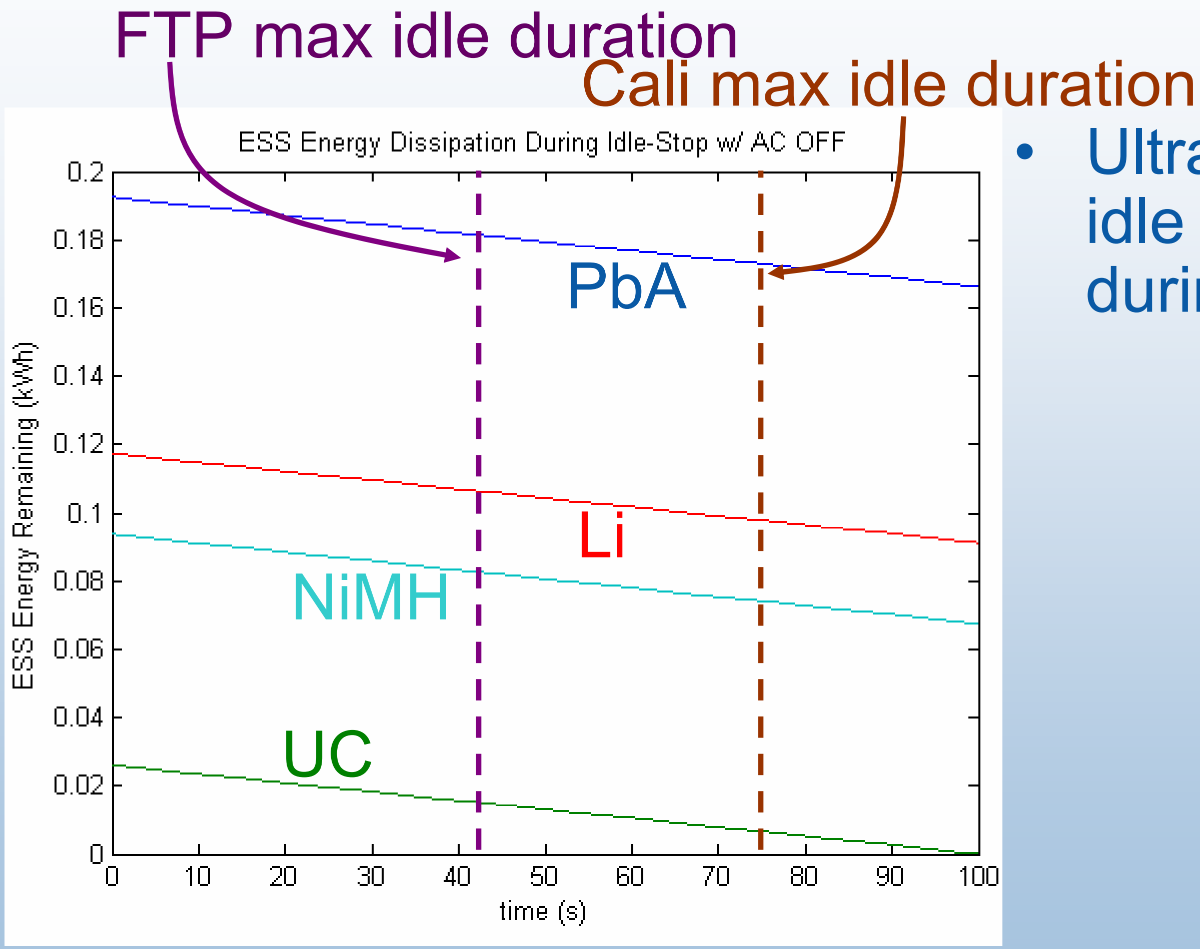


ESS Energy Dissipation with AC on is a Challenge for Longer Idle-times



- Ultracap requires ICE restart after ~30s (with 75% SOE)
- More advanced UCs will operate the same [with same system voltage], but in lower volume pack.
- UC can extend idle operation (energy) if next generation is offered in >2600F capacity (and maintains today’s pack volume)

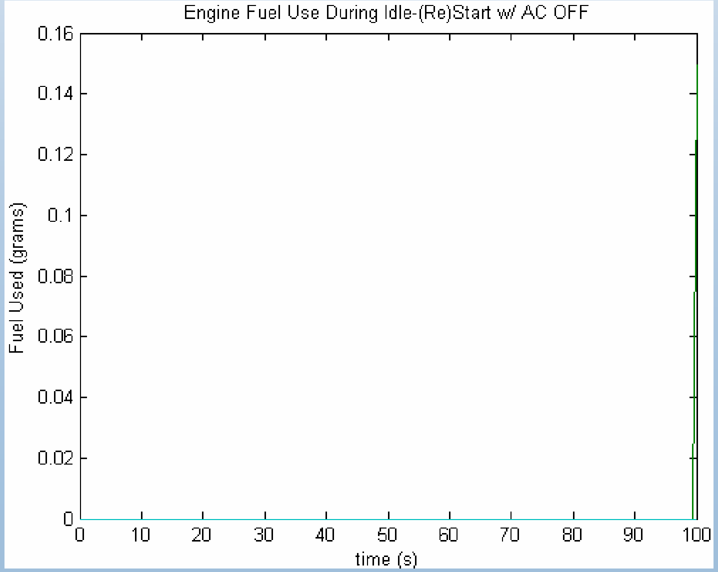
ESS Energy Dissipation with AC off is Much Less Challenging

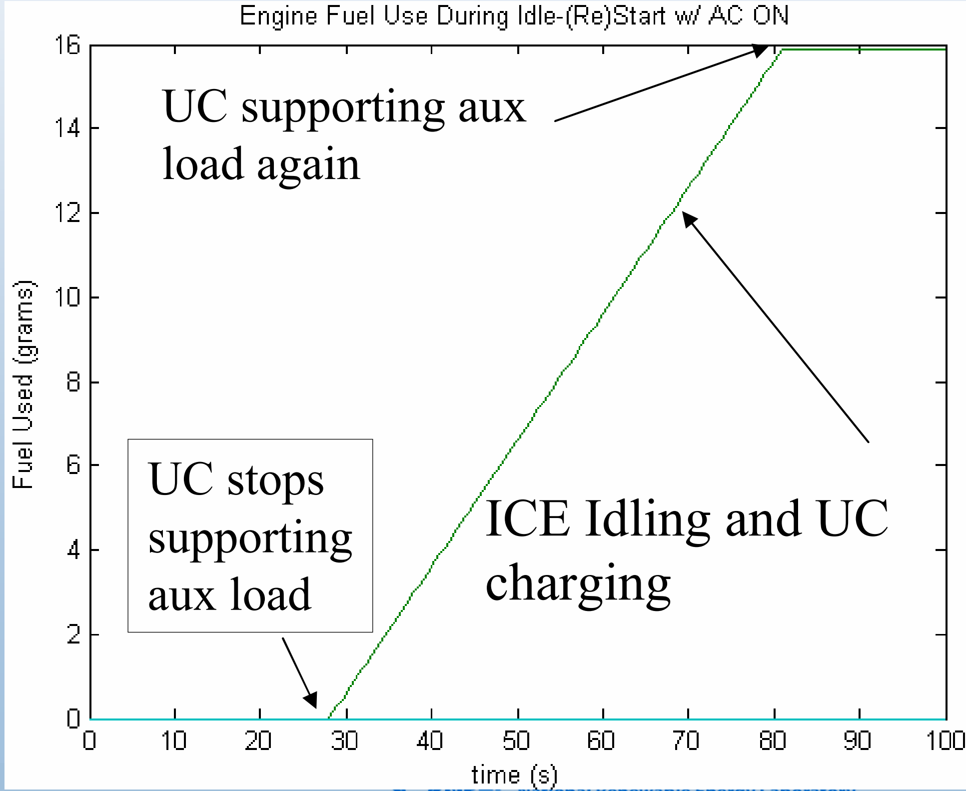


- Ultracap does not require idle restart with AC off during stops

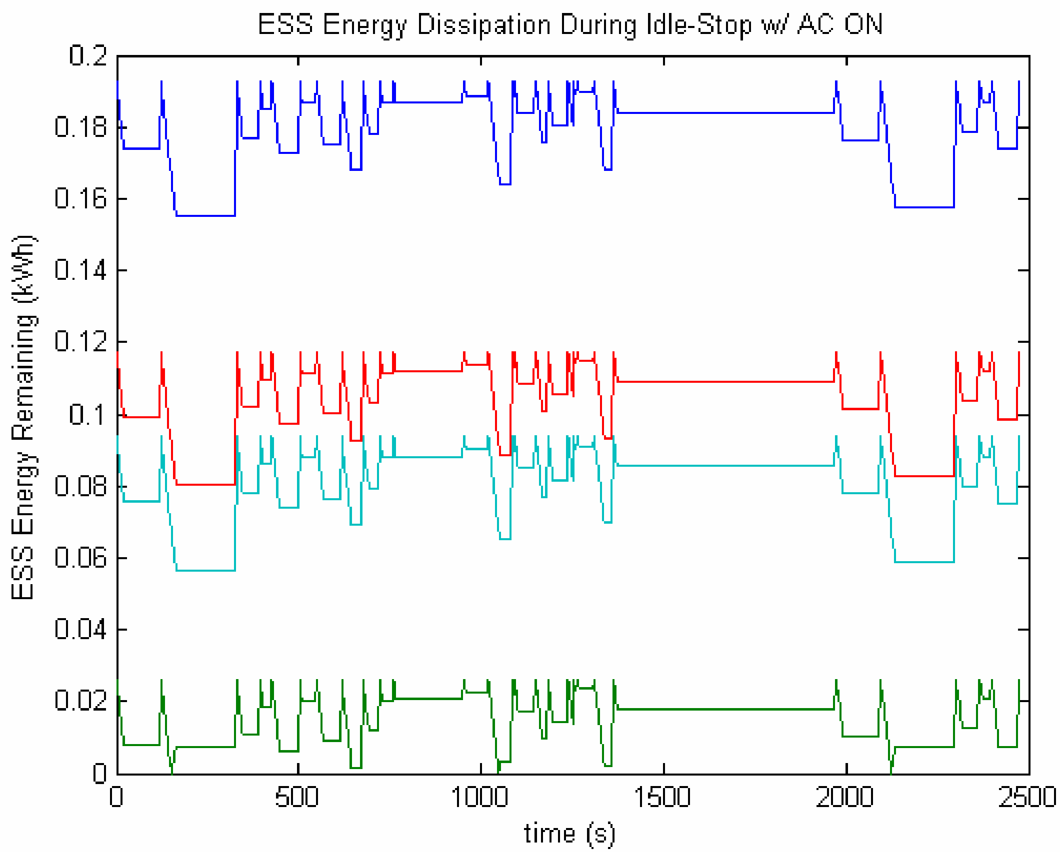
What is Fuel Usage of Idle-Restart?

- Ignoring any fuel needed for restart event
  - Idling Fuel Consumption Rate: 0.4 g/s
- With the AC on:
  - Fuel use per idle event is up to 16 grams vehicle with UCs,
  - Zero impact for batteries (up to 100 sec)
- With the AC off
  - Zero/Negligible impact on FE for all ESS devices (up to 100 s)

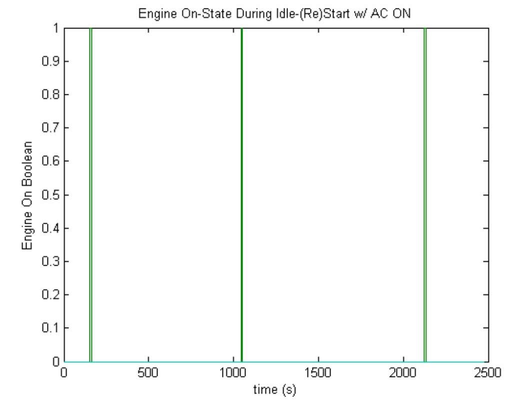


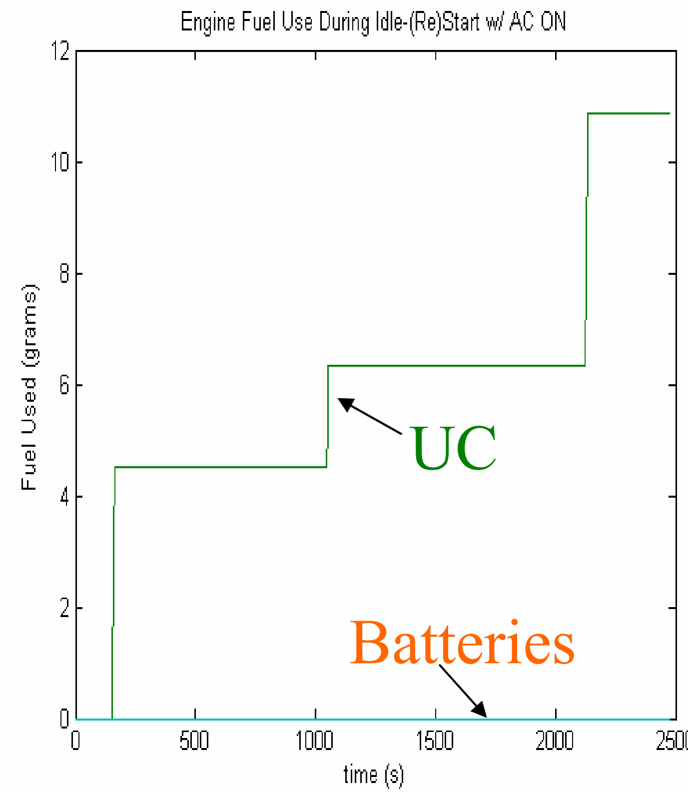


Total Idle-Restart Fuel Use over the FTP (AC on)



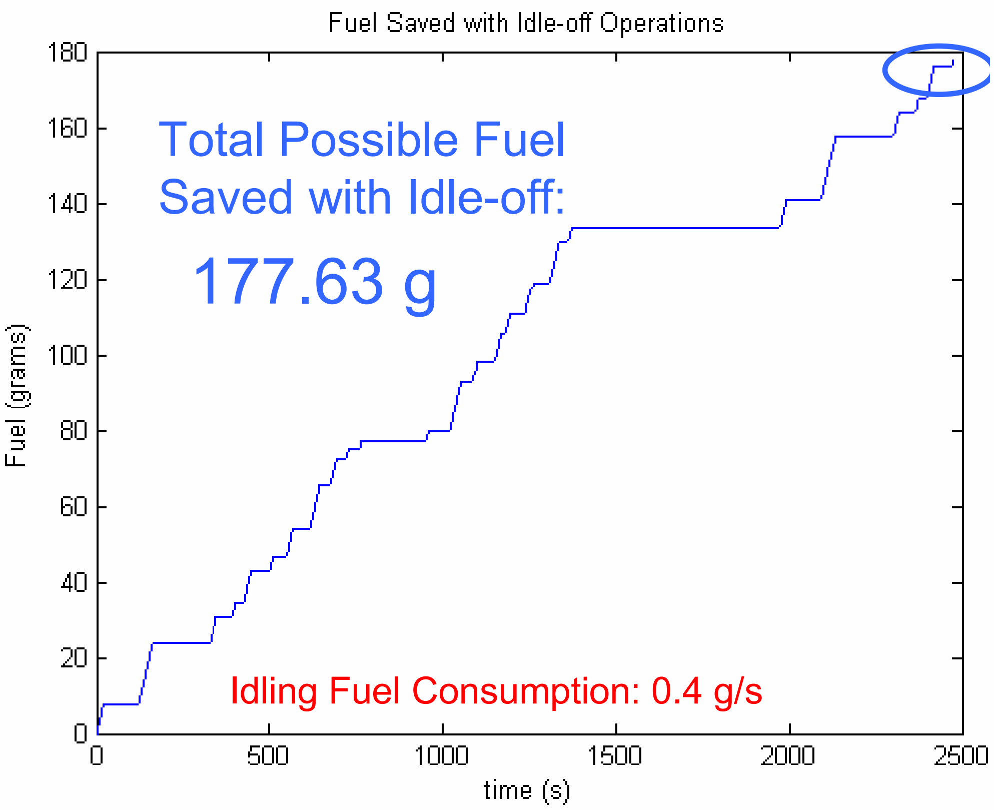
- PbA
- Li
- NiMH
- UC

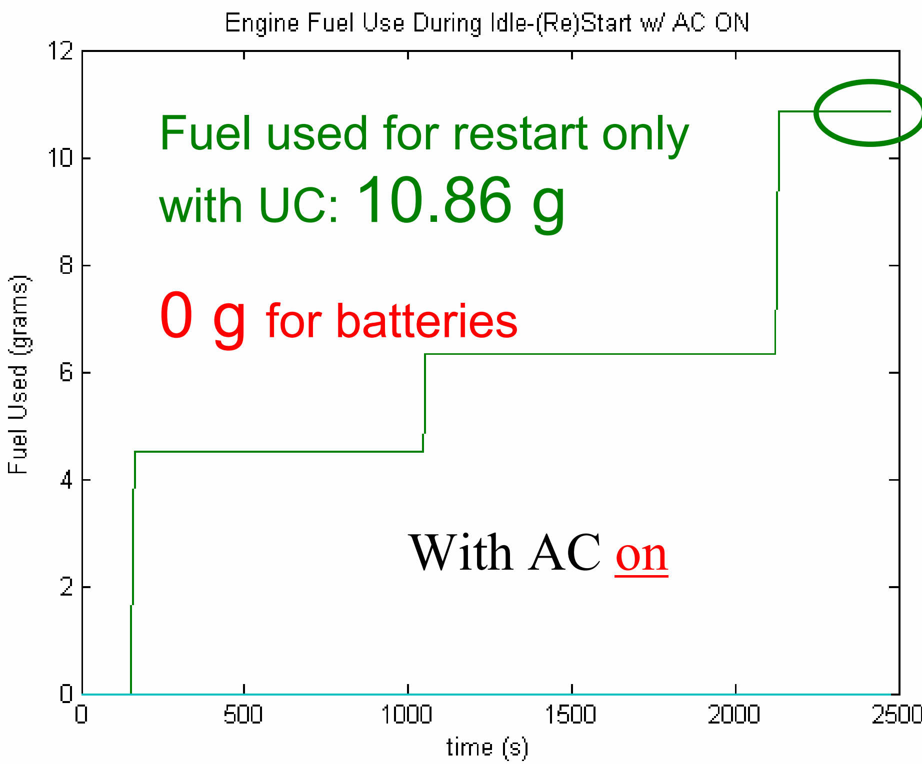




We assumed that the total energy to run AC will eventually come from fuel, with either batteries or Ucaps.

Total Idle-Restart Fuel Use Over the FTP





- 10.86g/177.63g = 6.1% reduction in idle-off fuel savings with ultracapacitors when AC is on (UC is at 75% SOE before idles)
- If UC is @ 100% SOE before idles → 1.12g/177.63g = 0.63% reduction in idle-off fuel savings

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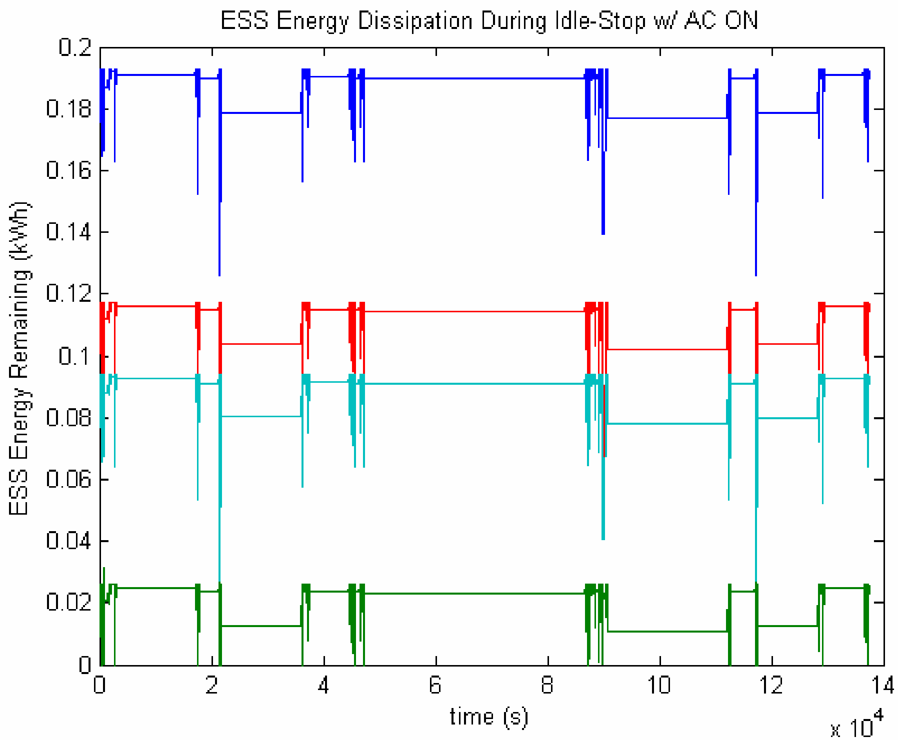
Total Idle-Restart Fuel Use Over the California Real-World Cycle (AC on)



- PbA
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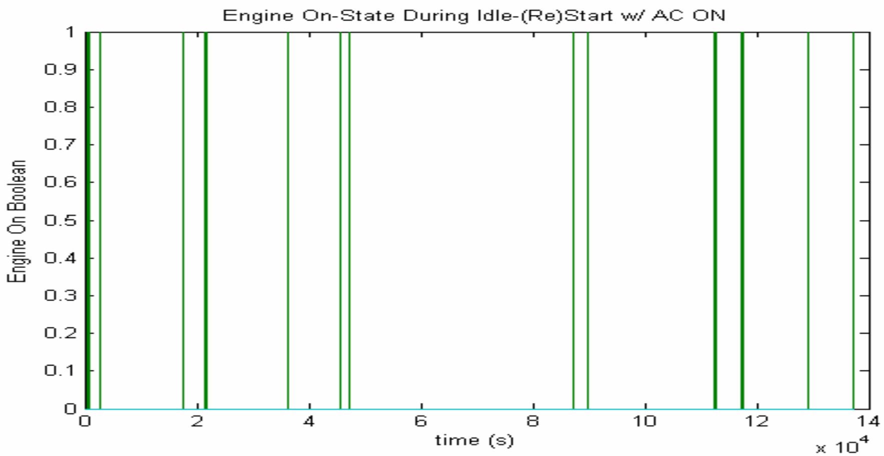
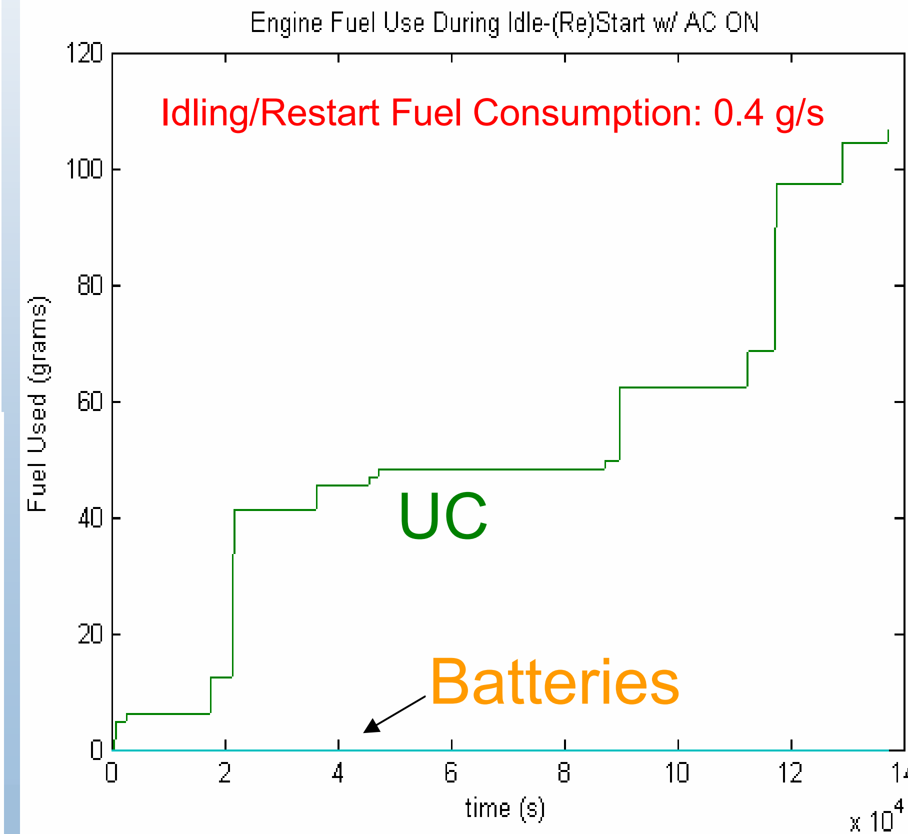
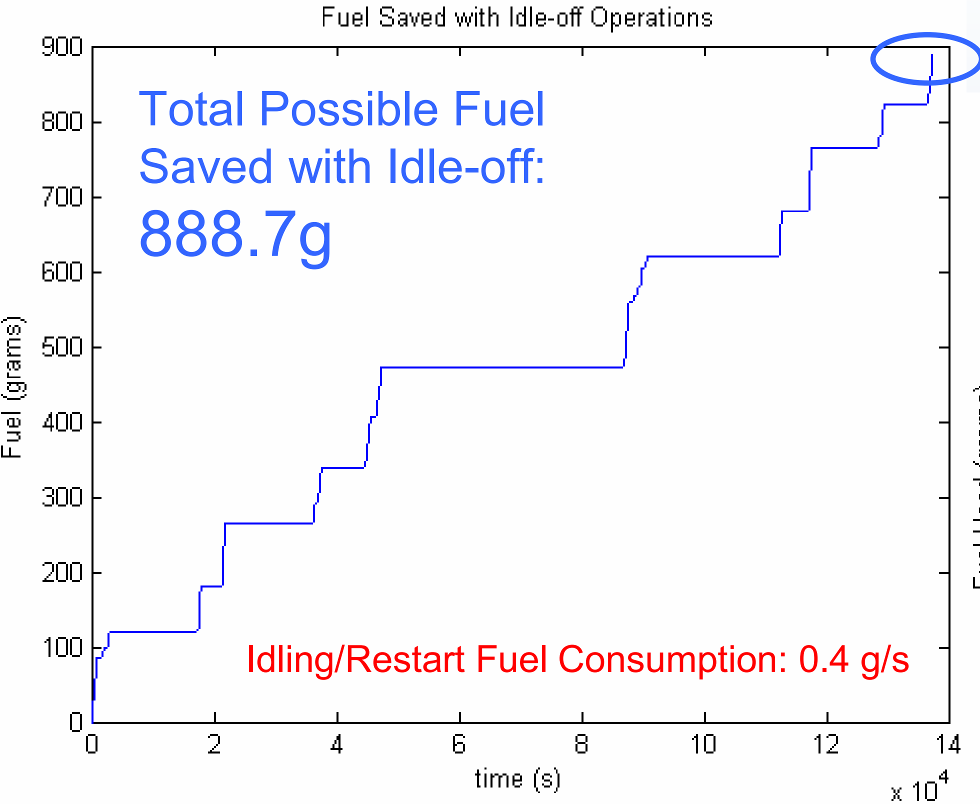
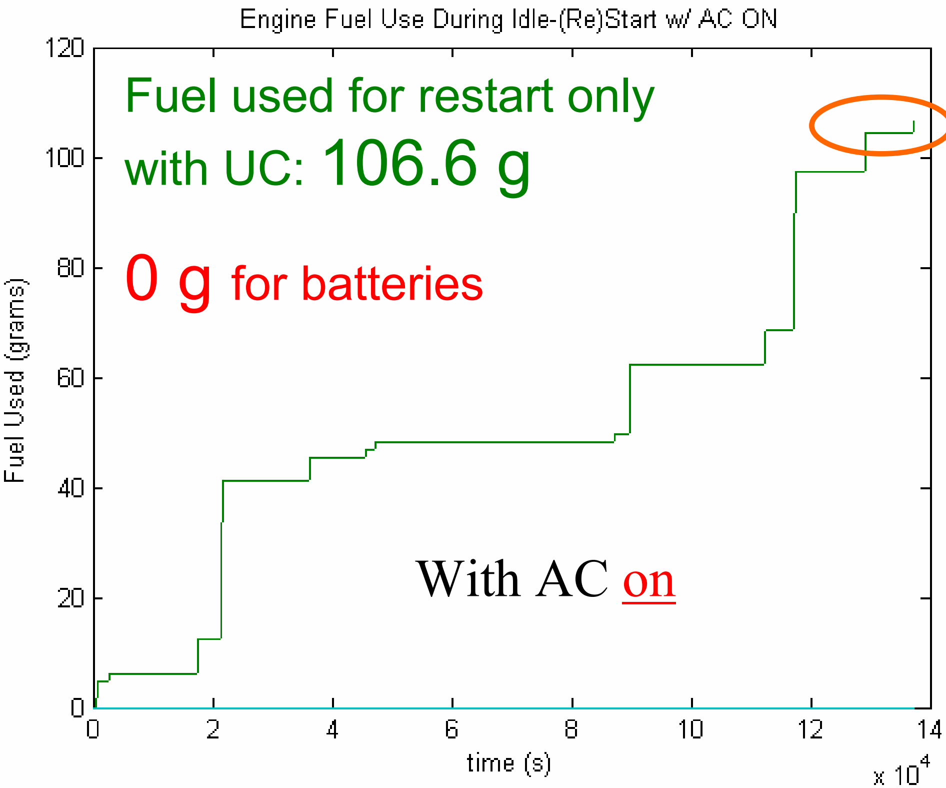




Total Idle-Restart Fuel Use Over the California Real-World Cycle





106.6g/888.7g = 12.0% reduction in idle-off fuel savings with ultracapacitors when AC is on (UC SOE is 75% SOC before idles)

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What is FTP Fuel Economy of Midsize Car with Start-Stop Operation and Impact of Auxiliaries?

- 2005 Chevy Malibu, 6 cyl, 3.5 L, Auto:
  22/32 MPG City/Hwy → Unadjusted* 24.4/41.0 MPG
  - With 0.4 g/s idle fuel usage, the maximum possible Idle-off operation could increases FTP fuel economy by up to 16.17% -OR- to 28.40 mpg unadjusted
    - Idle-restart, decreases the FTP fuel economy gain to 15.04% -OR- to 28.12 mpg unadjusted
    - In real operation, FTP fuel economy with idle-off operation might be 5%-10%
  - Unadjusted impact of Idle-restart due to AC operation with Ucaps is 0.28 mpg – a 1% decrease in FE
    - This drops to 0.03 mpg – a 0.10% decrease in FE, if UC_{SOC}=100% before idle-off

* Adjusted Numbers are reduced by 10% City / 22% Highway

What is <u>FTP</u> Fuel Economy of Standard Truck with Stat-Stop Operation and Impact of Auxiliaries?

- 2005 GMC Silverado C1500 2WD, 8 cyl, 5.3 L, Auto(4): 16/20 MPG City/Hwy → Unadjusted* 17.8/25.6 MPG

  C15 Silverado Hybrid 2WD .... A-4 ...... 5.3/8 .... 18/21

  - Assuming 0.48 g/s Idle Fuel Rate
  - Potential (maximum possible) <u>Idle-off</u> operation could increase FTP fuel economy by up to 13.83% - to <u>20.24 mpg unadjusted</u>
  - <u>Idle-restart</u>, decreases the FTP fuel economy gain to 12.88% - to <u>20.17 mpg unadjusted</u>
  - In real operation, FTP fuel economy with idle-off operation might be 5%-10%
  - Unadjusted impact of Idle-restart is <u>0.17 mpg</u> – a <u>0.8% decrease in FE</u>

* Adjusted Numbers are reduced by 10% City / 22% Highway

Summary

- Ucap applications are most likely in HEVs with Start-Stop strategies.
  - This provides the biggest opportunity if engine shutdown becomes a regulation/mandate during idles.
- Ucaps + batteries may have some applications in Mild HEVs, even full hybrids but added cost and volume could be issue.
- Ucaps have potential in hybrids with no downsizing of engine or fuel cell – Benefits?
- Auxiliaries **with** AC: energy content could support
  - for about 30 seconds with 2600 F UCs
  - for more than100 seconds for batteries
- UCs could support auxiliaries with AC
  - 80-90% of FTP and 50% of Real-World Cycle with 2600 F devices
  - 100% of FTP and about 75% of Real-Word Cycle with 5000 F devices
- For midsize cars with UCs, idle-off fuel savings are reduced by
  - less than 6% on the FTP cycle (1% loss in total fuel economy).
  - less than 12% on a 'California Real-World' cycle.
- Idle-off operation, potentially could increase FTP fuel economy of standard truck by 14% and midsize car by 16%.
- Recommend to extend the analysis with updated assumptions and new technologies

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