© EVS-25 Shenzhen, China, Nov. 5-9, 2010
The 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition

Lithium batteries and ultracapacitors alone and in combination in hybrid vehicles: Fuel economy and battery stress reduction advantages

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Abstract – Most vehicles presently use batteries for energy storage, but there are vehicle designs in which ultracapacitors alone or in combination with batteries can increase the efficiency of the vehicle and in addition lead to significantly longer battery cycle life. Ultracapacitors can be used alone in charge sustaining hybrid vehicles (HEVs) if the energy storage requirement is less than 150Wh. Simulations show that when ultracapacitors are used alone in HEVs, the roundtrip efficiency of the energy storage is 95-98% and the engine efficiency in on/off operation can be maintained near the peak efficiency value. Vehicle simulations were also run for plug-in hybrid vehicles (PHEVs) using advanced batteries with high energy density (>300 Wh/kg). The simulations were run with the batteries alone and in combination with ultracapacitors. Simulation results for the electric useage (Wh/mi) and all-electric range and fuel economy (mpg) for the PHEVs using batteries in combination with ultracapacitors and batteries alone are presented. In all cases, the vehicles operate in a more ideal manner using batteries in combination with ultracapacitors than with the batteries alone. In addition, the dynamic stress on the batteries due to high current pulses are greatly reduced using the ultracapacitors. *Copyright Form of EVS25.*

Keywords: ultracapacitors, batteries, combination, plug-in hybrid

1. Introduction

Most hybrid vehicles use batteries for energy storage. The batteries must provide both the energy and power required by the vehicle. In all cases, this requires compromises in designing the battery in that it can not be optimized for either energy density or power capability. In addition, in most cases the battery is oversized (stores much more energy than is used by the vehicle) in order to achieve long cycle life even for the shallow cycles experienced in charge sustaining hybrid vehicles like the Toyota Prius. As discussed in this paper, another approach to providing energy storage for hybrid vehicles, both charge sustaining and plug-in designs, is to utilize ultracapacitors either alone or in combination with batteries. In this approach, the batteries can be optimized for energy density and cycle life and ultracapacitors can provide the power both for acceleration and regenerative braking. The ultracapacitors would be deep discharged to one-half rated cell voltage and still provide cycle life of 500,000 to one million cycles.

In the first section of the paper, the energy storage characteristics of lithium batteries and ultracapacitors are presented and compared. Of particular interest is the comparative power capability of lithium batteries and carbon/carbon ultracapacitors for charge/discharge conditions to be encountered in hybrid vehicles. In the next section of the paper, the design of charge sustaining hybrid vehicles using ultracapacitors alone in place of batteries is discussed in terms of the sizing of the ultracapacitor unit and control strategies that optimize the fuel economy improvements achievable. The final section of the paper deals with the use of a combination of batteries and ultracapacitors in plug-in hybrid vehicles. The emphasis in this section is on the use of ultracapacitors with advanced batteries having energy densities greater than 200 Wh/kg. It is likely that these batteries will not have proportionally high power density and will require the assist of ultracapacitors to achieve all-electric operation even on the FUDS driving cycle. Detailed vehicle simulation results are presented for both the charge sustaining and plug-in hybrid vehicle designs.

2. Energy storage considerations

Battery and ultracapacitor characteristics

A number of lithium batteries and ultracapacitors have been tested in the laboratory at the University of California-Davis [1-3]. A summary of the test results for the batteries is given in Table 1 and for the ultracapacitors in Table 2. For both energy storage technologies, the devices with the highest energy density typically have the lowest power capability. The pulse power capabilities shown in the tables were calculated using the following relationships:

Batteries: $P = EF(1-EF)\, V_{oc}^2/R$
Ultracapacitors: $P = 9/16(1-EF)\, V_{rated}^2/R$

where EF is the efficiency of the pulse ($EF = V_{pulse}/V_{oc}$).

The matched impedance power which is often cited for both battery and ultracapacitor devices is calculated as follows:

$$P_{\text{match imped.}} = V^2/4R$$

For charge sustaining hybrids, it seems reasonable to cite the power capability of devices for pulse power efficiencies of 90-95%. For PHEVs and EVs operating in charge depleting modes for the battery, it is reasonable to cite the power for efficiencies of 75-80%. In all instances, the power capability is proportional to V^2/R indicating that high power capability requires a low resistance R.

Table 1: Summary of the performance characteristics of lithium-ion batteries of various chemistries

Battery Developer /Cell type	Electrode chemistry	Voltage range	Ah	Resist. mOhm	Wh/ kg	W/kg 90% effic.*	W/kg Match. Imped.	Wgt. (kg)	Density gm/cm3
Enerdel HEV	Graphite/ Ni MnO2	4.1-2.5	15	1.4	115	2010	6420	.445	----
Enerdel EV/PHEV	Graphite/ Ni MnO2	4.1-2.5	15	2.7	127	1076	3494	.424	----
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	140	1220	3388	.787	2.4
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	63	1225	3571	.35	2.1
GAIA Cylind.	Graphite/ NiCoMnO2	4.1-2.5	40 7	.48 3.6	96 78	2063	5446 3472	1.53 .32	3.22 ---
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	90	1393	3857	.07	2.2
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11	2.2	70	990	2620	.34	1.83
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	3.8	1.15	35	2460	6555	.26	1.91
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	1.8	60	144	577	1550	.043	2.6
Quallion Cylind.	Graphite/ NiCo	4.2-2.7	2.3	72	170	445	1182	.047	2.8
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	165	1278	3147	.41	----
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	113	1100	3085	.42	---
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	46	395	1093	1.04	1.8

* power density $P = \text{Eff.}*(1-\text{Eff.})\, Voc^2/R$, $P_{\text{match. imped.}} = V^2/4R$

Table 2: Summary of ultracapacitor device characteristics

Device	V rated	C (F)	R (mOhm)	RC (sec)	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell*	2.7	2885	.375	1.08	4.2	994	8836	.55	.414
Maxwell	2.7	605	.90	.55	2.35	1139	9597	.20	.211
Skeleton Technologies	2.8	1600	1.3	2.1	5.8	800	7140	.22	.13
Yunasko**	2.7	55	4	.22	5.5	5695	50625	.009	---
Yunasko**	2.7	450	1.3	.58	5.89	2766	24595	.057	.045
Yunasko**	2.7	510	.9	.46	5.0	2919	25962	.078	.055
Ness	2.7	1800	.55	1.00	3.6	975	8674	.38	.277
Ness	2.7	3640	.30	1.10	4.2	928	8010	.65	.514
Ness (cyl.)	2.7	3160	.4	1.26	4.4	982	8728	.522	.379
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	.210 (estimated)	.151
Panasonic (propylene carbonate)	2.5	1200	1.0	1.2	2.3	514	4596	.34	.245
EPCOS	2.7	3400	.45	1.5	4.3	760	6750	.60	.48
LS Cable	2.8	3200	.25	.80	3.7	1400	12400	.63	.47
BatScap	2.7	2680	.20	.54	4.2	2050	18225	.50	.572
Power Sys. (activated carbon, propylene carbonate) **	2.7	1350	1.5	2.0	4.9	650	5785	.21	.151
Power Sys. (graphitic carbon, propylene carbonate) **	3.3 3.3	1800 1500	3.0 1.7	5.4 2.5	8.0 6.0	486 776	4320 6903	.21 .23	.15 .15
JSR Micro (AC/graphitic carbon)	3.8	1000 2000	4 1.9	4 3.8	11.2 12.1	900 1038	7987 9223	.113 .206	.073 .132

(1) Energy density at 400 W/kg constant power, Vrated - 1/2 Vrated

(2) Power based on P=9/16*(1-EF)*V2/R, EF=efficiency of discharge

* Except where noted, all the devices use acetonitrile as the electrolyte

** All device except those with ** are packaged in metal containers

Table 3: Comparisons of the power capabilities of various devices for HEV and PHEVs using the different methods for calculation

Device				
Lithium batteries 60% SOC	Matched impedance	USABC Min/max	Efficient pulse EF =95%	Efficient pulse EF =80%
Kokam NCM 30Ah	2893	2502	550	1848
Enerdel HEV NCM 15 Ah	5491	4750	1044	3507
Enerdel EV NCM 15 Ah	2988	2584	568	1908
EIG NCM 20 Ah	2688	2325	511	1721
EIG FePhosph. 15 Ah	2141	2035	458	1540
Altairnano LiTiO 11 Ah	1841	1750	350	1180
Altairnano LiTiO 3.8 Ah	4613	4385	992	3341
Ultracapacitors $V_0 = 3/4V_{Rated}$				
Maxwell 2890F	8836	4413	994	
Nesscap 3100F	8730	4360	982	
Batscap 2700F	18224	9102	2050	
ApowerCap 450F	22838	11406	2569	
LSCable 3200F	12446	4609	1038	
JSR 2000F	9228	6216	1400	

Comparisons of the power capabilities of lithium batteries and ultracapacitors

There has been considerable discussion in the literature [4-6] comparing the power capability of lithium-ion batteries and ultracapacitors. The conclusions vary from statements that lithium batteries have power capability equal to that of ultracapacitors to statements that ultracapacitors have an order of magnitude higher power capability than lithium batteries. Detailed comparisons of the power capability of ultracapacitors and batteries taken from [4] are shown in Table 3. As indicated in the table, neither of the extreme statements is valid in general and that comparisons should be made between specific devices for specific applications. Comparisons are often made based on the matched impedance power of the two types of devices. These comparisons indicate that most ultracapacitors have a power capability (W/kg) of 3 to 6 times that of lithium batteries. However, for vehicle applications the matched impedance power is not appropriate and should not be the basis of comparison.

For charge sustaining HEV applications, a good basis of comparison is the W/kg at 95% efficiency at the SOC at which the devices will be used in the vehicle. On this basis, there are lithium batteries with the same power capability as some carbon/carbon ultracapacitors, but there are some ultracapacitors with power capability twice that of the highest power lithium batteries presently available for vehicle applications. In other words, it is not possible to make general statements that are applicable to all devices of either type. The issue is further complicated when one notes that the density of the lithium batteries is about twice that of carbon/carbon ultracapacitors (2.2 gm/cm^3 for the batteries and 1.2 gm/cm^3 for the ultracapacitors). Hence on a volume basis W/L at 95% efficiency, the differences between the batteries and ultracapacitors are often quite small. Hence for HEVs, batteries alone and ultracapacitors alone can be an option with the decision being based on cycle life and cost in addition to relative power capability [4].

For plug-in hybrid and battery electric vehicle applications, the maximum useable power density from the lithium-ion battery can be higher than in an HEV because the peak power of the driveline is used less frequently and consequently charge/discharge efficiently is less important. For example, a pulse power efficiency of 80% is probably sufficient and most of the lithium batteries have a power capability of greater than 1000 W/kg, 2200 W/L for that efficiency. In addition, the battery is larger (heavier) in these vehicles and as a result, the power density requirement is less demanding. For PHEVs and EVs, the best application of ultracapacitors is likely to be in combination with batteries designed for high energy density, long cycle life, and low cost. In those cases, as discussed in a later section of the paper, the ultracapacitors greatly reduce the peak currents and dynamic stress on the batteries and thus extend their cycle life.

3 Hybrid vehicles using ultracapacitors alone

Vehicle design considerations

Table 4 Energy storage unit requirements for various types of electric drive mid- size passenger cars

Type of electric driveline	System voltage V	Useable energy storage	Maximum pulse power at 90-95% efficiency kW	Cycle life (number of cycles)	Useable depth-of-discharge
Electric	300-400	15-30 kWh	70-150	2000-3000	deep 70-80%
Plug-in hybrid	300-400	6-12 kWh battery 100-150 Wh ultracapacitors	50-70	2500-3500	deep 60-80%
Charge sustaining hybrid	150-200	100-150 Wh ultracapacitors	25-35	300K-500K	Shallow 5-10%
Micro-hybrid	45	30-50 Wh ultracapacitors	5-10	300K-500K	Shallow 5-10%

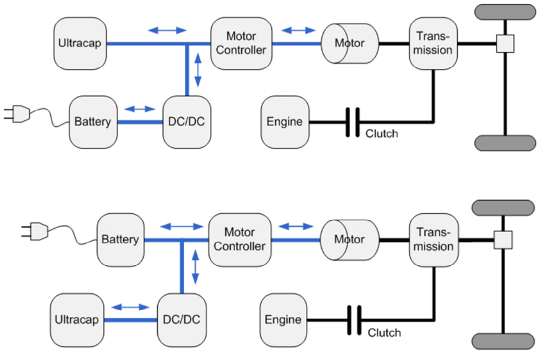


Figure1: Schematics of powertrains using ultracapacitors and batteries

The energy storage requirements vary a great deal depending on the type and size of the vehicle being designed and the characteristics of the electric powertrain to be used. Energy storage requirements for various vehicle designs and operating modes are shown in Table 4 for a mid-size passenger car. Requirements are given for electric vehicles and both charge sustaining and plug-in hybrids. These requirements can be utilized to size the energy storage unit in the vehicles when the characteristics of the energy storage cells are known. In some of the vehicle designs considered in Table 4, ultracapacitors are used to provide the peak power rather than batteries.

In the cases using only ultracapacitors, the key issue is the minimum energy (Wh) required to operate the vehicle in real world driving because the energy density characteristics of ultracapacitors are such that the power and cycle life requirements will be met in most cases if the unit is large enough to met the energy storage requirement. As shown in Table 4, for passenger car applications, the energy storage in the ultracapacitor can be 150 Wh or less even if the ultracapacitor is used alone for energy storage.

Powertrain control strategies with ultracapacitors

Schematics of hybrid powertrains using ultracapacitors are shown in Figure 1. If the ultracapacitor is used alone, there is no need for special electronics if the motor electronics can handle the increased voltage swing of the ultracapacitors. If the ultracapacitors are used in combination with batteries, there is a need for additional electronics to control the power from either the battery or the ultracapacitors as shown in Figure 1.

When ultracapacitors are used alone as the energy storage unit in a charge sustaining hybrid (HEV), the objective of the control strategy is to permit the engine to operation near its maximum efficiency. As shown in [7-9], this can be done by operating the hybrid vehicle on the electric drive only when the power demand is less than the power capability of the electric motor; when the vehicle power demand exceeds that of the electric motor, the engine is operated to meet the vehicle power demand plus to provide the power to recharge the ultracapacitor unit. In this mode, the electric machine is used as a generator and the engine operating point is selected along its maximum efficiency line (torque vs. RPM). The recharging power is limited by the power of the electric machine because ultracapacitors can have pulse power efficiency greater than 95% for W/kg values of over 2000 W/kg (see Table 2). This control strategy is referred to as the "sawtooth" strategy because a plot of the ultracapacitor state-of-charge (SOC) has the form of a saw blade.

Vehicle simulation results

Simulations of mid-size passenger cars using the ultracapacitors in micro-hybrid and charge sustaining hybrid powertrain designs were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis. All the powertrains were in the same vehicle having the following characteristics: test weight 1660 kg, C_d=.3, A_F=2.25 m^2, RRCF =.009. The engine map used in the simulations was for a Ford Focus 2L, 4-cylinder engine. The rated engine power was 120 kW for the conventional ICE vehicle and the micro-hybrid and 110 kW for the charge sustaining hybrids. All the hybrids use the single-shaft arrangement similar to the Honda Civic hybrid. The same induction electric motor map was used for all the vehicle designs.

Table 5: Summary of the vehicle fuel economy simulation results using ultracapacitors for various driving cycles

L/100 km/ mpg

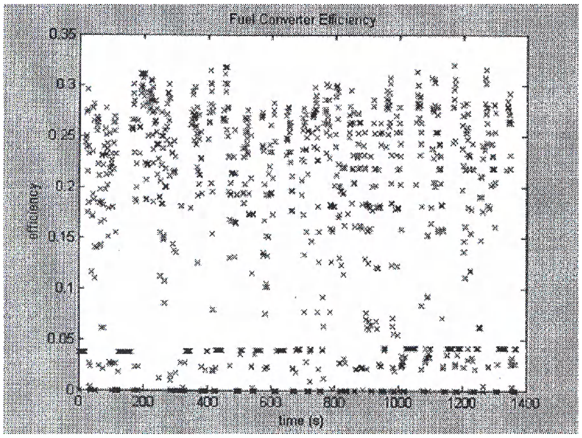
Driveline type	Energy storage type	Voltage and weight cells (kg)	EM Peak kW	FUDS	HWFET	US06	ECE-EUDC
ICE baseline				10/ 23.8	6.9/ 34.4	9.6 24.7	9.7/ 24.6
Micro-HEV	Lead-acid/ ultracaps	48					
	Carbon/carbon	6 kg	6	5.7/ 41.7	5.3/ 44.7	7.8/ 30.6	5.9/ 40.2
	Hybrid carbon	3 kg	6	7.3/ 32.8	6.3/ 38.0	8.9/ 26.7	7.1 33.4
Charge sustaining hybrid	Ultracaps	200					
	Carbon/carbon	30 kg	35	5.4/ 43.8	5.0/ 47.9	7.1/ 33.6	5.5/ 43.2
	Hybrid carbon	13 kg	35	5.8/ 40.9	5.2/ 45.8	8.0/ 29.9	5.8/ 41.3
Plug-in hybrid .	12 kWh Li battery (200 Wh/kg) and ultracaps	300	70 kW with 45 kW from caps				
	Carbon/carbon	40 kg	45	5.5/ 43.2	5.0/ 47.7	7.0/ 33.9	5.5/ 42.9
	Hybrid carbon	18 kg	45	5.8 41.2	5.2/ 46.2	7.9/ 30.2	5.8/ 41.2

The simulation results are summarized in Table 5 for a conventional ICE vehicle and each of the hybrid designs. Results are given for fuel usage in terms of both L/100 km and mpg for various driving cycles. It is clear from Table 5 that large improvements in fuel usage are predicted for all the hybrid powertrains using ultracapacitors for energy storage. The simulation results will be discussed separately for each hybrid design.

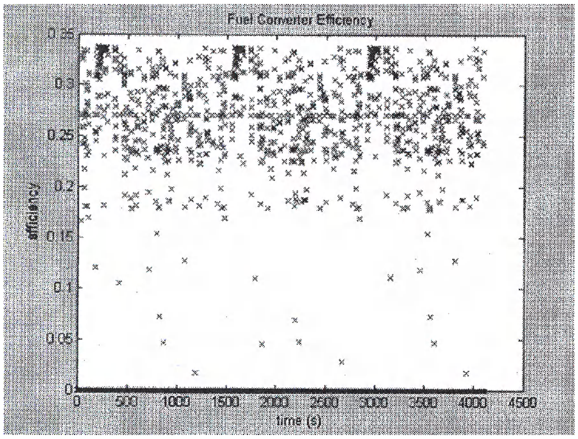
Micro-hybrids

The results for the micro-hybrids are particularly interesting and surprising, because of the large fuel economy improvements predicted. These improvements were about 40% on the FUDS and ECE-EUD cycles and 20% on the Federal Highway and US06 cycles using the carbon/carbon ultracapacitor units. The improvements are significantly less using the hybrid carbon units because of their lower round-trip efficiencies. In the micro-hybrid designs, the rated engine power used was the same as that in the conventional ICE vehicle in order that the performance of the hybrid vehicle when the energy storage in the ultracapacitors is depleted would be the same as the conventional vehicle. The ultracapacitors were used to improve fuel economy with only a minimal change in vehicle acceleration performance. The control strategy used was "sawtooth" strategy discussed in the previous paragraph. As shown in Figure 2, this resulted in a large improvement in average engine efficiency from 19% in the ICE vehicle to 30% in the micro-hybrid even though the electric motor had a peak power of only 6 kW.

Additional computer simulations were made for higher motor power (up to 12 kW) and larger ultracapacitor energy storage (up to 50 Wh). It was found that the improvements in fuel economy were only marginally greater. Using a motor power of 3 kW reduced the fuel economy improvement on the FUDS by more than 50%. Note from Table 4 that the fuel economy improvements using the carbon/carbon ultracapacitors were for all the cycles greater than those using the hybrid carbon devices. This was the case because the round-trip efficiencies for the carbon/carbon units were 95-98% and those of the hybrid carbon units were 75-90% for the various driving cycles. As shown in Table 2, the hybrid carbon devices had higher energy density, but even though their power density for 95% efficiency was relatively high (1050 W/kg), it was not proportionally higher – that is twice as high- as the carbon/carbon devices with lower energy density. These results show clearly that it is essentially to develop high energy density ultracapacitors with proportionally higher power density; otherwise their use in vehicle applications will be compromised.



Engine operating efficiency for the ICE vehicle - average engine efficiency .19



Engine operating efficiency for the micro-hybrid - average engine efficiency .30

Figure 2: A comparison of engine efficiencies for a conventional ICE vehicle and a micro-hybrid on the FUDS cycle using carbon/carbon ultracapacitor

Charge sustaining hybrids

The fuel economy simulation results for charge sustaining hybrids are also shown in Table 4 for a mid-size passenger car using both carbon/carbon and hybrid carbon ultracapacitors. Using the carbon/carbon ultracapacitor unit, the fuel savings are about 45% for the FUDS and ECE-EUD cycles and about 27% for the Federal Highway and US06 cycles. These improvement values are higher than for the micro-hybrid, but not by as large a factor as might be expected. The prime advantage of the high power electric driveline in the charge sustaining hybrid is that it yields large fuel economy improvements even for high power requirement driving cycles like the US06. The fuel economy improvements using the hybrid carbon ultracapacitor unit are not much less (5-10%) than those with the carbon/carbon unit even though the round-trip efficiency of the hybrid carbon unit is only 85-90% compared to 98% for the carbon/carbon unit. Since the weight/volume of the hybrid carbon unit is relatively small - 43% of that of the carbon/carbon unit, it appears that the charge sustaining hybrid application is a better one for the hybrid carbon technology than the micro-hybrid application.

4. Plug-in hybrid vehicles using advanced batteries and ultracapacitors

Control strategy for a plug-in hybrid vehicle (PHEV)

For plug-in hybrid vehicles (PHEV), batteries and ultracapacitors would be used in combination with the batteries providing the energy and the ultracapacitors the power. This powertrain schematic is shown in Fig.1. The control strategies in the charge depleting mode is to limit the power from the battery to the average power needed by the vehicle with the ultracapacitor providing the additional power during vehicle accelerations. The ultracapacitors also accept all the energy recovered during regenerative braking. If engine operation is needed, the "sawtooth" strategy is used with the ultracapacitors being recharged using engine power. In the charge sustaining mode of operation of the PHEV, the electric drive is operated using only the ultracapacitors like that previously described. The PHEV operating strategies are summarized in Fig.3.

Simulations of plug-in hybrid vehicles using advanced batteries and ultracapacitors

A detailed study of plug-in hybrids using advanced batteries is presented in [10]. Only the results of that study will be summarized and discussed in this paper. The characteristics of the advanced batteries used in the simulations are given in Table 6.

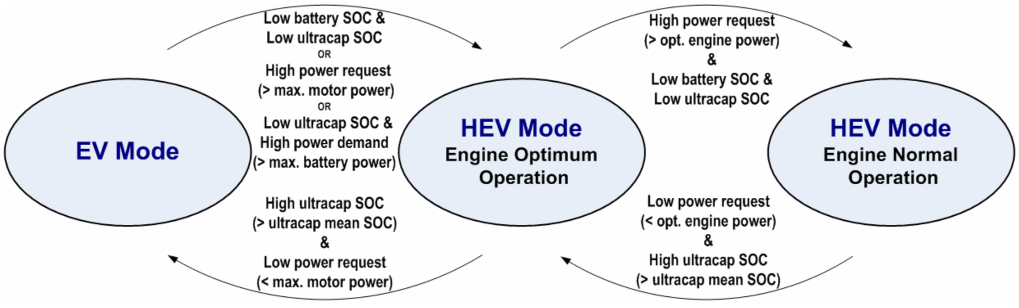


Figure 3: Summary of the operating strategy used in the simulation of plug-in hybrid vehicles

Table 6: Characteristics of present and future battery cell technologies for EVs and PHEVs

Chemistry Anode/cathode	Cell voltage Max/nom.	Ah	Wgt. kg	R mOhm	EV Wh/kg	HEV W/kg 95%	EV W/kg 75%	Cycle life (deep)	Thermal stability
Present technology batteries									
Graphite/ $NiCoMnO_2$	4.2/3.6	30	.787	1.5	140	521	2060	2000-3000	fairly stable
Graphite/ Mn spinel	4.0/3.6	15	.424	2.7	127	540	2120	1500	fairly stable
Future technology batteries									
Graphite/ composite MnO_2	4/3.6	5	.09	20	200	250	1350	----	fairly stable
Silicon carbon composites/ composite MnO_2	4/3.6	20	.24	4.5	295	621	2250	---	fairly stable
Rechargeable Zinc-Air	1.3/1.15	20	60	6.6	385	156	616	----	very stable
Present Technology Power devices									
supercapacitor Activated carbon/activated carbon	2.7/1.35	500F	.068	1.3	5.5	2320	11600	500K	Very stable
Power battery Lithium titanate oxide	2.8/2.5	4	.23	1.15	40	1310	5170	20-50 K	Very stable

Table 7: The advanced battery and ultracapacitor units used in the simulations

Lithium-ion batteries				
EIG $NiCoMnO_2$	30 kg	20 Ah cells	60 in series	3.5 kWh useable
Composite MnO_2	32 kg	40 Ah cells	60 in series	4.6 kWh useable
Silicone composite	22 kg	30 Ah cells	60 in series	4.6 kWh useable
Zinc-air batteries				
Zn-air	32 kg	60Ah cells	180 in series	9.5 kWh useable
Carbon/carbon ultracapacitors				
Symmetric C/C	20 kg	1350F cells	110 in series	100 Wh useable

The battery and ultracapacitor units used in the simulations are given in Table 7. Simulations were performed with the batteries alone and in combination with the ultracapacitors. The nominal energy storage unit voltage was 240V (approx.) in all cases with the maximum currents limited to about 300A even in the cases of the batteries alone. In all cases, the batteries were depleted to 30% SOC from 100% SOC.

Simulation results

All the PHEV simulations were performed using the following vehicle inputs:

C_D =.27, $A_F = 2.2\ m^2$, f_r =.008
test weight = 1650 kg (approx.)
Engine: Honda 1.3L, iVTEC engine map, scaled to 90 kW
Electric motor: Honda hybrid Civic AC PM 2006 efficiency map, scaled to 70 kW
DC/DC inverter: constant efficiency 0.96
Transmission: 5-speed manual (3.11, 2.11, 1.55, 1.0, .71, FD=3.95), automatically shifted in the model, but future models would incorporate the DCT (dual clutch transmission) as a convenient means to have smooth, fast shifting and to decouple the engine when it is not needed to provide power.

Fuel and electricity use characteristics

The simulation results are summarized in Tables 8 and 9 showing results for vehicle operation in the charge depleting and charge sustaining modes of the PHEV.

Table 8: Simulation results for the advanced batteries with ultracapacitors

Battery Type (1)	cycle	Range mi.	kW max. control	kW max bat.	Eff. Bat .	kW max. Cap.	Eff. Cap.	Wh/mi Bat.	Operat. mode	mpg 20mi	mpg 40mi	Ch. Sus. HEV mpg
Compos . MnO2	FUD	22	40	18	.94	40	.97	215	AE	none	97	52.8
32kgbat	HW	20	45	18	.91	45	.96	227	AE	none	109	56.3
20kgcap	US06	30	68	21	.91	68	.94	180	blended	71.9	56	38.3
Si Carb/ Compos . MnO2	FUD	20	40	18	.94	40	.97	220	AE	none	99	52.8
22kgbat	HW	20	45	19	.91	45	.97	225	AE	none	110	56.8
20kgcap	US06	30	68	21	.91	68	.94	190	blended	71.1	52	38.4
Rech. Zn-air	FUD	40	45	19	.87	45	.97	228	AE	none	none	54.5
32kgbat	HW	38	45	19	.81	45	.97	242	AE	none	none	57.7
20kgcap	US06	66	68	21	.82	68	94	149	blended	62.4	60	38.8

(1) weight of cells only

Table 9: Simulation results for the batteries alone

Battery Type (1)	cycle	Range mi.	kW max. control.	kW max. bat.	Eff. Bat.	Wh/mi Bat.	Operat. mode	mpg 20mi .	mpg 40mi	Mpg Ch. sus. HEV
EIG NiCoMn	FUD	27	30	30	.94	125	blended	134	85	47
30 kg	HW	24	20	20	.93	137	blended	110	87	47
	US06	57	58	58	.88		blended	48	45	37
Compos. MnO2	FUD	36	30	30	.92	135	blended	134	104	46.9
32kgbat	HW	31	20	20	.91	147	blended	167	113	46.6
	US06	64	58	58	.87	92	blended	48	48	34.1
Si Carb/ Compos. MnO2	FUD	35	30	30	.93	138	blended	138	106	46.9
22kgbat	HW	32	20	20	.92	148	blended	169	114	46.9
	US06	64	58	58	.88	87	blended	48	48	35.7
Rech. Zn-air	FUD	66	30	30	.84	139	blended	139	137	39.4
32kgbat	HW	63	20	20	.83	156	blended	169	169	41.1
	US06	93	36	36	.72	101	blended	48.5	48.5	30.1

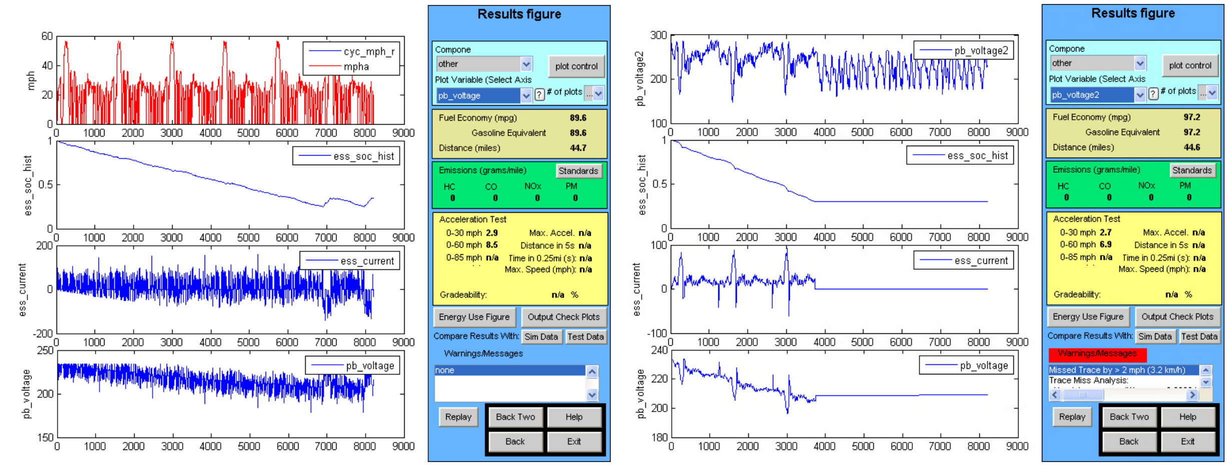
(1) weight of cells only

With the batteries in combination with the ultracapacitors, the PHEVs were able to operate in the all-electric mode until the battery SOC=30% on the FUDS and FED Highway driving cycles. In all cases for the US06 driving cycle, the vehicle had blended operation (engine and electric drive both needed) in the charge depleting mode. The use of the ultracapacitors with the batteries permits all-electric operation of the vehicle over a wide range of driving conditions with higher Wh/mi for all the driving cycles. Hence in the charge depleting mode, the fuel economy (mpg) is higher by 50-100% using the ultracapacitors for all the batteries. The fuel economy in the charge sustaining mode is also higher for all the driving cycles using the ultracapacitors, but only by 15-40% in most cases. The acceleration times of the vehicle were lower using the ultracapacitors than for the batteries alone. With the ultracapacitors, the acceleration times were 2.7 sec for 0-30 mph and 6.9 sec for 0-60 mph. For the batteries alone, the acceleration times varied somewhat with the battery used ranging from 2.9-3.2 sec for 0-30 mph and 8.6-9.8 sec for 0-60 mph. Hence in all respects, vehicle performance was improved using the ultracapacitors for all the batteries studied.

Reductions in battery stress using ultracapacitors

The current and voltage responses of the batteries with and without the ultracapacitors are shown in Figures 5-8 for the silicone carbon lithium-ion and the Zinc-air batteries for the FUDS and US06 driving cycles. The effects of the load leveling of the power demand from the batteries using the ultracapacitors are clearly evident in the figures. Both the average currents and the peak currents from the batteries are lower by a factor of 2-3 using the ultracapacitors. The minimum voltages of the batteries are significantly higher using the capacitors and the voltage dynamics (fluctuations) are dramatically reduced. Hence the stress on the battery and resultant heating are much reduced. The simulation results in Figures 5-7 also show that the ultracapacitors are utilized over a wide voltage range indicating that a large fraction of their usable energy storage (100 Wh) is being used to load level the batteries. This is only possible using a DC/DC converter between the battery and the DC- bus.

The simulation results also indicate that using ultracapacitors, batteries with a wide range of power characteristics can be used in PHEVs and also EVs without sacrificing vehicle performance and subjecting the batteries to high stress and resultant shorter cycle life. This could be especially important in the future as high energy density batteries such as Zinc-air and possibly lithium-air are developed. It is likely that those battery types will not have commensurate increases in useable power density and without ultracapacitors, the battery unit in PHEVs and EVs would be sized by the maximum power requirement (kW) rather than the range (mi)/energy requirement (kWh). This would significantly increase weight, volume, and the cost of the battery unit. It is also unlikely that the air electrode will have charge acceptance capability and thus regenerative braking performance approaching that of ultracapacitors or even lithium-ion batteries. This is another advantage of the use of ultracapacitors with the air-electrode batteries.

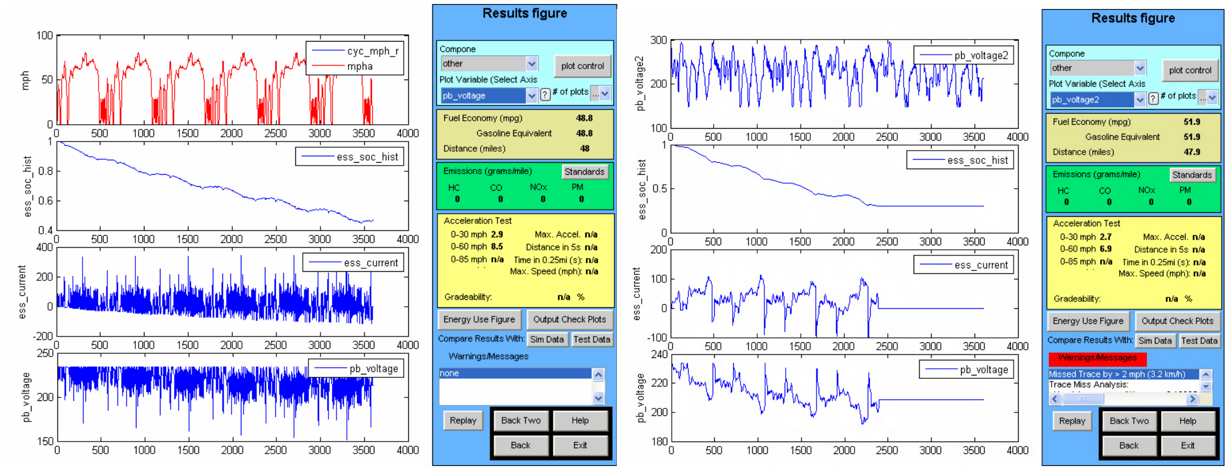


Compone: other
Plot Variable (Select Axis: pb_voltage
Fuel Economy (mpg) 89.6
Gasoline Equivalent 89.6
Distance (miles) 44.7
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-30 mph 2.9 Max. Accel. n/a
0-60 mph 8.5 Distance in 5s n/a
0-85 mph n/a Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Warnings/Messages: none

Compone: other
Plot Variable (Select Axis: pb_voltage2
Fuel Economy (mpg) 97.2
Gasoline Equivalent 97.2
Distance (miles) 44.6
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-30 mph 2.7 Max. Accel. n/a
0-60 mph 6.9 Distance in 5s n/a
0-85 mph n/a Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Warnings/Messages
Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

FUDS without ultracaps FUDS with ultracaps

Figure 5: The Si Carbon lithium battery on the FUDS with and without ultracapacitors

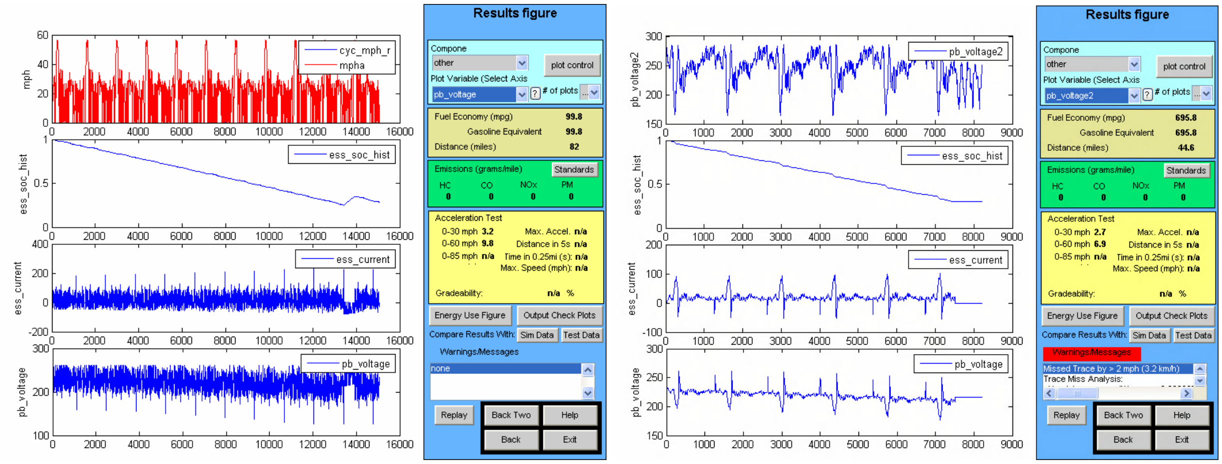


Compone: other
Plot Variable (Select Axis: pb_voltage
Fuel Economy (mpg) 48.8
Gasoline Equivalent 48.8
Distance (miles) 48
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-30 mph 2.9 Max. Accel. n/a
0-60 mph 8.5 Distance in 5s n/a
0-85 mph n/a Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Warnings/Messages: none

Compone: other
Plot Variable (Select Axis: pb_voltage2
Fuel Economy (mpg) 51.9
Gasoline Equivalent 51.9
Distance (miles) 47.9
Emissions (grams/mile) HC 0 CO 0 NOx 0 PM 0
Acceleration Test
0-30 mph 2.7 Max. Accel. n/a
0-60 mph 6.9 Distance in 5s n/a
0-85 mph n/a Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Warnings/Messages
Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

FUDS without ultracaps FUDS with ultracaps

Figure 6: The Si Carbon lithium battery on the US06 with and without ultracapacitors



Results figure
Compone: other
Plot Variable (Select Axis: pb_voltage
Fuel Economy (mpg) 99.8
Gasoline Equivalent 99.8
Distance (miles) 82
Emissions (grams/mile): HC 0, CO 0, NOx 0, PM 0
Acceleration Test
0-30 mph 3.2
0-60 mph 9.8
0-85 mph n/a
Max. Accel. n/a
Distance in 5s n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Warnings/Messages: none

Results figure
Compone: other
Plot Variable (Select Axis: pb_voltage2
Fuel Economy (mpg) 695.8
Gasoline Equivalent 695.8
Distance (miles) 44.6
Emissions (grams/mile): HC 0, CO 0, NOx 0, PM 0
Acceleration Test
0-30 mph 2.7
0-60 mph 6.9
0-85 mph n/a
Max. Accel. n/a
Distance in 5s n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %
Warnings/Messages
Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

Zinc-air on the FUDS without ultracaps

Zinc-air on the FUDS with ultracaps

Figure 7: The Zinc-air battery on the FUDS with and without ultracapacitors

5. Summary and conclusions

The performance of ultracapacitors and lithium batteries is reviewed based on test data taken at the University of California-Davis. It was found that ultracapacitors are commercially available with energy densities of 4.5-5 Wh/kg and power density of 1-2kW/kg with a pulse efficiency of 95%. Lithium batteries of various chemistries were tested. It was found that batteries consisting of graphite and manganese oxide/spinel had energy densities of about 140-160Wh/kg and power densities of 0.5-1.0 kW/kg with pulse efficiencies of 95%. Comparisons of the power densities of ultracapacitors and lithium batteries indicated that the best ultracapacitors had power densities a factor of 2-3 higher than the high power batteries, but there are some batteries with higher power capability than the lower power capacitors. For use in hybrid vehicles, high power density is very important for ultracapacitors.

The application of ultracapacitors in hybrid-electric vehicles is considered in detail utilizing vehicle simulation results. The use of ultracapacitors alone is analyzed for micro- and mild/full charge sustaining hybrids and in combination with high-energy density batteries for plug-in hybrids. It was found that ultracapacitors could be used in place of batteries in the charge sustaining hybrids resulting in fuel economy improvements of 25-50% even for relatively small electric drive systems of 6-10 kW. The ultracapacitor units only stored 50-100 Wh of useable energy and their efficiency was high being 95-98%.

Vehicle simulations were also performed for plug-in hybrid vehicles that used ultracapacitors combined with advanced, high energy density batteries. The batteries had energy densities of 200-400 Wh/kg, but only moderate power capability of 300-1000 W/kg for 90% efficient pulses. The simulation results indicated that the advanced batteries combined with ultracapacitors could provide all-electric operation on the FUDS and Federal Highway cycles in the charge depleting mode and excellent fuel economy in the charge sustaining mode. Vehicle operation with the advanced batteries without the ultracapacitors required blended operation on all driving cycles. Comparisons of the current/voltage/power profiles of the batteries with and without the ultracapacitors indicated the peak currents and thus the stress on the batteries were reduced by about a factor of three using the ultracapacitors. This reduction is expected to lead to a large increase in battery cycle life.

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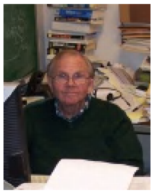
7. Authors



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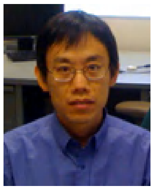

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