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Supercapacitors in Micro- and Mild Hybrids with Lithium Titanate Oxide Batteries: Vehicle Simulations and Laboratory Tests

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Supercapacitors in Micro- and Mild Hybrids with Lithium Titanate Oxide Batteries: Vehicle Simulations and Laboratory Tests

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Abstract

The use of lithium titanate Oxide (LTO) batteries with supercapacitors in micro- and mild hybrid vehicles has been studied. The study involves vehicle simulations and laboratory tests of carbon/carbon supercapacitors and 20Ah LTO cells from EIG, Korea. Cycle testing of the LTO cells/module on a cycle to simulate their use with supercapacitors indicated that their charge acceptance was excellent even at a charging power of 2000W (500W/cell). The test data indicated that the LTO battery would be an excellent choice for micro-hybrid applications.

Simulations of micro- and mild hybrid vehicle operation have been run using lead-acid and EIG LTO battery technologies in 16V and 48V system. It is clear from the results that the LTO batteries can function well in both the micro- and mild hybrids. The LTO batteries are much smaller than the lead-acid batteries and are more efficient. The LTO batteries had an efficiency of 95-97% while the lead-acid batteries had an efficiency of 85-88%. The effect on fuel economy of the higher efficiency of the LTO batteries was not significant for either the FUDS or highway driving cycle. This was true for even the accessory load of 800W.

Keywords: supercapacitor, battery, hybrid vehicle, simulation, fuel economy

1 Introduction

The mass marketing of micro-hybrid passenger cars is well underway around the world. In most cases, specially designed lead-acid batteries are used and the engine is turned off when the vehicle stops as long as the battery can accept the recharge in a reasonable [x]. Unfortunately the charge acceptance of the lead-acid battery degrades in a relatively short time and the stop-go feature of the vehicles stops working. There are a several auto manufacturers [x] who have begun to use supercapacitors with the lead-acid batteries. The supercapacitors perform the engine starting function at all times and provide the accessory load when the vehicle stops are short. This approach has been found to significantly extend the life of the lead-acid battery. Other auto manufacturers are considering the use of lithium batteries in place of the lead-acid battery in stop-go micro-hybrids. The lithium ion battery must have high power and long life. Likely the best lithium chemistry for this application is the lithium titanate oxide (LTO) battery. The USABC has funded a project [x] to develop a LTO battery for the stop-go application. The study reported in this paper involves consideration of various aspects of the application of LTO batteries with supercapacitors in stop-go hybrid vehicles. The batteries used in the study are 6Ah and 20Ah cells from EIG in Korea.

2 Testing of EIG lithium titanate oxide batteries (LTO)

EIG, Korea provided 6Ah and 20Ah cells to UC Davis for testing for use in hybrid vehicle applications. The 6Ah cells would be used in high voltage applications and the 20Ah cells would be used in 12V systems. The cells were tested at constant current and constant power and in pulse test to determine their resistance. The results of the tests are shown in Table 1 and 2. The 6Ah cells are high power cells (1075 W/kg)$_{95\%}$) with a relatively low energy density of 40 Wh/kg. The 20Ah cells have a higher energy density (70 Wh/kg), but lower power density capacity (381 W/kg)$_{95\%}$) than the 6 Ah cells. Both cells will have excellent charge acceptance capability and long cycle life [x]. The 20Ah cells were further tested for the 12V micro-hybrid application and the characteristics of both cells were used in simulations of hybrid vehicles to be discussed later in the paper.

Table 1: EIG cell 6Ah LTO cell

Constant Current test

Discharge current	Ah	Time(sec)	Resistance mOhm
2A	6.05	10891.7	
3A	6.00	7204.9	
6A	5.71	3425.1	
12A	5.42	1625.1	
30A	5.18	621.5	
60A	4.90	294.1	1.0
80A	4.80	217.5	.875

Weight .276 kg

Constant Power test

Discharge power	Time (sec)	Wh	Energy density Wh/kg	Power density W/kg
10w	2166.6	11.4	41.7	36.3
20w	1396.4	10.6	38.6	72.7
30w	1042.1	10.	37.9	109.0
60w	565.4	9.3	33.9	218.1
90w	388.8	8.0	29.2	327.2
120w	287.1	6.8	24.7	436.3
200w	169.2	4.3	15.8	727.2

Calculation of the 95% efficient pulse power: P = .95 x .05 x $(2.5)^2$ /.001 = 297W, 297/.276 = 1075 W/kg

Table 2: UC Davis test data for the EIG 20 Ah LTO cell

Constant current A	*Ah*	*Resistance mOhm 75% SOC*
4	*20.9*	
10	*20.9*	
20	*20.7*	
40	*20.5*	
100	*20.3*	*1.2*
200	*20.1*	*1.2*

Constant power W	*W/kg*	*Wh*	*Wh/kg*
20	*31*	*50.3*	*77.5*
30	*46*	*48.6*	*75.0*
50	*77*	*47.3*	*73.0*
100	*154*	*47.2*	*72.8*
200	*309*	*45.6*	*70.4*
300	*463*	*43.3*	*66.8*
400	*617*	*41.2*	*63.6*

Cell weight .648 kg

Calculation of the 95% efficient pulse power: P = .95 x .05 x $(2.5)^2$ /.0012 = 247W, 247/.648 = 381 W/kg

3 Testing of advanced carbon/carbon supercapacitors

Carbon/carbon supercapacitors with energy and power capability better than those commercially available from Maxwell and Ness (4.2 Wh/kg, 1000 W/kg $_{95\%}$) have been tested at UC Davis [1]. The more advanced devices were developed by Skeleton Technologies in Estonia and Yunasko in Ukraine. The characteristics of the advanced devices based on UC Davis test data are given in Tables 3 and 4.

Table 3: Skeleton 3200F Device characteristics

Carbon/carbon with graphene, acetronitrile 3.4V Packaged Weight 400 gm, volume 284 cm3

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

Table 4: Yunasko 1200F Supercapacitor

Constant current discharge data 2.75 – 1.35V

Current A	Time sec	Capacitance F	Steady-state Resistance mOhm
30	57.3	1273	--
60	29.1	1293	---
100	17.8	1290	---
150	12.0	1281	.10
250	7.15	1276	.08
300	5.8	1261	.10
350	5.0	1268	.11

Constant power discharges data 2.75 – 1.35V

Power W	W/kg *	Time sec	Wh	Wh/kg
44	200	79.8	.975	4.43
72	327	51.0	1.02	4.64
102	464	35.6	1.01	4.59
152	690	24.0	1.01	4.59
200	909	18.1	1.01	4.59
250	1136	14.5	1.01	4.59
300	1364	12.0	1.00	4.55
350	1591	10.3	1.00	4.55
400	1818	9.0	1.00	4.55

* weight of device - .220 kg as tested

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
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Matched impedance power: $P= V_R^2 / 4\ R_{ss}$, (W/kg) = 15, 400

$P=9/16 \times (1- \text{eff})\ V_0^2 /R = 9/16 \times (.05)\ (2.75)^2 /.00011 = 1934W$
$(W/kg)_{95\%\ packaged} =1934/.22 = 8791$, 11,868 W/L

Device	V rated	C (F)	R mOhm	RC sec	Wh/kg	W/kg (95%)	W/kg Match. Imped.	Wgt (kg)	Vol. (L)
Yunasko	2.75	1275	0.11	0.14	4.55	8791	78125	.22	.163

Table 5: Yunasko 16V module (6 x 1200F cells)

Constant current discharge data 16.2-8.1 V

Current A	Time sec	Capacitance F	Steady-state Resistance mOhm
10	168	207	
25	67	207	
50	33	205	
100	16	201	.5
150	11	208	.8
200	8	204	.3

Constant power discharges data 16.2-8.1 V

Power W	W/kg *	Time sec	Wh	Wh/kg *
157	127	126	5.5	4.4
300	240	65	5.42	4.34
450	360	43.5	5.44	4.35
600	480	32.4	5.40	4.32
900	720	21.4	5.35	4.28
1500	1200	12.6	5.25	4.2
2000	1600	9.3	5.17	4.14

* cell weight - 1.25 kg

The supercapacitor from Skeleton has a higher energy density by a factor of two than the commercial devices and also higher by nearly a factor of two. Hence it is well suited for hybrid vehicle applications. The device from Yunasko has very high power – nearly a factor of 10 higher than the commercial devices. Its energy density is about the same as the commercial devices. The Yunasko devices have been assembled in a 16V module which has been tested at UC Davis. The characteristics of the 16V module are given in Table 5.

The Yunasko 16V unit would be ideal for use in micro-hybrid, because its efficiency if very high and there would be very small loss as the energy is transferred to and from the components in the system.

4 Cycle testing of LTO cells for micro-hybrid applications

A detailed study of the use of supercapacitor with lead-acid batteries in micro-hybrid applications is discussed in [2, 3]. In that study, a test cycle was developed for cycling a lead-acid battery as if it will in a system with supercapacitors in a micro-hybrid vehicle. That cycle was used to life cycle a lead-acid battery for micro-hybrid applications. It was found that the charge acceptance of the lead-acid battery degraded rapidly over the 400 cycles of the test. That test cycle was based on a vehicle accessory load of 500W and a battery charge power of 400W. In a recent study [4] of 12V battery requirements for start-stop applications by NREL for the USABC, it was found that the accessory load should be 750W and the battery recharge power should be 2000W. These test conditions were used in the present tests of batteries for micro-hybrid applications. The test cycle used previously for the lead-acid battery and that used for the LTO battery based on the new information [4] are compared in Table 6. The charge times for the lithium batteries were decreased compared those for the lead-acid battery to reflect the higher ability of the lithium batteries to accept charge.

Detailed cycle testing of a 12V Gel lead-acid battery using the cycle given in Table 6 is discussed in [3]. It was found that the lead-acid battery could not be recharged even at 400W after a relatively few cycles as shown in Figure 1. The lead-acid battery meet the other parts of the cycle after several days of testing, but its charge acceptance characteristics were not suitable for the micro-hybrid application.

Cycle tests of the LTO lithium battery were made using both single cells and a 16V module consisting of six of the 20Ah cells (see Figure 2-3). Both the cell and module were tested using the test cycle given in Table 6. The module was cycle through 124 cycles and the cell was cycled through 400 cycles. As shown in Figures 2-3, the charge acceptance of the LTO battery was excellent and the battery could be recharge at 2000W at all parts of the cycle. The cell voltages remained below 2.8V and the variation between the cells was relatively small (less than 50mv in most cases). The difficulty encountered was providing the 3 kW to start the engine and maintaining a cell voltage greater than 1.5V. On a cell basis, this power corresponds to 770 W/kg which is a high value for this battery. The LTO battery seems well suited for the micro-hybrid application, but it will require a higher power cell than the 20 Ah cell tested in this study.

Table 6: Battery test cycles for lead-acid and lithium batteries

Lead-acid			Lithium LTO	
Time (s)	Step		Time(s)	Step
40	0.5kW discharging		40	0.75kW discharging
1	3kW discharging Engine start		1-2	3kW discharging Engine start
5	Rest		5	Rest
32	0.4kW charging,		9	2.0kW charging,
42	Rest		42	Rest
41.4	0.4kW charging		11	2.0kW charging
85	Rest		85	Rest
11	0.5kW discharging		11	0.75 discharging
1	3kW discharging Engine start		1-2	3kW discharging Engine start
17	Rest		17	Rest
31.6	0.4kW charging		9	2.0kW charging
120	Rest		120	Rest
14	0.5kW discharging		14	0.75kW discharging
1	3kW discharging Engine start		1-2	3kW discharging Engine start
20	Charging to ΔAh = 0		9	Charging to ΔAh = 0
5	Rest V_4			Rest V_4

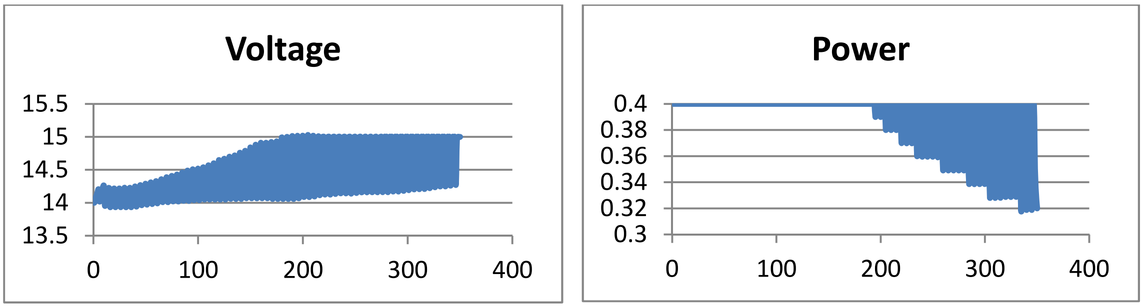


Figure 1: Recharge voltage and power of the 12V Gel lead-acid battery at the end of the test cycle

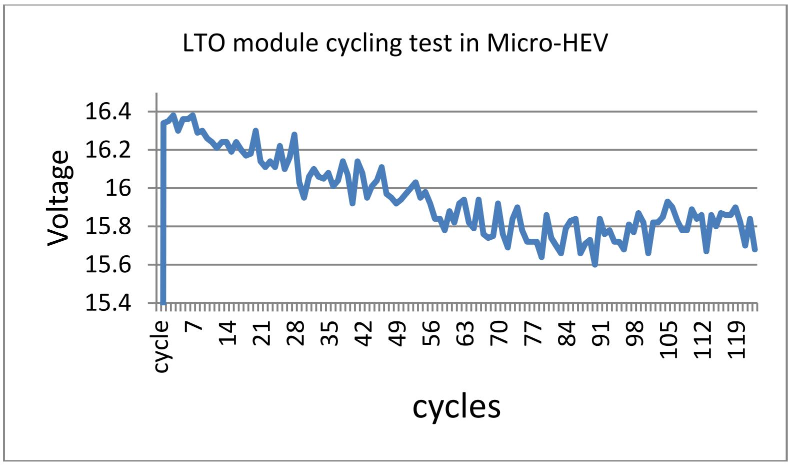


Figure 2: Voltage at the end of a recharge step for the LTO module

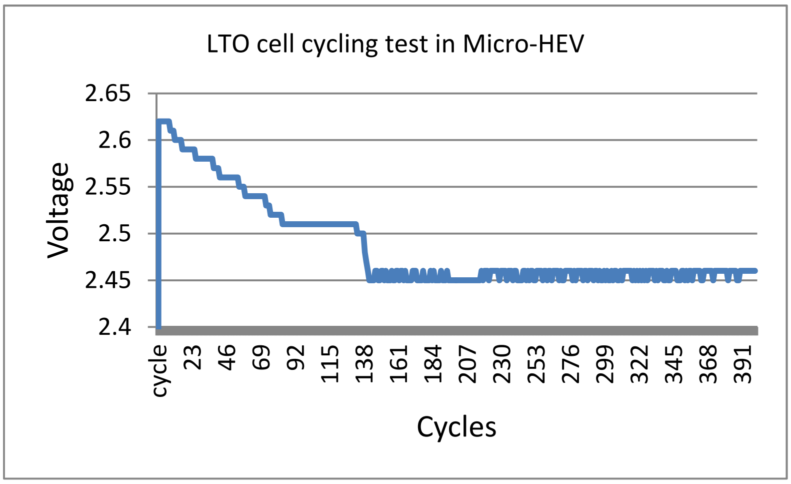


Figure 3: Voltage at end of a recharge step for the LTO cell

5 Simulation results using LTO batteries in micro- and mild-hybrids

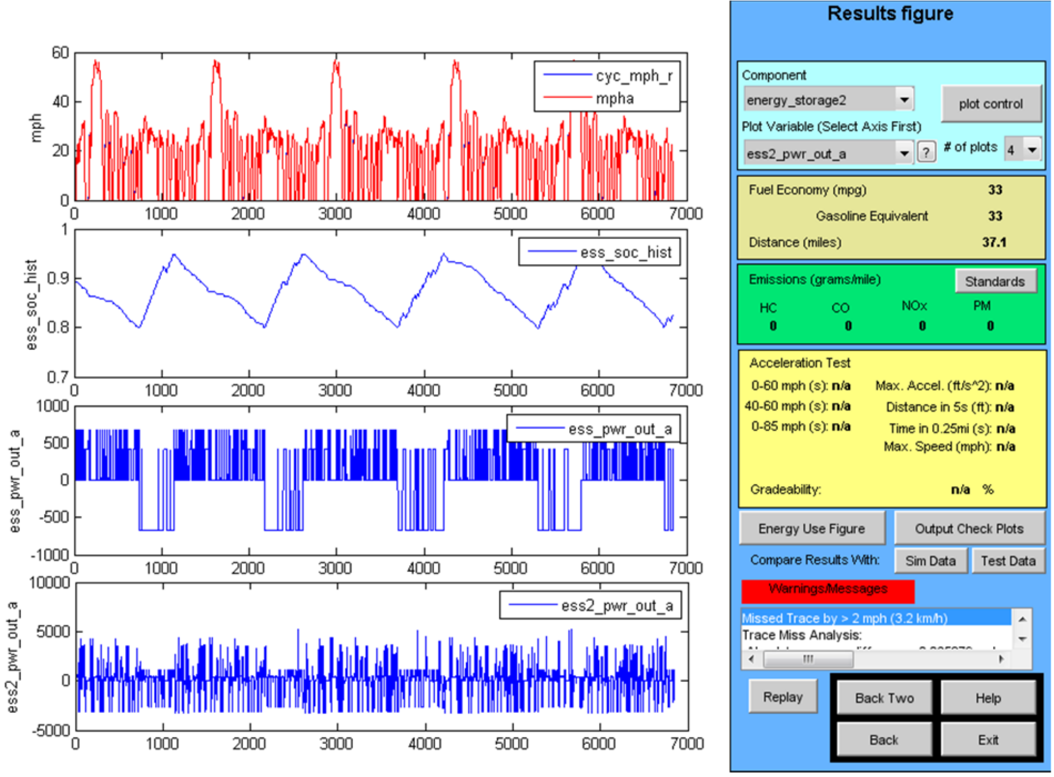
Simulations of micro- and mild hybrid vehicle operation have been run using lead-acid and EIG LTO battery technologies in 16V and 48V system. Both systems used the batteries in combination with carbon/carbon supercapacitors. The batteries provide the accessory and acceleration loads when the supercapacitors are depleted and need to be recharged from the engine. The 16V system utilized a 4 kW electric motor and the 48V system used a 12 kW motor. Both systems utilized a parallel hybrid configuration with a 120kW engine in the mid-size passenger car being simulated. The accessory load of 400W or 800W was provided by the capacitors when the vehicle was stopped if their state-of-charge permitted: otherwise the accessory load was provided by the batteries. The results of the simulations are given in Table 7and Figures 4 and 5. It is clear from the results that both the lead-acid and LTO batteries can function well in both the micro- and mild hybrids. However, the LTO batteries are much smaller than the lead-acid batteries and more efficient. The LTO batteries had an efficiency of 95-97% while the lead-acid batteries had an efficiency of 85-88%. The effect on fuel economy of the higher efficiency of the LTO batteries was not significant for either the FUDS or highway driving cycle. This was true for even the accessory load of 800W. As expected the increase in fuel economy was greater for the mild-hybrid than for the micro-hybrid although it was significant for both hybrids. Decisions on the battery type to use will depend to a large extent on the cycle life of the battery in the two hybrid applications. Experience to date indicates that the lead-acid battery will not have satisfactory cycle life and the LTO battery will be the better choice. It seems likely that both hybrid systems could function satisfactorily with only the LTO battery, but the battery will have to be larger than would be needed with supercapacitors.

Table 7: Hybrid vehicle simulation results using lead-acid and Lithium titanate oxide (LTO) batteries

Mid-size Passenger car: weight 1660 kg, C_D =.3, A_f=2.2m^2 , f_r=.009

Mild hybrid 48V	Weight of caps kg	Energy stored Wh	Weight of the battery	Energy stored Wh	FUDS Mpg*	Highway Mpg*
Lead-acid	13	50	38	950	37.7/35.1	45.7/44.9
LTO	13	50	6	240	38.1/34.9	46.3/45.2
Micro-hybrid 16V						
Lead-acid	4	16	12	300	32.4/30.0	41.8/40.5
LTO	4	16	4	180	33.5/30.2	41.6/40.7
Conventional vehicle					26	37

* mpg accessory load 400W/800W



Component energy_storage2

Plot Variable (Select Axis First) ess2_pwr_out_a

# of plots 4

Fuel Economy (mpg) 33

Gasoline Equivalent 33

Distance (miles) 37.1

Emissions (grams/mile)

HC	CO	NOx	PM
0	0	0	0

Acceleration Test

0-60 mph (s): n/a

40-60 mph (s): n/a

0-85 mph (s): n/a

Max. Accel. (ft/s^2): n/a

Distance in 5s (ft): n/a

Time in 0.25mi (s): n/a

Max. Speed (mph): n/a

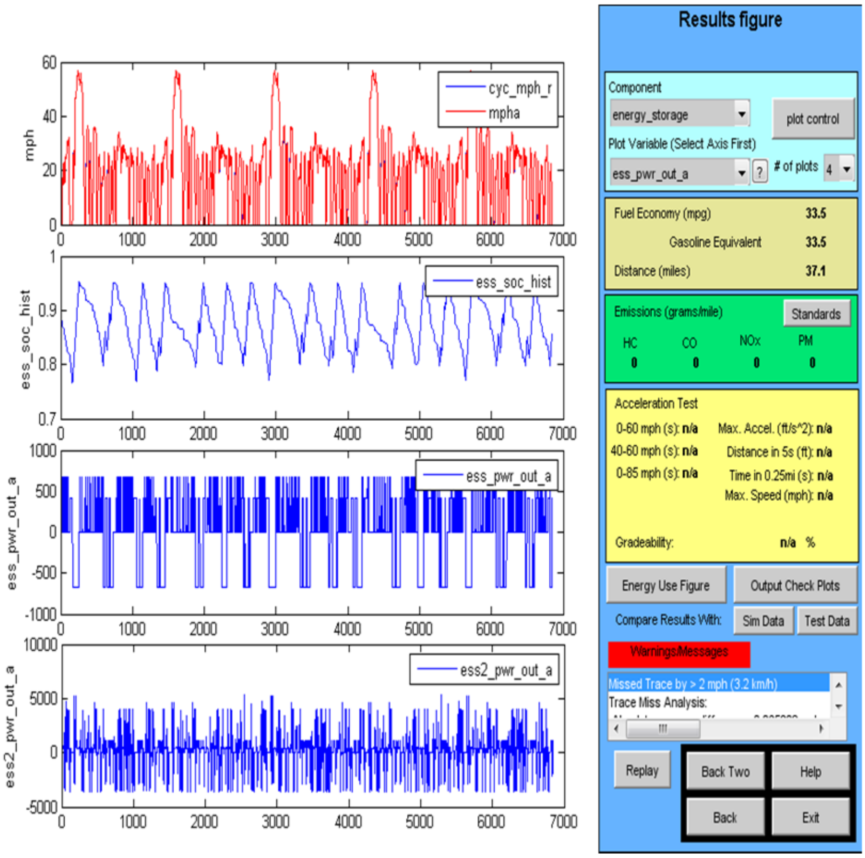
Gradeability: n/a %

Compare Results With:

Missed Trace by > 2 mph (3.2 km/h)

Trace Miss Analysis:

Figure 4: 16V Micro-hybrid with LTO battery and Maxwell supercapacitors on the FUDS



Component: energy_storage

Plot Variable (Select Axis First): ess_pwr_out_a

# of plots: 4

Fuel Economy (mpg) 33.5

Gasoline Equivalent 33.5

Distance (miles) 37.1

Emissions (grams/mile)

HC	CO	NOx	PM
0	0	0	0

Acceleration Test

0-60 mph (s): n/a
40-60 mph (s): n/a
0-85 mph (s): n/a
Max. Accel. (ft/s^2): n/a
Distance in 5s (ft): n/a
Time in 0.25mi (s): n/a
Max. Speed (mph): n/a
Gradeability: n/a %

Missed Trace by > 2 mph (3.2 km/h)
Trace Miss Analysis:

Figure 5: 16V Micro-hybrid with lead-acid battery and Maxwell supercapacitors on the FUDS

6 Summary

The use of lithium titanate Oxide (LTO) batteries with supercapacitors in micro- and mild hybrid vehicles has been studied. The study involved vehicle simulations and laboratory tests of carbon/carbon supercapacitors and 20Ah LTO cells from EIG, Korea. Test data are presented for advanced carbon/carbon supercapacitors from Skeleton Technologies, Estonia and Yunasko, Ukraine. These supercapacitors are ideal for use in stop-go micro-hybrids with batteries. The EIG LTO batteries had an energy density of 77 Wh/kg and modest power capability of about 400 (W/kg)$_{95\%\ \text{pulse}}$. Cycle testing of the LTO cells/module on a cycle to simulate their use with supercapacitors indicated that their charge acceptance was excellent even at a charging power of 2000W (500W/cell). The test data indicated that the LTO battery would be an excellent choice for micro-hybrid applications.

Simulations of micro- and mild hybrid vehicle operation were run using lead-acid and EIG LTO battery technologies in 16V and 48V system. It is clear from the results that the LTO batteries can function well in both the micro- and mild hybrids. The LTO batteries are much smaller than the lead-acid batteries and are more efficient. The LTO batteries had an efficiency of 95-97% while the lead-acid batteries had an efficiency of 85-88%. The effect on fuel economy of the higher efficiency of the LTO batteries was not significant for either the FUDS or highway driving cycle. This was true for even the accessory load of 800W. As expected the increase in fuel economy was greater for the mild-hybrid than for the micro-hybrid although it was significant for both hybrids. Decisions on the battery type to use will depend to a large extent on the cycle life of the battery in the two hybrid applications.

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