Ultracapacitors and Batteries for Hybrid Vehicle Applications

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Abstract

This paper is concerned with application of batteries and ultracapacitors in various types of hybrid-electric vehicles. The requirements for and the characteristics of the various energy storage options are considered in detail and approaches presented for comparing the different options for charge sustaining and plug-in hybrid vehicle designs. Simulation results are given using batteries and ultracapacitors that indicate that using either technology relatively large improvements (25-60%) in fuel economy can be achieved in charge sustaining hybrids if the control strategy utilized emphasizes engine operation near maximum efficiency. Such a control strategy, which operates the vehicle alternately in all-electric and engine-powered battery/ultracapacitor charging modes, has been termed the “sawtooth” because of the form of the resultant state-of-charge profiles. This control strategy results in significant fuel economy improvements on both the city (FUDS) and highway driving cycles.

The analysis of combinations of batteries and ultracapacitors indicates that for most applications and battery types, it does not appear to be advantageous to combine the two technologies. However, for a charge sustaining micro-hybrid, the combination of a relatively small ultracapacitor pack (40 Wh) with a high energy density, modest power lead-acid battery appears to offer good potential for achieving fuel economy improvements of about 25%. Another possible combination can be a larger ultracapacitor pack (100 Wh) with a high energy density (200 Wh/kg), modest power lithium-ion battery in plug-in hybrids having all-electric ranges of greater than 15 miles. In both applications, it is important that the ultracapacitor have high power capability (W/kg >1000 for 95% efficiency) and a useable energy density of at least 5 Wh/kg.

Simulations results are presented for PHEV conversions of the 2004 Prius using lithium-ion batteries (A123). Using an optimized control strategy during the charge depleting mode of operation, fuel economies (gasoline only) of 350-500 mpg are projected for vehicles with an all-electric range (blended) of 20 miles using a battery storing about 6 kWh (5 kWh useable).

Keywords: ultracapacitors, vehicle batteries, hybrid vehicles

1. Introduction

It is well recognized that the future development and successful marketing of hybrid-electric vehicles of various types are highly dependent on the performance and cost of the energy storage technologies available. There seems to be high confidence that the performance and cost of the other mechanical and electrical components in hybrid-electric drivelines are suitable for hybrid vehicle applications, but there remains considerable uncertainty regarding the energy storage technologies. For example, nearly all the announcements of auto companies concerning plug-in hybrids include a statement to the effect that a particular vehicle will be marketed in a given year if the status of lithium-ion battery technology permits. Whether a particular energy storage technology is suitable for use in a particular type of hybrid depends both on its characteristics and the requirements for energy storage in the vehicle design. This paper is concerned with both the requirements for energy storage in various types of hybrid vehicles and the characteristics of the energy storage devices being developed. In the paper, both charge sustaining and plug-in hybrids will be considered and batteries and ultracapacitors used alone and in combination will be evaluated for those applications.

2. Hybrid vehicle applications and associated energy storage requirements

From a vehicle performance point-of-view, energy storage requirements are defined in terms of the peak power and energy storage capacity (Wh or kWh). The vehicle designer is also interested in the weight and volume of the energy storage unit which follows once the energy and power densities of the technologies are known. It is important to recognize that the energy capacity and the peak power refer to the useable energy capacity and the useable peak power from the energy storage unit for the particular application of interest. By "useable' is meant the "quantity" that can be utilized from the storage unit consistent with other system constraints such as the effect of round-trip efficiency on peak power, depth of discharge on energy capacity and cycle life, and maximum charge voltage on energy capacity, cycle life and safety. These further considerations in most cases result in storage unit performance that is significantly less than one would infer from the name-plate ratings given by the manufacturer of the batteries or ultracapacitors.

A second difficulty in quantifying the peak power and energy requirements are that the useable power and energy requirements can be highly dependent on the control strategy linking operation of the engine and electric drive system. In the case of a charge sustaining hybrid, the useable energy required can vary from 100-300Wh depending on how often and at what power level the engine is used to recharge the energy storage unit (References 1, 2). In the case of the plug-in hybrids, the peak power requirement depends on the blending strategy of the electric motor and engine when the vehicle is operating in the "all-electric" mode (References 3, 4).

Energy and power requirements for selected hybrid vehicle designs and operating strategies are shown in Table 1 for a mid-size passenger car. Requirements are given for both charge sustaining and plug-in hybrids. These requirements can be utilized to size the battery and ultracapacitors in the vehicles when the characteristics of the energy storage devices are known. In the case of batteries, the depth-of-discharge and cycle life requirements vary markedly between the charge sustaining and plug-in hybrid designs. In charge sustaining hybrids, the batteries are maintained in a narrow state-of-charge range with the cycles being shallow, high power in both charge and discharge, and very large in number. The batteries in a plug-in hybrid are used much like in an electric vehicle (EV) with the need to fully charge the battery and discharge it to relatively low states-of- charge. In a plug-in hybrid, the energy storage unit must be capable of providing the power required by the electric motor for the useable range of state-of-charge (over the all-electric range of the vehicle) and be capable of operation in the charge sustaining mode for hundreds of thousand of cycles after it has been depleted to its minimum state-of-charge.

Table 1: Energy storage requirements for various types of hybrid-electric vehicles

Type of hybrid driveline	System voltage V	Useable energy storage	Maximum pulse power at 90% efficiency kW	Cycle life (number of cycles)	Useable depth-of-discharge
Plug-in	300-400	6-12 kWh	50-70	2500-3500	deep 60-80%
Charge					Shallow

sustaining	150-200	100-150 Wh	25-35	300K-500K	5-10%
Micro-hybrid	45	30-50 Wh	5-10	300K-500K	Shallow 5-10%

3. Energy storage options

The energy storage unit in a hybrid-electric vehicle can in principle consist of batteries or ultracapacitors or a combination of them. In practice, it is likely that it would consist of one or the other in most cases, but there are vehicle designs in which the combination could make sense. Whether one would consider using a combination depends primarily on the design of the batteries and what trade-offs are needed in the battery design to meet the power, energy, and cycle life requirements. For all battery types, it is necessary to reduce energy density and deep discharge cycle life in order to attain very high power capability. Hence there may be instances in the design of plug-in hybrids in which it is reasonable to consider a combination of batteries and ultracapacitors. This is most likely to be the case for plug-in hybrids with relatively short all-electric range (that is less than 10-15 miles). For charge sustaining hybrids, either batteries or ultracapacitors can be utilized, but except in the case of lead-acid batteries in a micro-hybrid, it is not likely that a combination of batteries and ultracapacitors would make sense.

There has been and continues to be many programs to develop batteries for hybrid-electric vehicles. Many of the past efforts have focused on lead-acid and nickel metal hydride with the present and future efforts focusing on lithium-ion. Some R&D is also continuing on lead-acid for the special micro-hybrid application. The development of ultracapacitors for vehicle applications started in about 1990 and continues to the present time. Most of the development has been focused on microporous carbon (double-layer) devices, but presently R&D is being done on ultracapacitors using other forms of carbon and metal oxide materials in hybrid devices with characteristics between those of batteries and the double-layer ultracapacitors. The performance characteristics of ultracapacitors and batteries suitable for hybrid vehicles are summarized in the following sections.

4. Ultracapacitor characteristics

The characteristics of ultracapacitors are relatively straightforward to describe as ultracapacitors are basically deep discharge devices whose power capacity for discharge and charge are essentially the same at all states-of-charge (voltages between the rated and minimum values). The energy density varies only slightly with discharge rate up to power density values of about 1000 W/kg. As discussed in References 5-7, ultracapacitors of a number of different types are being developed. A summary of the physical and performance characteristics of various ultracapacitors is given in Table 2. The characteristics vary significantly depending on the materials used in the electrodes, but the useable energy density varies between 4-8 Wh/kg with a useable peak power capability (95% efficiency) of 800-1400 W/kg.

Double-layer carbon/carbon ultracapacitors can have a cycle life of hundreds of thousands of cycles for deep discharges between rated and one-half rated voltage. However, the cycle life is dependent on the maximum cell voltage used in the tests with the cycle life decreasing significantly for maximum voltages greater than 2.5V/cell (Reference 8).

Table 2: Performance characteristics of various ultracapacitors

Device	V rated	C (F)	R (mOhm)	RC (sec)	Wh/kg (1)	W/kg (95%) (2)	W/kg Match. Imped.	Wgt. (kg)	density gm/cm3
Maxwell**	2.7	2800	.48	1.4	4.45	900	8000	.475	1.48
ApowerCap	2.7	55	4	.22	5.5	5695	50625	.009	---
Ness	2.7	1800	.55	1.00	3.6	975	8674	.38	1.37
Ness	2.7	3640	.30	1.10	4.2	928	8010	.65	1.26
Ness	2.7	5085	.24	1.22	4.3	958	8532	.89	1.25
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	.210 (estimated)	1.39
Panasonic (propylene carbonate)	2.5	1200	1.0	1.2	2.3	514	4596	.34	1.39
EPCOS	2.7	3400	.45	1.5	4.3	760	6750	.60	1.25
LS Cable	2.8	3200	.25	.80	3.7	1400	12400	.63	1.34
BatScap	2.7	2600	.3	.78	3.95	1366	12150	.50	---
Power Sys. (activated carbon, propylene carbonate)	2.7	1350	1.5	2.0	4.9	650	5785	.21	1.4
Power Sys. (graphitic carbon, propylene carbonate)	3.3	1800	3.0	5.4	8.0	825	4320	.21	1.4
Fuji Heavy Industry-hybrid (AC/C)	3.8	1800	1.5	2.6	9.2	1025	10375	.232	1.62

(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

5. Battery characteristics

There are a number of ways to express battery performance. The simplest approach is to state the energy density (Wh/kg) and peak power density (W/kg) as is done in Table 3. This approach is good for showing the relative performance of various types of batteries, but does not show the detailed performance of a particular battery, which requires knowledge of the Ragone curve (Wh/kg vs. W/kg for constant power discharges), battery open circuit voltage and resistance vs. state-of-charge, capacity (Ah) vs. discharge current and temperature, and the charging characteristics of the battery at various rates and temperatures. Those detailed characteristics can be found in the literature (Reference 9). The battery designs denoted as EV are most suitable for plug-in hybrids and those denoted as HEV are suitable for charge sustaining hybrids. To date batteries designed specifically for plug-in hybrids are not available.

The cycle life of the batteries is a key issue. As noted previously, batteries for charge sustaining hybrids must sustain hundreds of thousands of shallow cycles of a few percent state-of-charge. Testing of both nickel metal hydride and lithium-ion batteries indicate that those battery types seem to have satisfactory cycle life for charge sustaining hybrids. However, testing has indicate that standard high power lead-acid batteries have only limited cycle life for shallow discharges and considerable R&D (References 10-11) has been done to improve the cycle life of lead-acid batteries for hybrid vehicle applications. Batteries for use in plug-in hybrids should have a cycle life of at least 2000-3000 relatively deep discharge cycles of at least 50-60%. Limited testing (References 12-13) of both nickel metal hydride and lithium-ion batteries have indicated that the batteries are likely to have the required cycle life, but much additional testing is needed to confirm this and to determine the effect of depth of discharge and the charging algorithms on cycle life for batteries having the power characteristics need for plug-in hybrids of limited all-electric range (less than 20 miles).

With the lithium-ion batteries, there is the additional issue of safety for large arrays of relatively large Ah cells need in vehicle applications. This has lead to a number of lithium-ion battery chemistries currently being developed and the clear trade-offs between energy density and safety apparent between them (see Table 3). This trade-off in energy density is of greater importance of plug-in hybrids than for charge sustaining hybrids. The battery chemistries can also affect the useable state-of-charge range for long cycle life and that must be considered in ranking batteries for plug-in hybrids. Detailed data in this area for the various battery chemistries is not yet available.

6. Comparisons of battery and ultracapacitor solutions

In previous sections of the paper, the energy storage unit requirements for hybrid vehicles have been cited in general terms and the present status of various batteries and ultracapacitor technologies have been summarized. In this section, typical designs of energy storage units will be discussed for both charge sustaining and plug-in hybrid vehicles utilizing the various battery and ultracapacitor technologies. The examples will be for a mid-size passenger car, but similar approaches could be pursued for other vehicle types.

Table 3: Characteristics of various technologies/types of batteries for use in vehicle applications

Battery Technology	Applic. type	Ah	V	Wh/kg At C/3	Resist mOhm	W/kg Match. Imped.	W/kg 95%eff.	Max. Useable SOC,
Lead-acid								
Panasonic	HEV	25	12	26.3	7.8	389	77	28%
Panasonic	EV	60	12	34.2	6.9	250	47	----
Nickel Metal Hydride								
Panasonic EV	EV	65	12	68	8.7	240	46	----
Panasonic EV	HEV	6.5	7.2	46	11.4	1093	207	40%
Ovonic	EV	85	13	68	10	200	40	----
Ovonic	HEV	12	12	45	10	1000	195	30%
Saft	HEV	14	1.2	47	1.1	900	172	30%
Lithium-ion								

Saft	HEV	12	4	77	7.0	1550	256	20%
Saft	EV	41	4	140	8.0	476	90	----
Saft	HEV	6.5	4	63	3.2	3571	645	20%
Shin-Kobe	EV	90	4	105	.93	1344	255	------
Shin-Kobe	HEV	4	4	56	3.4	3920	745	18%
A123	HEV	2.2	3.6	90	12	3857	735	20%
Altairnano	EV	11	2.8	70	2.2	2620	521	60%
GAIA	HEV	40	4.0	96	.48	5446	1034	20%
Altairnano	HEV	2.5	2.8	35	1.6	6125	830	60%
Quallion	EV	2.5	4.0	200	43.4	1960	372	-----
Quallion	HEV	1.2	4.0	100	23.2	4044	768	-----

Consider first charging sustaining hybrid vehicles. In this case, the energy storage unit is sized by both useable power (kW) and energy storage (Wh) requirements. For batteries, the key issues are the power requirement and the minimum useable energy consistent with high cycle life for shallow cycles. The total energy stored in the battery unit is of secondary importance as far as operation of the vehicle is concerned, but it has a strong effect on the weight, volume, and cost of the unit. For 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 if the unit is large enough to met the energy requirement. A previous study (Reference 14) of hybrid vehicles using combinations of ultracapacitors and batteries indicated that a combination of batteries and ultracapacitors only makes economic sense for micro-hybrids using a lead-acid battery. In that case, the ultracapacitor would store a small quantity of energy (less than 50 Wh) and be used only to assist in accelerating the vehicle and recovering a small amount of energy during braking.

Energy storage units for charge sustaining hybrid powertrains for mid-size passenger cars are shown in Table 4. For each application, the useable power and energy, total energy stored, and incremental state-of-charge for the unit and its weight and volume are shown in the table. The results shown in Table 4 indicate that for charge sustaining hybrids, either batteries or ultracapacitors can be used alone. All the units listed should function satisfactorily for the applications indicated with the decisions concerning their relative attractiveness based to a large extent on cost, which at the present time is uncertain for all the systems. The results in Table 4 also indicate that a combination of lead-acid batteries and ultracapacitors would result in a relatively low weight unit for a micro-hybrid having a maximum electric motor power of 5-10 kW. The economics of such a combination should be attractive because of the low cost of the lead-acid batteries.

Table 4: Characteristics of various technologies/types of batteries for use in vehicle applications

Charge sustaining hybrids

Technology	C or Ah	System voltage	SOC %	Total energy Wh *	Max. Power kW **	Pulse efficiency %	Weight of cells kg	Volume of cells L
ultracapacitors								
Carbon/carbon	2400	160	75	100	>40	90	22	15

microporousC/ graphitic C	2400	160	75	150	27	90	18	13
Lithium-ion batteries								
Graphite/ Ni Co Al	9	160	6.6	1500	31	91	24	11
Iron phosphate 2.2 Ah cells	11	160	5.5	2000	27	91	23	11
Lithium titanate 11 Ah	11	160	5.5	1800	27	90	26	14
Lithium titanate 2.5 Ah	4	160	16.6	600	27	90	16	9
Nickel metal hydride (Prius)	10	160	6.25	1600	14 25	90 80	35	19

Micro-hybrids

Lead-acid	50	45	5	1800	5	90	53	19
Lead-acid/ ultracapacitors	28 4000	45	10 75	1000 50	15	95	29 10 39 total	10 8 18 total
Nickel metal hydride (Prius)	24	45	10	1100	10	90	24	13

* The minimum useable energy storage for the charge sustaining hybrid is 100 Wh. The useable energy storage requirement for the micro-hybrid is 50 Wh.

** The minimum power required by the charge sustaining hybrid is 27 kW at an efficiency of at least 90%. The minimum power for the micro-hybrid is 5 kW with 10 kW being desirable at least 90% efficiency.

Next consider energy storage units for plug-in hybrid vehicles (PHEV). A key design parameter for PHEVs is the all-electric range. In the present study, storage units will be considered for all-electric ranges of 10, 15, 20, 30, and 40 miles. The acceleration performance of all the vehicles will be the same (0-60 mph in 8-9 seconds). For the batteries, the useable depth of discharge will be taken to be 70%. For the ultracapacitors, it is assumed that they can be cycled from rated to one-half rated voltage using 75% of the total stored energy. In the PHEV, the battery will initially be sized by the energy needed to sustain a specified all-electric range. Hence the weight and volume of the battery pack follow directly from its energy density (Wh/kg, Wh/l). This means that battery technologies with high energy density will be strongly favored for PHEV applications. However, the batteries must also be able to meet the power requirements of the PHEV powertrain which can approach those of the battery powered EV. Unfortunately battery designs to attain the maximum energy density in most cases require a sacrifice in power capability as shown in Table 3. Calculated power density requirements for PHEVs of various ranges and maximum power are given in Table 5 for batteries having energy densities of 70, 100, and 200 Wh/kg. The values shown are for a mid-size passenger car having an energy useage of 250 Wh/mi in the all-electric mode and maximum electric motor power of 50 and 70 kW.

Table 5: Battery sizing and power density for various ranges and motor power

			Battery 200 Wh/kg			Battery 100 Wh/kg			Battery 70Wh/kg		
Range miles	kWh *needed	kWh** stored	** kg	50 kW kW/kg	70kW kW/kg	kg	50kW kW/kg	70kW kW/kg	kg	50kW kW/kg	70kW kW/kg
10	2.52	3.6	18	2.78	3.89	36	1.39	1.94	51	.98	1.37

15	3.78	5.4	27	1.85	2.59	54	.92	1.30	77	.65	.91
20	5.04	7.2	36	1.39	1.94	72	.69	.97	103	.49	.68
30	7.56	10.8	54	.93	1.30	108	.46	.65	154	.32	.46
40	10.1	14.4	72	.69	.97	144	.35	.49	206	.24	.34

* Vehicle energy useage from the battery: 250 Wh/mi

** Useable state-of-charge for batteries: 70%, weights shown are for cells only

The required power densities for all-electric ranges of 20 miles and less are high especially for high energy density batteries. When the power density required exceeds that of the battery, it is of interest to consider using an ultracapacitor to augment the power of the battery. The useable pulse power from a battery depends on the efficiency that is acceptable for a particular application. The power/efficiency relationship for a battery can be written as

$$P = Eff\,(1-Eff)V_0^{\,2} / R$$

where V0 is the open-circuit voltage of the battery and R is its resistance (Ohm). The power densities for efficiencies of 95% and 80% for the various battery technologies shown in Table 3 are given in Table 6. If it is assumed that 80% efficiency is satisfactory for use of the battery in the charge depleting mode of the PHEV, it can be concluded from Tables 3 and 6 that ultracapacitors would be needed by the 200 Wh/kg lithium-ion and the 70 Wh/kg nickel metal hydride batteries. This result is shown in Table 7. The energy storage unit weights for the PHEVs of various all-electric ranges and battery energy density are given in Table 8. The combination of ultracapacitors and 200 Wh/kg lithium-ion batteries have the lowest weight for all the ranges. This arrangement would also yield the highest efficiency during the charge sustaining mode of vehicle operation. As noted above, ultracapacitors should be used with 70 Wh/kg nickel metal hydride batteries for PHEV applications due to their limited power capability. Even using ultracapacitors, it appears the all-electric range with nickel metal hydride batteries is limited to about 15 miles as otherwise the weight of the energy storage unit would exceed 100 kg.

Table 6: Battery and ultracapacitor pulse power characteristics for 80% and 95% efficiencies

Battery technology	95% efficiency kW/kg	80% efficiency kW/kg
GAIA	1.03	3.47
Quallion 200	.37	1.25
Quallion 100	.768	2.58
A123	.74	2.47
Altairnano	.52	1.75
Panasonic EV nickel mt. hyd	.05	.16
Ultracaps		
LS Cable Batscap	1.4	2.8
Maxwell Nesscap	.95	1.9
APowercap	3.0	6.0
Fuji	1.0	2.0

Battery power: $P= Eff.\,(1-Eff)\,V_0^{\,2} / R$

Ultracapacitor power: $P= 9/16\,(1-Eff)\,V_0^{\,2} /R$

Table 7: Battery/ultracapacitor combinations for various all-electric ranges

Wh/kg	100	200	100	90	70	70
						Panasonic

Range miles	GAIA	Quallion 200	Quallion 100	A123	Altairnano	Nickel mt.hyd.
10	N/N *	Y/Y	N/N	N/N	N/N	Y/Y
15	N/N	Y/Y	N/N	N/N	N/N	Y/Y
20	N/N	Y/Y	N/N	N/N	N/N	Y/Y
30	N/N	Y/Y	N/N	N/N	N/N	Y/Y
40	N/N	N/N	N/N	N/N	N/N	Y/Y

* X/X means need at 50kW/need at 70kW yes Y or no N

Table 8: Storage unit weights using a combination of batteries and ultracapacitors for various all-electric ranges

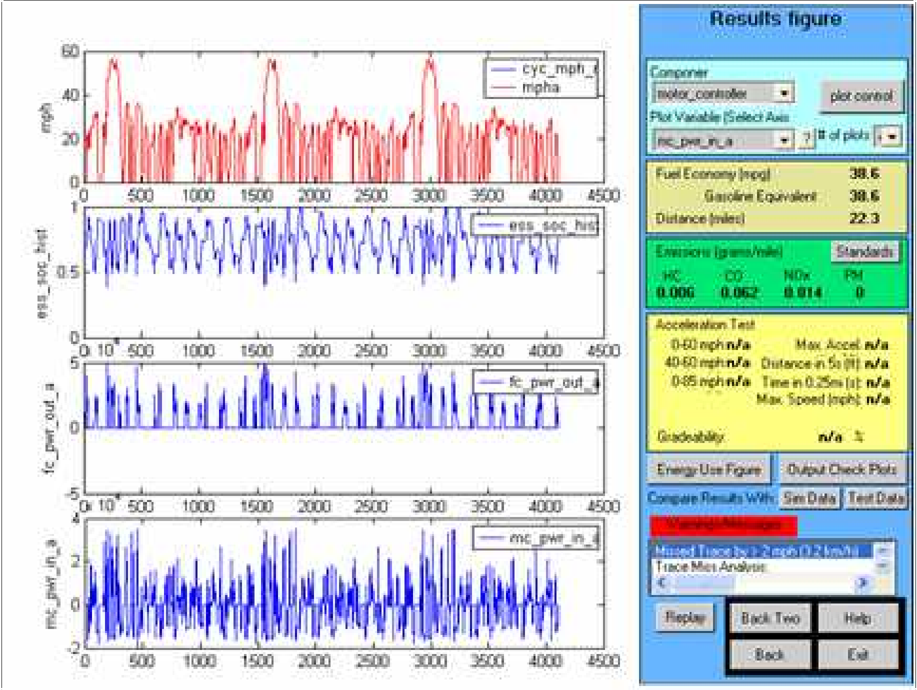
Wh/kg	5	200		100		70	
Range miles	Ultracap kg *	Battery Kg**	Combin-ation kg	Battery kg	Combin-ation kg	Battery kg	Combin-ation kg
10	20	18	38	36	56	51	71
15	20	27	47	54	74	77	97
20	20	36	56	72	92	103	123
30	20	54	74	108	128	154	174
40	20	72	92	144	164	206	226

* The ultracapacitor unit stores 100 Wh useable energy

** Weights shown are for cells only, packaging into modules not included

7. Hybrid vehicle simulation results

In the previous section, various energy storage options for hybrid vehicles were discussed in detail and how the options compare in terms of weight, size, efficiency, and power capability. In this section, simulation results are presented for micro-hybrid, moderate/full charge sustaining hybrid, and plug-in hybrid vehicles using the various energy storage technologies. All the simulations were performed using the Advisor program as the simulation tool. The block diagrams and control strategy files for Advisor have been modified by students at UC Davis and the battery and ultracapacitor files are based on data taken at UC Davis. The control strategies utilized in the simulations are intended to maximize the engine operating efficiency by restricting the operation of the vehicle in two modes to the maximum extent possible. One mode is an all-electric mode with the engine off and receiving no fuel and a second mode in which the engine is both powering the vehicle and recharging the batteries or ultracapacitors. Even in the charging sustaining hybrid designs, the electric driveline is sized to provide all-electric operation a significant fraction of the time when the energy storage unit is sufficiently charged. This type of control strategy has been called a “sawtooth” strategy as the state-of-charge of the battery or ultracapacitor resembles the blade of a saw (see figure 1). A number of papers and presentations describing this approach to hybrid vehicle design and control can be found in References 15-17. In this paper, a summary of past results will be presented along with some new results for plug-in hybrid vehicles.



Fuel Economy (mpg) 38.6
Gasoline Equivalent 38.6
Distance (miles) 22.3

Emissions (grams/mile)

HC	CO	NOx	PM
0.006	0.062	0.014	0

Acceleration Test
0-60 mph n/a
40-60 mph n/a
0-85 mph n/a
Max. Accel. n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability n/a %

Figure 1: Characteristics of the “sawtooth’ strategy outputs on the FUDS cycle

The distinction between micro, mild/moderate, and full hybrid designs is concerned primarily with the maximum (peak) power of the electric driveline. The maximum power varies between 5-10 kW for micro-hybrids to 50-60 kW in full hybrids in mid-size passenger cars. Mild/moderate hybrids utilize 20-30 kW electric motors. The engine is not significantly down-sized for micro- and mild/moderate hybrids, but it can be significantly down-sized for full hybrids and plug-in hybrids. The sizing of the energy storage units for the various hybrid designs has been discussed in the previous sections.

In most cases for charge sustaining (CS) hybrids, the energy storage unit is designed to provide the power for the electric motor with high efficiency (at least 90%) and store sufficient energy that it can operate within a specified range of state-of-charge for most expected driving patterns (driving cycles). For CS hybrid powertrain designs, like the Prius, having a generator in addition to the electric motor, the energy storage unit provides only part of the peak power of the motor. For plug-in hybrids, the energy storage unit must provide both the power for all-electric operation and the energy required to meet the all-electric range of the vehicle.

A summary of simulation results for charge sustaining hybrids is given in Table 9 for a range of maximum electric driveline power. The fuel economy improvement increases with electric driveline power for the same engine and energy storage unit. Increasing the size of the energy storage unit has only a small effect on fuel economy once it is large enough to provide the required power at high efficiency. Increasing the power of the electric driveline (motor and energy storage) improves both the performance and fuel economy of the vehicle, but at significantly increased cost. Hence in CS hybrid, it is possible to uncouple performance and fuel economy, but not fuel economy and cost. Some cost relief can be achieved by down-sizing the engine at the expense of vehicle performance. The most appropriate trade-offs between performance, fuel economy, and cost will be determined in the marketplace by future sales of hybrids. The results in Table 9 indicate that there are good prospects for fuel economy improvements (20-25%) on the FUDS cycle with micro-hybrids using lead-acid batteries and ultracapacitors if the sawtooth control strategy were used to the maximum extent possible with the relatively low power electric motor. For moderate/full hybrids, fuel economy improvements of 50-60% on the FUDS cycle are projected for mid-size passenger cars using either batteries or ultracapacitors. Fuel economy improvements on the Highway cycle are smaller, but still about 25%.

Simulation results for plug-in hybrid vehicles are given in Table 10. The results are for a Prius converted to be a plug-in hybrid using lithium-ion batteries. Fuel economy projections are shown for all-electric ranges of 10-40 miles. The driveline configuration and component sizes used in the simulations are those for the 2004 Prius except for the possible incorporation of a higher power DC/DC unit between the battery and the DC buss. The control strategy has been modified to be appropriate for a plug-in hybrid in which the all-electric operation is maximized and high engine efficiency is maintained during the charge depletion mode. When the battery is depleted to the minimum specified state-of-charge (SOC=.2), the vehicle reverts to the control strategy used in the standard UC Davis Prius simulation. The simulation results indicate that the large potential for fuel savings with a plug-in version of the Prius using lithium-ion batteries.

Table 9: Advisor simulation results for various hybrid vehicles using the Sawtooth control strategy

Driveline type (1)	Energy storage type	Voltage weight	EM peak kW	FUDS Mpg	Average Engine efficiency	Highway mpg	Average Engine efficiency
ICE baseline				24.8	.19	33.8	.23
Micro-HEV	Lead-acid/caps	50 10 (caps)	5	29.7	.23	43.0	.28
			10	33.7	.26	43.0	.28
Moderate/ full CS	A123 Li-ion	220 23	27	39.2	.32	44.2	.33
		220 23	45	39.9	.33	44.8	.33
		220 35	45	42.3	.33	47.4	.33
	C/C caps	220 20	27	38.3	.33	43.3	.33
		220 20	45	39.8	.33	43.9	.33

(1) All vehicles used a 120 kW engine scaled from the Ford Focus 4 cyl. from PSAT; vehicle test weight 1660 kg, Cd= .3, Af=2.25 m2, rolling resistance .009

The fuel economy vs. distance results for the FUDS and Highway cycles are for a PHEV Prius with an all-electric range (blended operation) of 20-30 miles depending on the type of driving. The battery weighs 70 kg and stores about 6 kWh of which 5 kWh is useable (minimum state-of-charge is .2). For all-electric operation, the fuel economy is very high and minimum gasoline would be used. The result would be that on days on which the vehicle traveled less than 30 miles, a large fraction of the gasoline would be saved even compared to the standard HEV Prius.

Table 10: PHEV Prius characteristics using lithium-ion batteries

All-electric operation-charge depleting mode

Vehicle configuration	Battery type Weight kg	FUDS mpg	FUDS Range miles	Highway mpg	Highway Range miles
Baseline Prius	Nickel metal hydride 31 kg	64	-----------	68	----------

PHEV Prius 20 kW max. battery	A123 Li-ion 35 kg 2.5 kWh useable	559	14.3 (1) 250 Wh/mi	382	10.3 (1) 208 Wh/mi
	A123 Li-ion 70 kg 5.0 kWh useable	515	28.0	363	20.5
	A123 Li-ion 94 kg 6.7 kWh useable	490	36.7	353	28.5
PHEV Prius 35 kW max. battery	A123 Li-ion 70 kg 5.0 kWh useable	861	22	No fuel used	15.5
	A123 Li-ion 94 kg 6.7 kWh useable	861	22	No fuel used	15.5

Fuel economy vs distance for a PHEV Prius (70 kg A123 Lithium-ion batteries)

FUDS cycle	Distance miles	mpg	Highway cycle	Distance miles	mpg
1	7.4	530	1	10.3	370
2	14.9	515	2	20.5	363
3	22.3	510	3	30.6	140
4	29.6	218	4	41.0	107
5	37.2	128	5	51.3	94
6	44.6	102	6	61.5	86
7	52.0	92	7	71.8	81
8	59.5	84	8	82	78
9	66.9	80	9	92	76
10	74.4	76	10	103.0	74

8. Summary and Conclusions

This paper is concerned with application of batteries and ultracapacitors in various types of hybrid-electric vehicles. The requirements for and the characteristics of the various energy storage options are considered in detail and approaches presented for comparing the different options for charge sustaining and plug-in hybrid vehicle designs. Simulation results are given using batteries and ultracapacitors that indicate that using either technology relatively large improvements (25-60%) in fuel economy can be achieved in charge sustaining hybrids if the control strategy utilized emphasizes engine operation near maximum efficiency. Such a control strategy, which operates the vehicle alternately in all-electric and engine-powered battery/ultracapacitor charging modes, has been termed the “sawtooth” because of the form of the resultant state-of-charge profiles. This control strategy results in significant fuel economy improvements on both the city (FUDS) and highway driving cycles.

The analysis of combinations of batteries and ultracapacitors indicates that for most applications and battery types, it does not appear to be advantageous to combine the two technologies. However, for a charge sustaining micro-hybrid, the combination of a relatively small ultracapacitor pack (40 Wh) with a high energy density, modest power lead-acid battery appears to offer good potential for achieving fuel economy improvements of about 25%. Another possible combination can be a larger ultracapacitor pack (100 Wh) with a high energy density (200 Wh/kg), modest power lithium-ion battery in plug-in hybrids having all-electric ranges of greater than 15 miles. In both applications, it is important that the ultracapacitor have high power capability (W/kg >1000 for 95% efficiency) and a useable energy density of at least 5 Wh/kg.

Simulations results are presented for PHEV conversions of the 2004 Prius using lithium-ion batteries (A123). Using an optimized control strategy during the charge depleting mode of operation, fuel economies (gasoline only) of 350-500 mpg are projected for vehicles with an all-electric range (blended) of 20 miles using a battery storing about
6 kWh (5 kWh useable).

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