INSTITUTE OF TRANSPORTATION STUDIES

Research Report – UCD-ITS-RR-14-19

# Present and Future Applications of Supercapacitors in Electric and Hybrid Vehicles

December 2014

Andrew Burke
Zhengmao Lin
Hengbing Zhao

Institute of Transportation Studies ◦ University of California, Davis
1605 Tilia Street ◦ Davis, California 95616
PHONE (530) 752-6548 ◦ FAX (530) 752-6572
www.its.ucdavis.edu

# Present and Future Applications of Supercapacitors in Electric and Hybrid Vehicles

Andrew Burke, Zhengmao Liu, Hengbing Zhao
Institute of Transportation Studies
University of California – Davis
Davis, CA, USA
afburke@ucdavis.edu

*Abstract*--**This paper is concerned with supercapacitors (electrochemical capacitors) and their applications in electric drive vehicles in place of or in combination with batteries. The electric drive vehicles considered are hybrid vehicles and fuel cell vehicles. The first section of the paper presents recent test data for advanced proto-type devices. The data for the new carbon/carbon device from Skeleton Technologies showed an energy density of 9 Wh/kg and 95% efficient power capability of 1730 W/kg. Both of these characteristics are significantly better than those of commercially available devices. Test data are shown for a hybrid supercapacitor from Yunasko that has an energy density greater than 30 Wh/kg and a 95% efficient power capability of 3120 W/kg. This device has the best performance of any supercapacitor device tested at UC Davis to date.**

**Various vehicle applications of supercapacitors have been reviewed in detail. Simulation results are presented for light duty vehicles using supercapacitors in place of lithium batteries in hybrid and fuel cell vehicles. It was found in all cases that the vehicles using the supercapacitors had the same as or better performance than those using batteries and in general were more efficient. The cost of supercapacitors compared to lithium batteries was discussed briefly. It was shown that when one recognizes that the energy stored in the capacitors is less than 1/10 that in the batteries for hybrid applications, the price of supercapacitors needs to decrease to about .5- 1 cent Farad for capacitors to be cost competitive with high power batteries at $500-700/kWh. In addition, there is a good possibility that the life of the capacitors would be equal to that of the hybrid vehicles.**

***Keywords – Supercapacitor; hybrid electric vehicle; fuel cell vehicle; fuel economy; simulation***

## I. INTRODUCTION

This paper is concerned with supercapacitors (electrochemical capacitors) and their applications in electric drive vehicles in place of or in combination with batteries. The electric drive vehicles considered are hybrid vehicles and fuel cell vehicles. Special attention is given to sizing the supercapacitor unit to minimize volume and cost and the control strategies that take advantage of the high efficiency and charge acceptance of supercapacitors compared to batteries. Present vehicle applications of supercapacitors include their use in braking systems and stop-go hybrids and future applications in charge sustaining and plug-in hybrids.

The most common electrical energy storage device used in vehicles is the battery. Batteries have been the technology of choice for most applications, because they can store large amounts of energy in a relatively small volume and weight and provide suitable levels of power for many applications. Shelf and cycle life have been a problem/ concern with most types of batteries, but people have learned to tolerate this shortcoming due to the lack of an alternative. In recent times, the power requirements in a number of applications have increased markedly and have exceeded the capability of batteries of standard design. This has led to the design of special high power, pulse batteries often with the sacrifice of energy density and cycle life. Supercapacitors have been developed as an alternative to pulse batteries. To be an attractive alternative, capacitors must have much higher power and much longer shelf and cycle life than batteries. By "much" is meant about one order of magnitude higher.

Supercapacitors have much lower energy density than lithium batteries. Their lower energy density and higher cost ($/kWh) are often given by auto driveline designers as the reason why they have not used supercapacitors. However, as discussed in this paper, the energy storage (kWh) requirement using supercapacitors is much smaller than using batteries in high power applications due to the much lower power capability (kW/kg) of the batteries. This can have a large effect on the effective energy density of the energy storage unit.

In the first section of this paper, recent test data for advanced proto-type devices are presented. The next sections are concerned with present and future applications, how supercapacitors units are sized in particular applications, and simulations of vehicles using supercapacitors in their drivelines for energy storage. The final section deals with the cost of supercapacitors and comparisons of their cost with that of lithium batteries.

## II. TEST RESULTS FOR ADVANCED SUPERCAPACITORS

A number of new supercapacitor devices have been tested in the laboratory at the University of California-Davis [1, 2]. These devices include carbon/carbon devices from Estonia (Skeleton Technologies) and Ukraine (Yunasko) and a hybrid device from Ukraine (Yunasko). As indicated in Tables 1, the carbon/carbon device from Skeleton Technology (Figure 1) has high power capability with no sacrifice in energy density. In fact, the Skeleton Technology device has the highest energy density (9 Wh/kg) of any carbon/carbon device tested at UC Davis. This is due to improved carbon (higher specific capacitance) and an increase in the rated voltage from 2.7V to 3.4V resulting from the use of an improved organic electrolyte. The Yunasko 5000F hybrid device (Figure 2) utilizes carbon and a metal oxide in both electrodes. Different metal oxides are used in the two electrodes and the percentages of the metal oxides are relatively small. Test results for the device are given in Table 2. The voltage range of the device is 2.7 - 1.35V. The energy density is 30 Wh/kg for constant power discharges up to 4 kW/kg. The device has a low resistance and consequently a high power capability of 3.1 kW/kg, 6.1 kW/L for 95% efficient pulses.

Table 1: Test data for the Skeleton Technologies 3200F device

Device characteristics: Packaged weight 400 gm; Packaged volume 284cm3

Constant current discharge data

| Current A | Time sec | Capacitance F | Resistance mOhm Steady-state R | RC sec |
|---|---|---|---|---|
| 50 | 107.7 | 3205 | | |
| 100 | 52.7 | 3175 | | |
| 200 | 25.5 | 3178 | .475 | 1.51 |
| 300 | 16.5 | 3173 | .467 | 1.48 |
| 350 | 14 | 3202 | .485 | 1.55 |
| 400 | 12 | 3168 | .468 | 1.48 |

Discharge 3.4V to 1.7V;
Resistance calculated from extrapolation of the voltage to t=0
Capacitance calculated from C= I*t disch/ delta from Vt=0

Constant power discharge data

| Power W | W/kg | Time sec | Wh | Wh/kg | Wh/L |
|---|---|---|---|---|---|
| 106 | 265 | 123.1 | 3.62 | 9.05 | 12.8 |
| 201 | 503 | 64.9 | 3.62 | 9.05 | 12.8 |
| 301 | 753 | 42.4 | 3.55 | 8.88 | 12.5 |
| 400 | 1000 | 31.1 | 3.46 | 8.65 | 12.2 |
| 500 | 1250 | 24.3 | 3.38 | 8.45 | 11.9 |
| 600 | 1500 | 19.8 | 3.3 | 8.25 | 11.6 |

Pulse power at 95% efficiency
$P = 9/16\,(1\text{-}\ eff)\ V_R^2/R_{ss}$, $(W/kg)_{95\%} = 1730$, $(W/L)_{95\%} = 2436$
Matched impedance power
$P = V_R^2 / 4\ R_{ss}$, (W/kg) = 15,400


Figure 1: Photograph of the 3200F Skeleton Technologies device


Figure 2: Photograph of the 5000F Yunasko Hybrid ultracapacitor 5000F device

Table 2: Characteristics of the Yunasko hybrid supercapacitor

<u>Constant current</u>

| | 2.7-2.0V | | | | 2.7-1.35 | | |
|---|---|---|---|---|---|---|---|
| Current A | Time sec | Ah | Resistance short time mOhm | | Time sec | Ah | Capacitance.F |
| 50 | 83.7 | 1.16 | | | 88.9 | 1.25 | 3556 |
| 100 | 36.1 | 1.0 | 1.53 | | 44.9 | 1.25 | 3870 |
| 150 | 25.1 | 1.05 | 1.59 | | 29.5 | 1.23 | 4060 |
| 200 | 7.1 | .39 | | | 21.1 | 1.17 | 3801 |
| 250 | 4.1 | .28 | | | 15.2 | 1.06 | 4130 |

<u>Constant power</u>

| | | 2.7-2.0V | | | | 2.7-1.35 | | |
|---|---|---|---|---|---|---|---|---|
| Power W | W/kg | Time sec | Wh | Wh/kg | | Time sec | Wh | Wh/kg |
| 55 | 743 | 164 | 2.5 | 33.8 | | 172 | 2.63 | 35.5 |
| 155 | 2094 | 58.1 | 2.5 | 33.8 | | 62.8 | 2.7 | 36.5 |
| 252 | 3405 | 23.8 | 1.66 | 22.4 | | 35.4 | 2.42 | 32.7 |
| 303 | 4095 | 16.6 | 1.4 | 18.9 | | 28.3 | 2.38 | 32.2 |
| 350 | 4730 | 11.9 | 1.16 | 15.7 | | 22.4 | 2.18 | 29.5 |
| 400 | 5405 | 8.3 | .92 | 12.4 | | 17.3 | 1.92 | 25.9 |
| 500 | 6756 | 4.3 | .60 | 8.1 | | 10.8 | 1.5 | 20.3 |

Weight 74 g, volume 38 cm3 pouch packaged
Pulse efficiency 95%
$P = .95x.05\ V^2/R = .95x.05x\,(2.7)^2/.0015 = 231$
$(W/kg)_{95\%} = 3120$, $(W/L)_{95\%} = 6078$

Table 3: Summary of supercapacitor device characteristics

| Device | V rate | C (F) | R (mOhm) (3) | RC sec | Wh/kg (1) | W/kg (95%) (2) | W/kg Match. Imped. | Wgt. (kg) | Vol. lit. |
|---|---|---|---|---|---|---|---|---|---|
| Maxwell | 2.7 | 2885 | .375 | 1.1 | 4.2 | 994 | 8836 | .55 | .414 |
| Maxwell | 2.7 | 605 | .90 | .55 | 2.35 | 1139 | 9597 | .20 | .211 |
| Vinatech | 2.7 | 336 | 3.5 | 1.2 | 4.5 | 1085 | 9656 | .054 | .057 |
| Vinatech | 3.0 | 342 | 6.6 | 2.25 | 5.6 | 710 | 6321 | .054 | .057 |
| Ioxus | 2.7 | 3000 | .45 | 1.4 | 4.0 | 828 | 7364 | .55 | .49 |
| Ioxus | 2.7 | 2000 | .54 | 1.1 | 4.0 | 923 | 8210 | .37 | .346 |
| Skeleton Technol. | 3.4 | 3200 | .47 | 1.5 | 9.0 | 1730 | 15400 | .40 | .284 |
| Skeleton Technol. | 3.4 | 850 | .8 | .68 | 6.9 | 2796 | 24879 | .145 | .097 |
| Yunasko* | 2.7 | 510 | .9 | .46 | 5.0 | 2919 | 25962 | .078 | .055 |
| Yunasko* | 2.75 | 480 | .25 | .12 | 4.45 | 10241 | 91115 | .060 | .044 |
| Yunasko* | 2.75 | 1275 | .11 | .13 | 4.55 | 8791 | 78125 | .22 | .15 |
| Yunasko* | 2.7 | 7200 | 1.4 | 10 | 26 | 1230 | 10947 | .119 | .065 |
| Yunasko* | 2.7 | 5200 | 1.5 | 7.8 | 30 | 3395 | 30200 | .068 | .038 |
| Ness | 2.7 | 1800 | .55 | 1.0 | 3.6 | 975 | 8674 | .38 | .277 |
| Ness | 2.7 | 3640 | .30 | 1.1 | 4.2 | 928 | 8010 | .65 | .514 |
| Ness (cyl.) | 2.7 | 3160 | .4 | 1.3 | 4.4 | 982 | 8728 | .522 | .379 |
| 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 |
| JSR Micro (graphitic carbon/ AC) * | 3.8 | 1100<br>2300<br>(plast.c ase) | 1.15<br>.77 | 1.211.6 | 10<br>7.6 | 2450<br>1366 | 21880<br>12200 | ..144<br>.387 | .077<br>.214 |

(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
(3) Steady-state resistance including pore resistance
* All devices except those with * are packaged in metal/plastic containers: those with * are laminated pouched packaged

A summary of the characteristics of the various supercapacitors tested at UC Davis are given in Table 3. Except for the devices from Skeleton Technologies and Yunasko, all the devices listed in the table are commercially available. Most of the commercial carbon/carbon devices have an energy density of 4-5 Wh/kg and a power capability of 1000 W/kg for 95% efficient pulses. The high power capability of the hybrid devices indicates that their increased energy density can be fully exploited in applications such as hybrid vehicles in which the device would be sized by the energy storage requirement.

## III. SIMULATION RESULTS FOR SELECTED APPLICATIONS

Vehicle applications of supercapacitors (electrochemical capacitors) have been discussed in the literature for many years beginning in the late 1980s [3]. These applications have been quite slow in materializing. However, at the present time there are a few of applications that have been commercialized. These include hybrid-electric transit buses in the United States and China [4, 5], electric braking systems in passenger cars [6], and recently in stop-go hybrid vehicles [7, 8]. This latter application is the first one that is potentially a mass market application in the world-wide auto industry. There are several potential future applications that are discussed later in this paper which could be large scale opportunities for supercapacitors. These future applications include plug-in hybrids and hybridized fuel cell vehicles. All these applications will be considered in the next section in which simulations of vehicles utilizing supercapacitors in their electrified drivelines are discussed.

In this section, simulation results are presented for a number of electric and hybrid vehicles that utilize electric motors in their driveline. All of these applications have the need for electric energy storage on-board the vehicle which can be recharged from an engine driven generator and/or regenerative braking and/or from the grid/wall-plug. In all cases, the energy storage unit could be either a battery or supercapacitor. In this section, the use of supercapacitors will be considered and in the next section comparisons will be made with systems using lithium batteries. The supercapacitors will be sized to meet the energy storage requirement (Wh or kWh) of the applications taking into account the capability of supercapacitors to use a large fraction of the energy stored with long cycle life (> 500,000 for most supercapacitor technologies). In addition, the supercapacitors can provide high power for both charge and discharge over their complete range of SOC (at least down to 75% depth of discharge on an energy basis). Batteries, on the other hand, can provide their maximum power only in short pulses (5-10 seconds) and only over a small range of state-of-charge. In order to attain cycle life comparable to supercapacitors, the usable change in the SOC of the battery is usually less than 10%. Further to achieve power capability (W/L) even close to some commercial supercapacitors, but not the high power proto-type supercapacitors, the energy density of the battery will be compromised. Hence comparing supercapacitors and batteries for a particular application is not a simple matter.

The various potential applications are considered separately in the following sections. All the simulations have been run using the **Advisor** vehicle simulation program modified with special routines at UC Davis [9-13].

### *A. Stop-Go Hybrids*

In this application, the engine is turned off and on when the vehicle stops and the accessory loads are met from the electric energy storage. The energy storage is recharged from regenerative braking and from an engine powered alternator or generator. In more advanced systems, the motor/generator can assist the engine during vehicle accelerations in addition to starting the engine at each stop. The electric motor/generator is small being less than 5 kW. In this application, the supercapacator can be used in combination with a lead-acid battery. The main use of the battery is to provide accessory loads when the time period of the stop is longer than can be sustained with the supercapacitor unit (ex. >60sec). This time can be extended by using larger supercapacitor units. This application was studied in [14-16]. These studies indicated that a supercapacitor unit storing 10-25 Wh would be sufficient for the stop-go application without motor assist during accelerations and up to about 50 Wh with motor assist capability. There seems little doubt that the cycle life of the supercapacitors can be that of the vehicle; however, the cycle life of the lead acid battery is still uncertain and is strongly dependent on its design/type, electrolyte, and separator [17, 18].

Simulations have been run for both subcompact and mid-size passenger cars [19, 20]. The results are shown in Tables 4 and 5. The results of the simulations for the subcompact micro-hybrid with power assist shown in Table 4 indicate that fuel economy improvements of up to 35% can be attained for urban driving using small supercapacitor units with electric motors of less than 5kW. The improvements are smaller, but still significant for highway driving. Results for a mid-size car are given in Table 5. The fuel economy improvements using a 4 kW electric motor are smaller than for the sub-compact, but still 26% for city driving and 12% on the highway. The supercapacitor unit using commercially available Maxwell capacitors weighed about 12 kg and stored 50Wh of energy. The simulation results for both the subcompact and mid-size cars indicate that supercapacitors should work well in micro-hybrids and that even with power assist the capacitor unit and electric motor can be of small size. The round-trip efficiency of the capacitor units are greater than 95% for all the cases.

Table 4: Summary of Advisor results for the 2001 Honda Insight

| Vehicle configuration * | mpg FUDS cycle | mpg Highway cycle |
|---|---|---|
| Conventional ICE | 42.7 | 56 |
| | | |
| Insight | | |
| NREL default | 55 | 75.2 |
| Micro-HEV** | | |
| Caps-LA bat, 4 kw EM | 59.7 | 75.9 |
| Caps-LA bat, 1 kw EM | 53.8 | 73 |
| | | |
| Mild-HEV | | |
| NMH bat, 10 kW EM | 77 | 83.6 |
| Ultracaps, 10 kW EM | 77.7 | 83.9 |

*Insight $C_D$=.25, $A_F$=1.9m$^2$, W=1036 kg, CVT, 50 kW 3 cyl. Engine
** Carbon/carbon supercapacitors, 20 Wh, 5 kg (cells)

### *B. Charge Sustaining Mild Hybrids*

Supercapacitors can be used alone in place of batteries in mild charge sustaining hybrid vehicles. As shown in [21, 22], 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 supercapacitor unit. In this mode, the electric machine is used as a generator and the engine operating point is near its maximum efficiency line (torque vs. RPM). The recharging power is limited by the power of the electric machine because most superacapacitors have a pulse power efficiency greater than 95% for W/kg values of 1-2.5 kW/kg (see Table 3). This control strategy is intended to keep the engine from operating in the low efficiency part of the Torque, RPM map. As indicated in Figure 3, the size (kW) of the electric motor can be relatively small even for large passenger cars using V-8 engines.

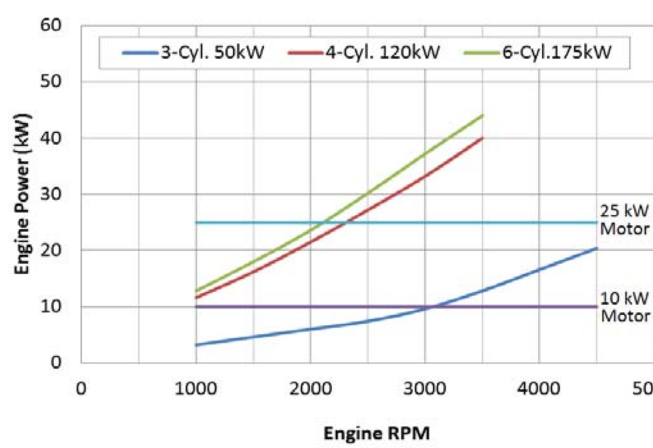


Figure 3: Minimum engine power for efficiency operation for various size engines

Table 5: Mild-HEV and Micro-HEV Advisor simulation results using carbon/carbon and hybrid supercapacitors

Mid-size passenger car: weight 1660 kg, $C_d$ .3, $A_f$ 2.2 m2, fr .009

| Energy storage system | Weight of the ultracaps (kg)* | Energy stored | mpg FUDS | mpg FEDHW | mpg US06 |
|---|---|---|---|---|---|
| Mild HEV 20 kW motor | | | | | |
| Yunasko hybrid | 12<br>6 | 300 Wh<br>150 Wh | 47.4<br>45.3 | 46.5<br>46.0 | 32.2<br>31.6 |
| JM Energy hybrid | 11 | 100 Wh | 47.8 | 47.2 | 31.9 |
| Yunasko C/C | 22 | 100 Wh | 46.0 | 46.4 | 31.6 |
| Maxwell C/C | 28 | 100Wh | 47.2 | 47.5 | 32.2 |
| Skeleton 2014 C/C 3200F | 13 | 115 | 47.8 | 47.0 | 31.9 |
| High power LiTiO battery | 14 | 1120 | 40.6 | 40.3 | 30.5 |
| | | | | | |
| ICE Ford Focus engine 120 kW | | | 25.5 | 36.8 | 26.8 |
| | | | | | |
| Fuel economy improvement | | | 80% | 27% | 19% |
| | | | | | |
| Micro start stop HEV | Supercap. with a lead- acid battery, 4 kW electric motor | | | | |
| Yunasko hybrid | 5 kg<br>3 kg | 150 Wh<br>75 Wh | 32.4<br>32.1 | 41.4<br>41.2 | 28.9<br>28.5 |
| Yunasko C/C | 11 kg | 50Wh | 32.2 | 41.2 | 28.6 |
| Maxwell C/C | 12 kg | 50 Wh | 32.3 | 41.3 | 28.3 |
| Skeleton C/C 3200F | 5 | 50Wh | 33.1 | 40.2 | 28.0 |
| Fuel economy improvement | | | 26% | 12% | 7% |

*weight of cells only without packaging in a pack

Simulations of mid-size passenger cars using supercapacitors in mild charge sustaining hybrid powertrains are given in Table 5 (top part). The simulations were performed using the **Advisor** vehicle simulation program modified with special routines at UC Davis [9-11]. The engine map used in the simulations was for a Ford Focus 2L, 4-cylinder engine. The engine rated power was 125 kW for both the conventional ICE vehicle and the hybrids. Special attention in the simulations was on the use of the advanced ultracapacitors whose characteristics were given in Tables 1-3. All the hybrids use the single-shaft arrangement similar to the Honda Civic hybrid. The same permanent-magnetic AC electric motor map (Honda Civic) was used in all the hybrid vehicle designs. The energy storage capacity of the supercapacitor unit was varied between 100-300Wh depending on the energy density of the cells.

The fuel economy simulation results are given for hybrids using carbon/carbon and advanced ultracapacitors. The influence of the supercap technology and the size (Wh) of the energy storage unit on the fuel economy improvement was of particular interest. The fuel economy improvements range from over 70% on the FUDS to about 20% on the US06 driving cycle, but the effect of supercapacitor size and technology on the improvement was small. The prime advantage of the larger energy storage (Wh) feasible with the higher energy density supercapacitors is that the larger fuel economy improvements can be sustained over a wide range of driving conditions. All the advanced supercapacitors have high power capability and thus can be used with the high power electric motor used in charge sustaining hybrid drivelines. Thus the advanced supercapacitor technologies give the vehicle designer more latitude in powertrain design and in the selection of the control strategies for on/off operation of the engine. Also shown in Table 5 are simulation results for a mild hybrid using a high power lithium titanate oxide (LTO) battery. The fuel economies for the vehicle using the battery are all lower than those using the supercapacitors primarily because the round-trip efficiency with the capacitors was higher than with the batteries. For example, for the FUDS cycle the efficiency was 98% with the capacitors and 91% with the lithium battery.

### *C. Fuel Cell Vehicles*

Simulations were performed for fuel cell vehicles using supercapacitors. The special simulation program for fuel cells that was developed at UC Davis is described in detail in [12, 13]. The application of the program to assess fuel cell operation with battery and supercapacitor energy storage can be found in [23]. A particular question that will be discussed in this paper is how supercapacitors can be best utilized in fuel cell vehicles. The simplest approach is to connect the supercapacitor unit directly to the fuel cell without electronics. A second approach is to place electronics between the supercapacitors and the fuel cell to match the voltage of the supercapacitors and the fuel cell as the power from the fuel cell is controlled according to a prescribed control strategy. Two strategies were employed – (1) the fuel cell was load leveled with the supercaps providing the peak power demands, (2) the fuel cell provided all the power up to a set level and the supercaps assisted when the power demand was higher than the set maximum level. Commercially available carbon/carbon supercapacitors were used in the simulations along with high efficiency DC/DC electronics. The vehicle inputs for the simulations are given in Table 6.

The results of the simulations are shown in Table 7 for the FUDS and USO6 driving cycles. Results are shown for supercapacitors and for a LiTiO power battery. In all cases, the use of energy storage improves the gasoline equivalent fuel economy. The various cases are compared in terms of a fuel economy improvement factor using the fuel cell vehicle without energy storage as the baseline. Fuel economy improvements up to 25% were attained with the most efficient arrangement being the supercapacitor unit connected directly to the fuel cell without electronics. This arrangement yielded an improvement of 25% on the FUDS cycle and 18% on the US06 cycle. Most of this improvement in fuel economy is due to energy recovery from regenerative braking which becomes possible with any of the energy storage units. The most efficient of the fuel cell power control approaches was the power assist strategy with the supercapacitors, but using the power assist strategy and electronics, the fuel economies with the supercapacitors were only about 1% better than with the batteries; however, the direct connection case of the supercapacitors was 5-8% better than the battery case with electronics. The comparisons between using supercapacitors or batteries with fuel cells are dependent on the characteristics of the batteries and supercapacitors available and the efficiency of the DC/DC electronics. Hence it is reasonable to conclude that either supercapacitors or high power batteries can be used with fuel cells and the effect on fuel economy would be not significantly different.

Table 6: Vehicle simulation parameters

| Vehicle and System Parameters | |
|---|---|
| Drag Coefficient | 0.3 |
| Frontal Area (m2) | 2.2 |
| Rolling Resistance | 0.01 |
| Vehicle Hotel Load (kW) | 0.3 |
| Vehicle Mass without energy storage (kg) * | 1500 |
| Electric Motor (kW) | 75 |
| **Fuel Cell Stack and Auxiliaries** | |
| Max. Net Power (kW) | 87.6 |
| Gross Power (kW) | 106 |
| Number of Cells | 440 |
| Cell Area (cm2) | 510 |
| Compressor (kW) | 17.2 |
| **Energy Storage units** | |
| Supercapacitor capacity (Wh) | 100 |
| Supercapacitor pack voltage | 432 |
| LiTiO battery Capacity (kWh) | 1.5 |
| LiTiO battery voltage | 405 |

Table 7: Comparisons of the fuel economies of fuel cell vehicles using supercapacitors and batteries with and without electronics

| Vehicle Topology | Drive Cycle | Fuel Economy / Improvement Factor | |
|---|---|---|---|
| | | Power Assist | Load Leveling |
| FC-Battery Hybrid with 1500 Wh Battery and Power Electronics | FUDS | 78.6 / 1.16 | 72.8 / 1.07 |
| | US06 | 56.6 / 1.12 | 51.9 / 1.02 |
| FC-UC Hybrid with 100 Wh UC and Power Electronics | FUDS | 79.2 / 1.16 | 78.8 / 1.16 |
| | US06 | 57.3 / 1.13 | 55.0 / 1.08 |
| FC-UC Hybrid with 100 Wh UC and without Power Electronics | FUDS | 85.0 / 1.25 | |
| | US06 | 59.6 / 1.18 | |
| FCV without Energy Storage | FUDS | 68.0 / ---- | |
| | US06 | 50.7 / ---- | |

## IV. LITHIUM BATTERIES vs. SUPERCAPACITORS AS HIHG POWER ENERGY STORGE

In most electrified vehicle applications, the powertrain designer has the choice between lithium batteries and supercapacitors for high power energy storage. At the present time (2014), the designers in most cases select lithium batteries because of their higher energy density and lower cost. As a result of this choice the designers have to over-size the battery to attain the required power and cycle life and also have to tolerate reduced efficiency of the vehicle compared to what it would have been using supercapacitors. In this section of the paper, these design compromises will be considered in detail.

The examples selected for discussion are the group of light-duty vehicles shown in Table 8 powered by mild hybrid and fuel cell drivelines. The energy storage unit in each vehicle could be either a lithium battery or a carbon/carbon supercapacitor. Note in Table 8 that the energy stored in the supercapacitor is in most cases less than 10% of the energy stored in the battery. Nevertheless, both the battery and the supercapacitors must provide the power required by the electric motor. This is not a problem for the mild hybrid vehicles in which the electric motors are relatively low power, but it is not reasonable to expect the battery alone to meet the maximum power required by the large motors in the fuel cell vehicles. As noted in Table 8, it has been assumed that the fuel cell will provide half the electric power to the motors in those vehicles when maximum power is demanded. This approach seemed better than doubling the size (kWh) of the batteries to meet the maximum power requirement. Also shown in Table 8 is the power density and corresponding efficiency at peak power for the battery and supercapacitor. In all cases the efficiency of the supercapacitor is higher than that of the battery which will be reflected in the energy efficiency of the vehicle.

Simulations were performed for the vehicles listed in Table 8. The battery used in the simulations was scaled from the 4 Ah lithium titanate oxide (LTO) cell developed by Altairnano [24]. This cell, which was designed to have high power capability, has an energy density of 35 Wh/kg and 95% efficient power density of 1305 W/kg. This power capability is comparable to that of commercially available carbon/carbon supercapacitors. The supercapacitor used in the simulations was a proto-type cell from Yunasko [25]. This cell had an energy density of 4.5 Wh/kg and a 95% efficient pulse power capability of about 8000 W/kg. As indicated in Table 9, the fuel economies calculated for the various vehicles with the supercapacitor energy storage were only 3-5% higher than with the high power LTO battery technology. The efficiency of both energy storage units was high (95-98%) for all the runs on the FUDS and HW cycles. The high efficiency on the driving cycles resulted because the occasional peak power on the cycles was only about one-half the peak power capability of the electric motors.

Further mild hybrid simulations showed that using the commercially available Maxwell supercapacitors which have a 95%efficient power capability of 1000 W/kg reduced the FUDS fuel economy by only 5%, but utilizing high energy density lithium batteries with 95% efficient power capability of 600-700 W/kg reduced the fuel economy by 20-25%. The efficiency of those batteries on the FUDS cycle was only 76% rather than 96% for the LTO battery technology. Hence to compete with supercapacitors in hybrid vehicles, special high power lithium batteries are needed and those batteries will be more expensive than the high energy density lithium batteries and be larger because of their lower energy density.

Table 8: Efficiencies of lithium batteries and carbon/carbon supercapacitors at peak power demand conditions

Mild hybrid vehicles

| Vehicle type | Eng. Pow kW | Electric motor kW | Battery kWh | battery kW/kg (1) | Battery efficiency | Supercap Wh | Supercap kW/kg (2) | Super cap efficiency |
|---|---|---|---|---|---|---|---|---|
| Compact | 97 | 15 | 1.0 | 1.4 | 94 | 75 | .9 | 97.5 |
| Mid-size | 125 | 25 | 1.5 | 1.5 | 93.5 | 100 | 1.1 | 97 |
| Full-size | 160 | 50 | 2.0 | 2.3 | 90 | 100 | 2.3 | 96 |
| Small SUV | 140 | 25 | 1.5 | 1.5 | 93.5 | 100 | 1.1 | 97 |
| Mid-size SUV | 150 | 40 | 2.0 | 1.8 | 92 | 150 | 1.2 | 97 |
| Delivery truck | 200 | 50 | 3.0 | 1.5 | 93.5 | 200 | 1.1 | 97 |

Fuel cell vehicles

| Vehicle type | Fuel cell kW | Electric motor kW | Battery kWh | Battery kW/kg (1), (3) | Battery efficiency (3) | Supercap Wh (4) | Supercap kW/kg (2) | Super cap efficiency |
|---|---|---|---|---|---|---|---|---|
| Compact | 60 | 95 | 1.0 | 8.6 | 78.5 | 75 | 5.7 | 90 |
| Mid-size | 75 | 110 | 1.5 | 6.6 | 84 | 100 | 5.0 | 91.5 |
| Full-size | 100 | 140 | 2.5 | 5.0 | 89 | 100 | 6.3 | 88.5 |
| Small SUV | 85 | 120 | 1.5 | 7.2 | 82.5 | 100 | 5.4 | 91 |
| Mid-size SUV | 100 | 125 | 2.0 | 5.6 | 86 | 150 | 3.8 | 93.5 |
| Delivery truck | 125 | 200 | 4.0 | 4.5 | 90 | 200 | 4.5 | 92 |

(1) Energy density of the battery is 90 Wh/kg based on the weight of cells, $(W/kg)_{95\%} = 1200$

(2) Energy density of supercap is 4.5 Wh/kg based on cell weight, $(W/kg)_{95\%} = 3000$

(3) fuel cell provides 50% of peak power

Table 9: Comparisons of the fuel economy of mild hybrid and fuel cell vehicles using supercapacitors and high power lithium batteries

Mild hybrid vehicles

| Vehicle type | Eng. Pow kW | Electric motor kW | Supercap. mpg (1) | Batteries mpg (2) |
|---|---|---|---|---|
| Compact | 97 | 15 | 47.4/49.8 | 45/47.7 |
| Mid-size | 125 | 25 | 41.1/44.2 | 40.3/43.1 |
| Full-size | 160 | 50 | 38.1/43.5 | 38.5/42.0 |
| Small SUV | 140 | 25 | 39.1/43.0 | 37.8/42.1 |
| Mid-size SUV | 150 | 40 | 36.2/39.5 | 34.3/38.4 |
| Delivery truck | 200 | 50 | 12.2/10.7 | 11.8/10.7 |

Fuel cell vehicles

| Vehicle type | Fuel cell kW | Electric motor kW | Battery kWh | Supercap. mpg gasol. Equiv (3) | Batteries mpg gasol. Equiv (3) |
|---|---|---|---|---|---|
| Compact | 60 | 95 | 1.0 | 83.8/79 | 80.3/78.1 |
| Mid-size | 75 | 110 | 1.5 | 78.4/71.9 | 73.5/70.6 |
| Full-size | 100 | 140 | 2.5 | 67.4/64.2 | 64.5/63.5 |
| Small SUV | 85 | 120 | 1.5 | 72.7/70.4 | 70.9/71.4 |
| Mid-size SUV | 100 | 125 | 2.0 | 65/61.6 | 61.5/61.2 |
| Delivery truck | 125 | 200 | 4.0 | 19.6/15.7 | 18.8/16.1 |

(1) Carbon/carbon supercapacitor 1200 F from Yunasko
(2) LiTiO battery from Altairnano 3.8 Ah
(3) mpg FUDS cycle/ mpg Highway cycle

## V. COST CONSIDERATIONS

Supercapacitors can not compete with batteries in terms of \$/Wh, but they can compete in terms of \$/kW and \$/unit to satisfy a particular vehicle application. Both energy storage technologies must provide the same power and cycle life and sufficient energy (Wh) for the application. The weight of the battery is usually set by the system power requirement and cycle life and not the minimum energy storage requirement. Satisfying only the minimum energy storage requirement would result in a much smaller, lighter battery than is needed to meet the other requirements. On the other hand, the weight of the supercapacitor is determined by the minimum energy storage requirement. The power and cycle life requirements are usually easily satisfied. Hence the unit can be a more optimum solution for many applications and its weight can be less than that of the battery even though its energy density is less than one-tenth that of the battery.

Consider the example of a charge sustaining hybrid like the Prius. If the energy stored in the capacitor unit is 125 Wh and that in the battery unit is 1500 Wh, the unit costs [1] of the capacitors and battery are related by

$$(\$/Wh)_{cap} = .012\ (\$/kWh)_{bat}$$

The corresponding capacitor costs in terms of cents/Farad and \$/kWh are given by

$$(cents/F)_{cap} = .125 * 10^{-3} * (\$/kWh)_{bat} * V_{cap}^{2}$$

$$(\$/kWh)_{cap} = 9.6 * 10^{4}\ (cents/F)_{cap} / V_r^{2}$$

The evaluation of the above equations for a range of battery costs is shown in Table 10.

Table 10: Relationships between supercapacitor and battery unit costs resulting in the same energy storage pack cost

| Battery cost \$/kWh | Battery cost* \$/kW | Ultracap cost cents/F $V_{cap}=2.6$ | Ultracap cost cents/F $V_{cap}=3.0$ | Ultracap cost** \$/kWh $V_{cap}=3.0$ | Ultracap cost \$/kW $V_{cap}=3.0$ |
|---|---|---|---|---|---|
| 300 | 30 | .25 | .34 | 3626 | 7.3 |
| 400 | 40 | .34 | .45 | 4800 | 9.6 |
| 500 | 50 | .42 | .56 | 5973 | 11.9 |
| 700 | 70 | .59 | .78 | 8320 | 16.6 |
| 900 | 90 | .76 | 1.0 | 10667 | 21.3 |
| 1000 | 100 | .84 | 1.12 | 11947 | 23.9 |

* battery 100 Wh/kg, 1000 W/kg; ** capacitor 5 Wh/kg, 2500 W/kg

The results shown in Table 10 indicate that for the charge sustaining hybrid application, supercapacitor costs of .5-1.0 cents/Farad wii be competitive with lithium battery costs in the range of \$500-700/kWh. Note also that the \$/kW costs of the capacitor unit are about one-fourth those of the batteries. The present price of supercapacitors is in the range of 1-2 cents/F, but with high volume production and increases in energy density, the price of capacitors will continue to decrease. In addition, high power batteries, being more expensive than high energy density lithium batteries, are likely priced at $1000/kWh or higher. Hence in the near future, it is likely that supercapacitor energy storage units for hybrid vehicle applications can be cost competitive with lithium battery units.

## VI. SUMMARY AND CONCLUSIONS

This paper is concerned with supercapacitors (electrochemical capacitors) and their applications in electric drive vehicles in place of or in combination with batteries. The electric drive vehicles considered are hybrid vehicles and fuel cell vehicles. In the first section of this paper, recent test data for advanced proto-type devices are presented. The data for the new carbon/carbon device from Skeleton Technologies showed an energy density of 9 Wh/kg and 95% efficient power capability of 1730 W/kg. Both of these characteristics are significantly better than those of commercially available devices. Test data are also shown for a hybrid supercapacitor from Yunasko that has an energy density greater than 30 Wh/kg and a 95% efficient power capability of 3120 W/kg. This device has the best performance of any supercapacitor device tested at UC Davis to date.

Various vehicle applications of supercapacitors have been reviewed in detail. Simulation results are presented for light duty hybrid and fuel cell vehicles using supercapacitors in place of lithium batteries. It was found in all cases that the vehicles using the supercapacitors had the same as or better performance than those using batteries and in general were more efficient. Simulations were made using carbon/carbon and advanced hybrid supercapacitors. Sufficient energy could be stored in the carbon/carbon devices for all the vehicles to perform well with high efficiency on appropriate driving cycles indicating that for hybrid vehicles supercapacitors can be used in place of the lithium batteries currently being used. The higher energy density of the new hybrid devices permits more energy to be stored, but the effect of the larger energy storage on vehicle performance and efficiency is small. It is expected that the increased energy density will reduce the unit cost ($/Wh) of the devices and in addition, make vehicle designers more comfortable using supercapacitors than in the past. The simulation results for the fuel cell vehicles indicated that the use of supercapacitors would permit the use of energy storage units storing much less energy and having higher efficiency than using lithium batteries.

The cost of supercapacitors compared to lithium batteries was discussed briefly. It was shown that when one recognizes that the energy stored in the capacitors is less than 1/10 that in the batteries for hybrid applications, the price of supercapacitors needs to decrease to about .5- 1 cent/Farad for capacitors to be cost competitive with high power batteries at $500-700/kWh. In addition, there is a good possibility that the life of the capacitors would be equal to that of the hybrid vehicles.

## REFERENCES


[1] Burke, A.F. and Miller, M., Performance Characteristics of Lithium-ion Batteries of Various Chemistries for Plug-in Hybrid Vehicles, EVS-24, Stavanger, Norway, May 2009.

[2] Burke, A.F. and Miller, M., The power capability of ultracapacitors and lithium batteries for electric and hybrid vehicle applications, Journal of the Power Sources (on the web), 2010.

[3] Miller, J., A brief history of supercapacitors, Batteries & Energy Storage Technology, Autumn 2007, pp. 61-78.

[4] Maher, B., Ultracapacitors Provide Cost and Energy Savings for Public Transportation Applications, Battery Power Product & Technology, Volume 10, issue 6, November/December 2006.

[5] Wu, X., Du, J., and Hu,C. Energy Efficiency and Fuel economy Analysis of a Series Hybrid Electric Bus Different Chinese City Driving Cycles, International Journal of Smart Home, Vol.7, No.5, pp 353-368, 2013.

[6] Mazda introduces supercapcitor-type regenerative braking, Automotive Engineering Magazine, P. Weissler, artticle on the internet, posted 20 February 2013.

[7] O'Dell, J., Engine Stop-start Systems Save Fuel at Low Cost, posted on the internet, 10/9/2012.

[8] Ingram, A., Micro-hybrids to Grow Fast: More than Start-Stop, Lss Than Mild Hybrid, posted on the internet, May 7, 2014.

[9] Burke, A.F., Miller, M., and Van Gelder, E., Ultracapacitors and Batteries for Hybrid Vehicle Applications, 23rd Electric Vehicle Symposium, Anaheim, California, December 2007.

[10] Burke, A.F., Ultracapacitor technologies and applications in hybrid and electric vehicles, International Journal of Energy Research (Wiley), Vol. 34, issue 2, 2009.

[11] Burke, A.F., Zhao, H., and Van Gelder, E., Simulated Performance of Alternative Hybrid-Electric Powertrains in Vehicles on Various Driving Cycles, EVS-24, Stavanger, Norway, May 2009.

[12] Zhao, H. and Burke, A.F., Optimization of Fuel Cell Vehicle Operating Conditions for Fuel Cell Vehicles, Journal of Power Sources, Vol 186, Issue 2, 2009, pp. 408-416.

[13] Zhao, H. and Burke, A.F., Modeling and Optimization of PEMFC Systems and its Application to Direct Hydrogen Fuel Cell Vehicles, UC Davis ITS, Research Report UCD-ITS-RR-08-30, 2008.

[14] Liu, Z., The Use of Ultracapacitors in Hybrid Vehicles, Master's Thesis, University of California-Davis, Transportation Technology and Policy Program, August 2014.

[15] Wishart, J. and Shirk, M., Quantifying the Effects of Idle-Stop Systems on Fuel Economy in Light-duty Passenger Vehicle, Idaho National Laboratory Report, INL/EXT-12-27320, December 2012.

[16] Asekar, A. K., Start-Stop System using Micro-Hybrid Technology for Increasing Fuel Efficiency, International Journal of Mechanical and Production Engineering, Vol. 1, Issue 6,,December 2013.

[17] AGM battery takes primary role for idle stop-start in micro-hybrids, SAE International , posted on February 14, 2012.

[18] Hecke, R., Battery performance verification in micr0-hybrid applications, Batteries International Winter 2012/2013.

[19] Burke, A.F., Miller, M., Zhao, H., Radenbough, M., Lui, Z., Ultracapacitors in Micro- and Mild Hybrids with Lead-acid Batteries: Simulations and Laboratory and in-Vehicle Testing, Proceedings of EVS27, Barcelona, Spain, November 2013.

[20] Burke, A.F., Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles, IEEE Journal, special issue on Electric Powertrains, April 2007.

[21] Burke, A.F. and Zhao, H., Projected fuel consumption characteristics of hybrid and fuel cell vehicles for 2015-2045, paper presented at the Electric Vehicle Symposium 25, Shenzhen, China, November 2010

[22] Burke, A.F., Ultracapacitors in Hybrid and Plug-in Vehicles, article in Encyclopedia of Automotive Engineering, Wiley, published online December 2012.

[23] Zhao, H. and Burke, A.F., Fuel Cell Powered Vehicles using Ultracapacitors, Fuel Cells, Vol. 10, Issue 5, September 2010.

[24] Manev, V, etals, Nano-Li4Ti5O12 based HEV Batteries, Advanced Automotive Battery and Ultracapacitor Conference, Fourth International Symposium on Large Lithium-ion Battery Technology and Applications, Tampa, Florida, May 2008.

[25] Maletin, Y., etals., Carbon Based Electrochemical Double Layer Capacitors of Low Internal Resistance, Energy and Environmental Research, Vol. 3, No. 2, pp.156-165, 2013.