Research Report – UCD-ITS-RR-10-01

Fuel Cell Powered Vehicles Using Supercapacitors: Device Characteristics, Control Strategies, and Simulation Results

January 2010

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Fuel Cell Powered Vehicles Using Supercapacitors
-- Device Characteristics, Control Strategies, and Simulation Results

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Abstract

The fuel cell powered vehicle is one of the most attractive candidates for the future due to its high efficiency and capability to use hydrogen as the fuel. However, its relatively poor dynamic response, high cost, and limited life time have impeded its widespread adoption. With the emergence of large supercapacitors (also know as ultracapacitors, UCs) with high power density and the shift to hybridization in the vehicle technology, fuel cell/supercapacitor hybrid fuel cell vehicles are gaining more attention. Fuel cells in conjunction with supercapacitors can create high power with fast dynamic response, which makes it well suitable for automotive applications. Hybrid fuel cell vehicles with different powertrain configurations have been evaluated based on simulations performed at the Institute of Transportation Studies, University of California-Davis. The following powertrain configurations have been considered:

(a) Direct hydrogen fuel cell vehicles (FCVs) without energy storage
(b) FCVs with supercapacitors directly connected in parallel with fuel cells
(c) FCVs with supercapacitors coupled in parallel with fuel cells through a DC/DC converter
(d) FCVs with fuel cells connected to supercapacitors via a DC/DC converter

Simulation results show that hybridization of fuel cell vehicles with supercapacitors with load leveling control can significantly reduce the stress on fuel cells electrically and mechanically and benefit fuel economy of the vehicles. Compared to fuel cell vehicles without energy storages, fuel cell-supercapacitor hybridization achieved fuel economy increases of up to 28% on the FUDS cycle and up to 24% on the US06 cycle for mid-size passenger vehicles. In general, the maximum fuel economy improvements are greater using supercapacitors than batteries. The simulation results show that the power assist control strategy is better than load-level control for batteries because of the lower losses in the DC/DC converter and batteries, but load level control is better for supercapacitors. The best approach for hybridization of the fuel cell vehicles is to use supercapacitors with load leveled control as it greatly mitigates the stress on fuel cells and results in a near maximum improvement in fuel economy and fuel cell durability.

Key words: fuel cell vehicles, fuel cell system, hybridization, supercapacitors, load leveling, power assist

1. Introduction

For reducing green house (GHG) gas emissions and fossil oil consumption, the development of next generation light duty vehicles (LDVs) has been accelerated by the government and private

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sectors since early 2000s. Hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs), fuel cell vehicles (FCVs), battery electric vehicles (BEVs) , alternative fuel (biofuel) vehicles have been developed. Electric drive vehicles such as BEVs and FCVs appear to the best options for reaching the goal of GHG reduction. The research and development has focused mainly on hydrogen fuel cells and batteries. Hydrogen is not a primary fuel. Like electricity used to charge batteries, it is an energy carrier and the hydrogen must be produced from another energy source and stored onboard the vehicle.

In automotive applications, fuel cell systems must be able to adapt to challenging operating conditions such as frequent start-up and stop and sudden change and widely varying power demand. These conditions are much easier to cope with if the fuel cell system is hybridized using batteries and/or ultracapacitors. In addition to mitigating the stress on the fuel cell via load leveling, the energy storage permits the capture of regenerative braking energy, which will benefit vehicle fuel economy and can potentially permit downsizing the fuel cell system. Different approaches to hybridizing fuel cells and energy storage technologies have been developed. It is of interest to simulate and evaluate these different hybridization configurations with different energy storage arrangements.

Considering hybridization of fuel cell vehicles, designers have a number of choices to consider. These alternatives include the physical arrangement of the power sources, selection of the energy storage technology and devices, and the control strategy for splitting power between the fuel cell and the energy storage unit. Hybridizing fuel cell vehicles with energy storage has been extensively studied in terms of powertrain arrangements [1-9], power source sizing [6,10-13], and energy management strategies [1,2,4,8,14,15]. Evaluations of these alternatives include the type/class of vehicle, fuel economy/consumption, and performance and cost of the vehicle.

In this paper, the performance and fuel consumption of mid-size hybrid fuel cell vehicles are simulated for different power source configurations using a fuel cell vehicle program recently developed [16,17] at the Institute of Transportation Studies, University of California-Davis. The following fuel cell powertrain arrangements are considered:

- Direct hydrogen fuel cell vehicles (FCVs) without energy storage
- FCVs with supercapacitors directly connected in parallel with the fuel cell
- FCVs with supercapacitors coupled in parallel with the fuel cell through a DC/DC converter
- FCVs with the fuel cell connected to supercapacitor dc-link via a DC/DC converter

These powertrain configurations are analyzed over the FUDS and US06 driving cycles. Simulations of fuel cell vehicles with different size of energy storage and fuel cell units are performed and analyzed. The evaluations focus on fuel economy/consumption and component /system efficiency for the same size vehicles having the same road load characteristics. Complexity and cost are not considered in the analysis.

2. Supercapacitor Characteristics

With the shift to hybridization in the late 1990s, energy storage technology for HEVs, PHEVs and FCVs has been extensively developed. Significant advances in terms of performance, lifetime and cost have been achieved. It is of interest to compare these technologies in terms of energy storage and power handling capacity. The Ragone plot of these technologies [18,19] is given in Figure 1. The solid lines show the current status and the dotted lines give an estimated future potential of different technologies. The sloping lines indicate the ratio of power density and energy density (P/E) of the technologies, which is an indication of their relative charging and discharging times. The supercapacitors can deliver very high power and be charged in a few seconds but have limited energy storage capacity. Lithium batteries can store 10-30 kWh and be completely charged and discharged in 10-20 minutes and can provide high pulse power for a few seconds much like capacitors, but with greater losses. On the other hand, the hydrogen fuel cell system has a very high system energy density due primarily to the characteristics of the hydrogen fuel and can deliver high power for long periods, but has relatively poor dynamic response due to the compressor needed to provide the air at the cathode of the fuel cell. Hence none of the technologies meets all of the needs of electric drive vehicles. Considering the need for long range between refueling and the ability to cope with rapid changes in power demand and frequent capture of regenerative braking energy, the combination of fuel cells and supercapacitors/batteries can take advantage of the strengths of each of the technologies and achieve performance in automotive applications better than that of internal combustion engines. Lithium batteries having relatively high energy density and high power density are ideal power sources for BEVs and PHEVs.

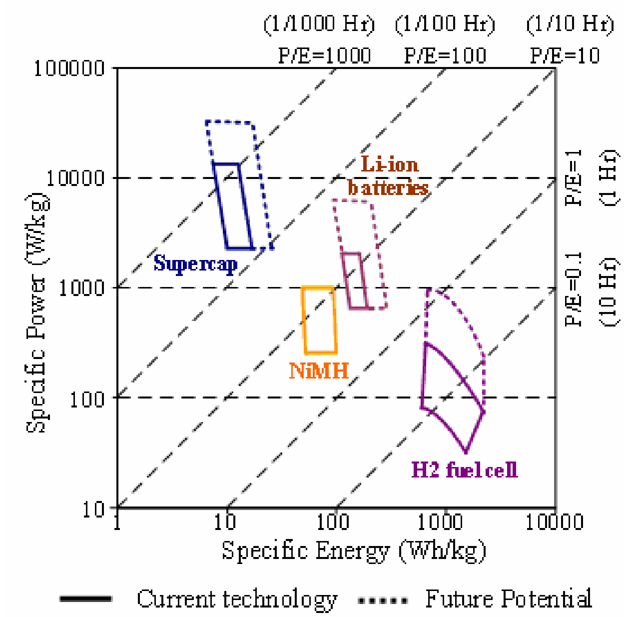

Figure 1 Ragone plot of energy storages for automotive applications
Modified image from [18,19]

Supercapacitors have been developed since the early 1990s. Large supercapacitors with cell capacitance ranging from 1000 Farad to 5000 Farad are commercially available from several companies including Maxwell, Ness, Power Systems, and Panasonic. The characteristics of these devices are summarized in Table 1 taken from [20]. Most of these supercapacitors utilize activated carbon and an organic electrolyte with cell voltages of 2.5-2.7V. Their useable energy density varies from 4-4.5 Wh/kg. Prototype cells with higher energy density (8-12 Wh/kg) utilize advanced carbons permitting higher voltage (3.3-3.8V). The supercapacitors have low resistance resulting in low charge and discharge losses and associated high power densities of 1000-2500 W/kg for 95% efficient pulses. As indicated in Table 2, lithium batteries also have high pulse power, but not as high as that of most supercapacitors. The highest power density lithium batteries are the lithium titanate oxide (LiTiO) cells from Altairnano. The devices used in the simulations in later sections of the paper are based on the carbon supercapacitor from APowerCap and the graphite/NiCoMnO2 Li-ion cells from EIG.

Table 1 Summary of performance characteristics of supercapacitor devices [20]

Device	V Rated	C (F)	R (mOhm)	RC (sec)	Wh/kg †	W/kg - 95% ††	W/kg Match. Imped.	Wgt. (kg)	Vol. lit.
Maxwell*	2.7	2885	0.375	1.08	4.2	994	8836	0.55	0.414
Maxwell	2.7	605	0.9	0.55	2.35	1139	9597	0.2	0.211
ApowerCap**	2.7	55	4	0.22	5.5	5695	50625	0.009	---
Apowercap**	2.7	450	1.4	0.58	5.89	2574	24595	0.057	0.045
Ness	2.7	1800	0.55	1	3.6	975	8674	0.38	0.277
Ness	2.7	3640	0.3	1.1	4.2	928	8010	0.65	0.514
Ness (cyl.)	2.7	3160	0.4	1.26	4.4	982	8728	0.522	0.38
Asahi Glass (propylene carbonate)	2.7	1375	2.5	3.4	4.9	390	3471	0.21 (estimated)	0.151
Panasonic (propylene carbonate)	2.5	1200	1	1.2	2.3	514	4596	0.34	0.245
EPCOS	2.7	3400	0.45	1.5	4.3	760	6750	0.6	0.48
LS Cable	2.8	3200	0.25	0.8	3.7	1400	12400	0.63	0.47
BatScap	2.7	2680	0.2	0.54	4.2	2050	18225	0.5	0.572
Power Sys. (activated carbon, propylene carbonate) **	2.7	1350	1.5	2	4.9	650	5785	0.21	0.151
Power Sys. (graphitic carbon, propylene carbonate) **	3.3	1800	3	5.4	8	486	4320	0.21	0.15
	3.3	1500	1.7	2.5	6	776	6903	0.23	0.15
Fuji Heavy Industry- hybrid (AC/graphitic Carbon) **	3.8	1800	1.5	2.6	9.2	1025	10375	0.232	0.143
JSR Micro (AC/graphitic carbon)**	3.8	1000	4	4	11.2	900	7987	0.113	0.073
		2000	1.9	3.8	12.1	1038	9223	0.206	0.132

† Energy density at 400 W/kg constant power, V_{rated} to $V_{rated}/2$

†† Power based on $P = 9/16 \cdot (1 - EF) \cdot V^2 / R$, EF = efficiency of discharge

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

** All device except those with ** are packaged in metal containers, these devices are in laminated pouches

Table 2 Comparisons of battery and supercapacitor characteristics

Battery Developer /Cell type	Electrode chemistry	Voltage range	Ah F	Resist. mOhm	Wh/kg	W/kg 90% effic.‡	Wgt. (kg)	Density gm/cm3
Supercap Apowercap	Activated carbon	2.7	450F	1.4	5.5	5150	0.057	1.3
Supercap JSR micro	Advanced carbon	3.8	2000F	1.9	12	2080	0.206	1.6
Kokam prismatic	Graphite/ NiCoMnO2	4.1-3.2	30	1.5	140	1220	0.787	2.4
Saft Cylind.	Graphite/ NiCoAl	4.0-2.5	6.5	3.2	63	1225	0.35	2.1
A123 Cylind.	Graphite/Iron Phosph.	3.6-2.0	2.2	12	90	1393	0.07	2.2
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	11	2.2	70	990	0.34	1.83
Altairnano prismatic	LiTiO/ NiMnO2	2.8-1.5	3.8	1.15	35	2460	0.26	1.91
EIG prismatic	Graphite/ NiCoMnO2	4.2-3.0	20	3.1	165	1278	0.41	----
EIG prismatic	Graphite/Iron Phosph.	3.65-2.0	15	2.5	113	1100	0.42	---
Panasonic EV prismatic	Ni Metal hydride	7.2-5.4	6.5	11.4	46	395	1.04	1.8

‡ Battery power density at full charge, P= Eff.*(1-Eff.) Voc^2 /R
Supercapacitor power density, P= 9/16*(1-Eff.) Voc^2 /R

3. Fuel Cell Systems, Fuel Cell Vehicles and Control Strategies

3.1 Optimal Operation Conditions

As a next generation power source for automotive applications, fuel cells can deliver electricity with high efficiency. However, the operation of the on-board auxiliaries such as the air supply compressor, cooling pump and radiator fan can significantly affect the performance of fuel cell system. Hence the operating strategy and resultant transients of the fuel cell system can have a significant impact on the system efficiency and thus vehicle fuel economy. There are two operating modes for the fuel cell system: fixed back pressure operation and optimum varying back pressure operation. In both modes, the air flow stoichiometry is optimized to maximize net output power and efficiency of the fuel cell system [16]. The optimum varying back pressure operation of a fuel cell system requires varying the back pressure and air supply stoichiometry as the power demand changes.

Figure 2 shows a plot of optimized net system efficiency vs. net power for a 106 kW fuel cell stack and a 17 kW twinscrew compressor operating at fixed back pressures of 1.1 atm, 1.5 atm, and 2.0 atm and optimum varying back pressure. Compared to fixed back pressure operation, the fuel cell system with the optimum varying back pressure operation can achieve higher system efficiency over the entire operating power range and maximize the system output power. It can be seen that the peak efficiency of a fuel cell system occurs near 25% of rated power for fixed high back pressure operation and 13% of rated power for the optimal operation. The efficiency of the fuel cell system is significantly lower in the very high or very low output power regions due to the high compressor power requirement in the high power region and low compressor efficiency in the low power region. Therefore, properly sizing the fuel cell system based on the average driving power instead of the maximum power required for acceleration can benefit fuel economy of hybrid fuel cell vehicles. Optimum varying back pressure operation of fuel cell systems will be adopted in the following powertrain configuration analysis.

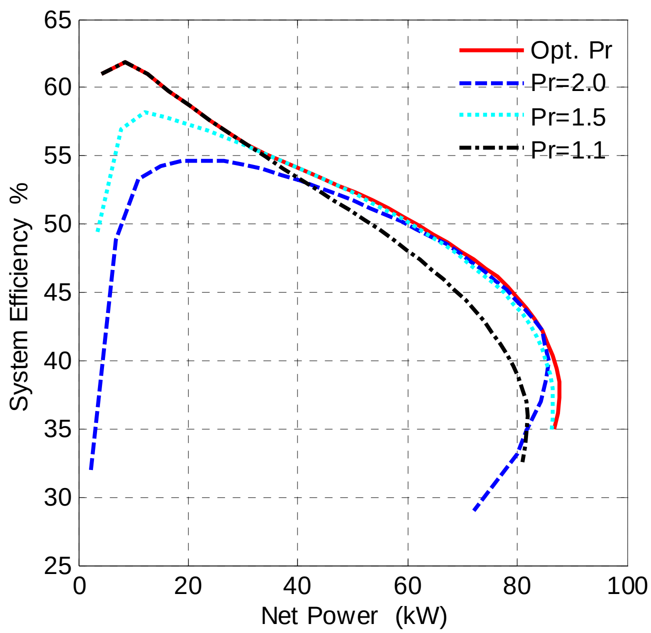

Figure 2 Optimized fuel cell system efficiency vs. net power

3.2 Fuel Cell Vehicle Powertrain Configurations

The optimal operation of a fuel cell system requires varying the back pressure and air supply stoichiometry ratio according to the change of the power demand. These rapid changes in the operating conditions of the fuel cell stack can have a major impact on the lifetime of the fuel cell stack due to the mechanical stresses on the MEA and the stack accessory components. Hybridization of fuel cell vehicles with energy storage can mitigate this stress and achieve better fuel economy. Considering hybridization of fuel cell vehicles, designers have many choices. These alternatives include the physical arrangement of the power sources, selection of the energy storage technology and devices, and the control strategy for splitting power between two power sources. There are several practical arrangements of power sources. Each of the power sources arrangements has its advantages and disadvantages relative to operating conditions, control complexity, development cost, vehicle performance, and fuel economy potential. Figure 3 illustrates schematically the fuel cell powertrain arrangements considered in this paper.

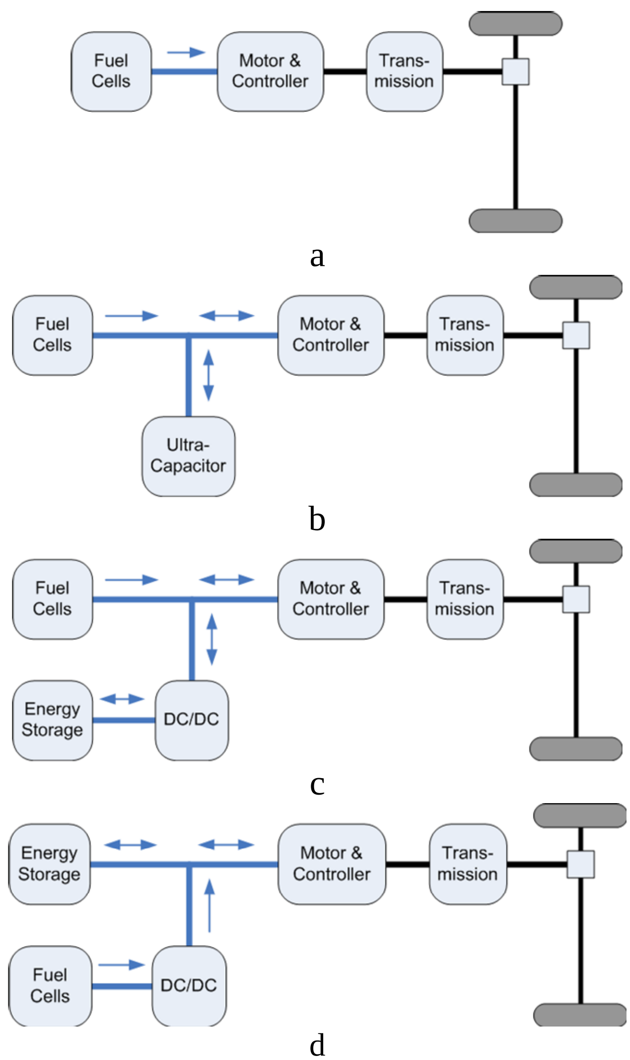

Figure 3 Powertrain configurations for fuel cell vehicles

(a) Direct hydrogen fuel cell vehicles without energy storage. This configuration is the simplest. No DC/DC converter is employed to control the DC-link voltage. The fuel cell stack voltage is the DC-link voltage. Because the dependency of fuel cell output current on the reactant flow rate limits its response to load transients, this configuration requires a bigger fuel cell stack and fast reactant supply system to satisfy a large variations in load power. The DC-link voltage has a large swing due to the slow response of the fuel cell system. This configuration is used as the baseline for comparing different powertrain configurations.

(b) FCVs with supercapacitors directly connected to fuel cells. The supercapacitors are directly connected in parallel with the DC-link (fuel cell stack). In this case, the voltages of the energy storage unit and fuel cell are equal. The relatively soft voltage-current characteristics of fuel cells allow supercapacitors to operate over a fairly wide range of voltage and to self regulate the DC-link voltage fluctuation. The supercapacitors will absorb the excess power from the stack and the regenerative braking energy and provide a fraction of transient power for vehicle acceleration. A diode is utilized before the fuel cells for preventing the DC-link from back feeding the fuel cells during vehicle regenerative braking. This configuration is less costly, less complex and more efficient.

(c) FCVs with energy storage such as supercapacitors or batteries coupled in parallel with fuel cells through a DC/DC converter. The fuel cell voltage is the DC-link voltage. The transient power provided by the energy storage is regulated by a DC/DC converter. The introduction of the DC/DC converter can maximize the utilization of supercapacitors or batteries during acceleration and cruise and regenerative braking. This configuration permits controlling the transient power from the fuel cell by applying different power split strategies such as power-assist or load-leveling control to mitigate the stress on the fuel cell stack [21]. The state of charge (SOC) of supercapacitors or batteries can be directly controlled within appropriate levels.

(d) FCVs with the fuel cell coupled with energy storage unit through a DC/DC converter**.** The energy storage voltage is the DC-link voltage. The steady power provided by the fuel cell passes through the DC/DC converter. The converter regulates the fuel cell power to avoid large fluctuation of the DC-link voltage. The SOC can be controlled indirectly.

Various FCV developers use different powertrain configurations and energy storage technology in their vehicles. There is a need to model the various fuel cell vehicle configurations and to simulate their performance/hydrogen consumption for different size fuel cell stacks and type and size of energy storage unit.

In practical applications, it is not necessary to maintain a constant DC-link voltage. A relatively slow change of the DC-Link voltage is acceptable for control purposes. In this study, the four fuel cell vehicle configurations (a-d) are evaluated via vehicle simulations. Supercapacitors are used in configurations (b), (c) and (d). NiMH and Li-ion batteries are utilized in the configuration (c) for comparison with the systems using supercapacitors.

3.3 Power Splitting Control Strategies

The fuel cell operation (power, voltage, current vs. time) and hydrogen consumption (fuel economy) are closely related to the strategy utilized to split power between the fuel cell and the energy storage as the vehicle is operated over various driving cycles. The general objective of any control strategy is to operate the fuel cell system only in its high efficiency region, avoiding operation in the very low power and very high power regions. Power assist and load leveling control strategies can be used in hybrid fuel cell vehicles. Power assist control splits the power/current demand of the traction motor i_{motor} based on the fuel cell voltage V_{fc} and the energy storage *SOC*. The current command for the energy storage device i_{ess} is expressed in equation (1) with the fuel cell providing the remaining current (equation 2).

$$i_{ess} = f_{fc}(V_{fc}) \cdot f_{ess}(SOC) \cdot i_{motor} \qquad (1)$$

$$i_{fc} = i_{motor} - i_{ess} \qquad (2)$$

where f_{fc} and f_{ess} are factors related to fuel cell voltage and energy storage device *SOC*, respectively. If the fuel cell voltage remains relatively high, it will provide most of the current to the motor. When the fuel cell voltage becomes low, the energy storage device will provide a large fraction of the current demanded by the motor.

In load leveling control, the fuel cell provides relatively steady power and the energy storage device provides transient power. The fuel cell current command i_{fc} is calculated by averaging the traction motor current i_{motor} over a specified time period such as 60 seconds.

$$i_{fc} = i_{av,60\sec} \qquad (3)$$

$$i_{ess} = i_{motor} - i_{av,60\sec} \qquad (4)$$

The implementation of the control strategies for power split is schematized in Figure 4. Both control strategies maintain the *SOC* of the supercapacitor or battery within a specified range. Compared to the power assist control, load leveling control permits the fuel cell to operate within a relatively narrow high efficiency region. This mitigates the stress on the fuel cell and maximizes fuel cell life by utilizing the energy stored in the supercapacitor or battery to meet high power transients. However, a significant fraction of the transient power passes through the DC/DC converter for leveling the fuel cell current, which introduces significant losses in the power electronics. A previous study [21] study showed that the load leveling approach can improve vehicle fuel economy over most of driving cycles.

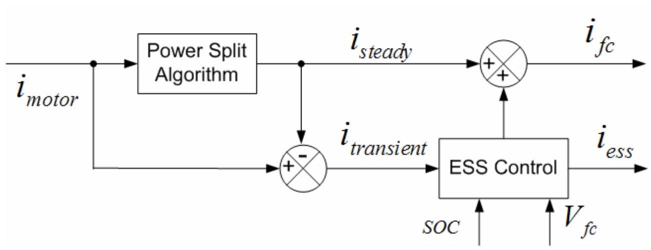

Figure 4 Schematic of power split control

For fuel cell vehicles with supercapacitors coupled directly in parallel with the fuel cell, no dc/dc converter is employed. The voltages of the supercapacitor unit and fuel cell are equal. The current of the supercapacitors is governed by the differential equation (5).

$$\frac{dV}{dt} = \frac{i_{cap}}{C} + R_{cap}\frac{di_{cap}}{dt}, \quad \frac{dV_{cap}}{dt} = \frac{dV_{fc}}{dt} \qquad (5)$$

4. Vehicle simulation

Simulations of the operation of hybrid fuel cell vehicles using various powertrain arrangements and energy storage technologies (supercapacitors and NiMH and Li-ion batteries) were performed using the UCD fuel cell vehicle simulation program [16,17]. The UCD fuel cell vehicle model is a forward-looking vehicle model developed using Matlab-Simulink®, which can simulate both the dynamics of the fuel cell system and the vehicle. Simulations were performed using both the power assist and load leveling control strategies. In the case of the load leveling control strategy, the fuel cell provides the average power requested by the vehicle over a specified period and the transient behavior of the air supply system can be ignored when the energy storage is coupled with fuel cell through power electronics. In that case, the quasi-steady model of the fuel cell operation was employed.

In addition to the choice of powertrain arrangements and energy storage technologies, the simulation have been run with different sizes (kW) of fuel cells and energy storage (Ah or Wh) in order to evaluate the potential of downsizing the fuel cell as a means of reducing system cost. The characteristics of the vehicle, energy storage and the fuel cell system are listed in Table 3. Increasing the averaging time in the load leveling control strategy leads to a larger fraction of transient power passing through the energy storage unit and results in greater losses in the charging and discharging of the energy storage unit. In this study, a 60-second simple moving average is used for leveling the power requirement for the fuel cell system.

Regenerative braking is limited by the maximum power of the traction motor and maximum *SOC* and voltage limits of the energy storage units. Permitting a large battery *SOC* swing can lead to a shortened cycle life for NiMH and Li-ion batteries. Hence the battery *SOC* is limited to the range between 0.6 and 0.8. In addition, the regenerative braking currents are limited to protect the batteries from over voltage. The minimum voltage of the supercapacitor is set as 50 percent of its rated voltage. The maximum usable energy is then 75 percent of the total energy stored in the capacitor. The supercapacitor $SOC = 1- [(V_{rated} – V)/(V_{rated}/2)]$ is controlled to be between 0.98 and 0.1. Empirical data of an APowerCap 450 F supercapacitor and an EIG NiCo 20 Ah Li-ion cell obtained from testing at UC Davis are utilized and scaled in the energy storage unit models (see Table 2). Data files for the NiMH battery in ADVISOR were used for that battery.

Table 3 Vehicle simulation parameters

	Case 1	Case 2
Vehicle and System Parameters		
Drag Coefficient	0.3	0.3
Frontal Area (m2)	2.2	2.2
Rolling Resistance	0.01	0.01
Vehicle Hotel Load (kW)	0.3	0.3
Vehicle Mass without energy storages (kg) §	1500	1460
Electric Motor (kW)	75	75
Fuel Cell Stack and Auxiliaries		
Max. Net Power (kW)	87.6	58.4
Gross Power (kW)	106	71
Number of Cells	440	440
Cell Area (cm2)	510	340
Compressor (kW)	17.2	13.5
Energy Storages		
Supercapacitor Capacity (Wh)	80/100/120/150/200	
Supercapacitor Module No. in Series	160	
Li-ion Battery Capacity (Ah)	6.0/7.5/9.0	
Li-ion Battery Module No. in Series	87	
NiMH Battery Capacity (Ah)	6.0/7.5/9.0	
NiMH Battery Module (11 cells) No.	24	

§ Without energy storage mass, recalculated based on the size and type of energy storages in the model.

Simulations were performed for mid-size vehicles without energy storage, with supercapacitors directly connected in parallel with the fuel cell, with the fuel cell connected to supercapacitor DC-Link via a DC/DC converter, and with supercapacitors, NiMH or Li-ion batteries coupled with the fuel cell through a DC/DC converter. All the powertrains were simulated in the same vehicle having the road load characteristics shown in Table 3 (column: case 1). A fuel cell stack having 440 cells with an active area of 510 cm^2 was used in the simulations. The fuel cell system employed a twinscrew compressor of 17.2 kW and generated a net output power of 87.6 kW. The total vehicle mass was adjusted to reflect the type and capacity of energy storage and was recalculated based on the specific energy of energy storage units. The rated traction motor power was 75 kW for all cases. An empirical efficiency map of a bi-direction DC/DC converter, indexed by the input/output voltage ratio and the output power, was employed in the model.

The simulation results for fuel cell vehicles with 60sec load leveling control over five FUDS and US05 cycles are summarized in Appendix I. The results show that hybridization with supercapacitors or batteries can improve the fuel economy of the fuel cell vehicles. The increases of the fuel cell system efficiency were small, about 1-3 percentage points for the fuel cell-supercapacitor hybridization with/without power electronics on both FUDS and US06 cycles, and 3-4 percentage points for hybridization with NiMH batteries or Li-ion batteries on both FUDS and US06 cycles. The increases of fuel cell system efficiency for fuel cell hybrids were much smaller than for conventional engine-hybrids for which the average engine efficiency is significantly increased by hybridization (by more than 50%).

It can also be seen that hybridization with supercapacitors can recover more regenerative braking energy than using batteries due to lower internal resistance and high power density of supercapacitors. The higher internal resistance of batteries not only limits the maximum braking power that batteries can absorb, but also introduces significant losses during charging and discharging batteries. Supercapacitors can achieve round-trip efficiency of 94-99% compared to 86-91% for Li-ion batteries and 82-87% for NiMH batteries on the FUDS and US06 cycles. Hence, supercapacitors are the best choice for load level control of fuel cells due to their high round-trip energy efficiency and high power density.

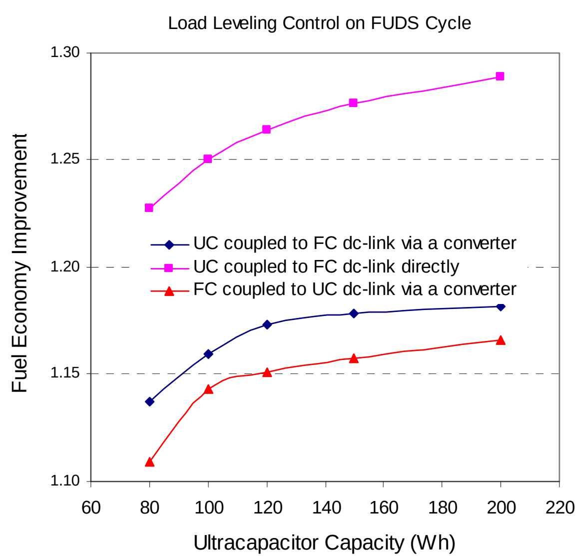

Figure 5 Fuel Economy Improvement of Various Fuel Cell-Supercapacitor Hybrid Vehicles on the FUDS cycle

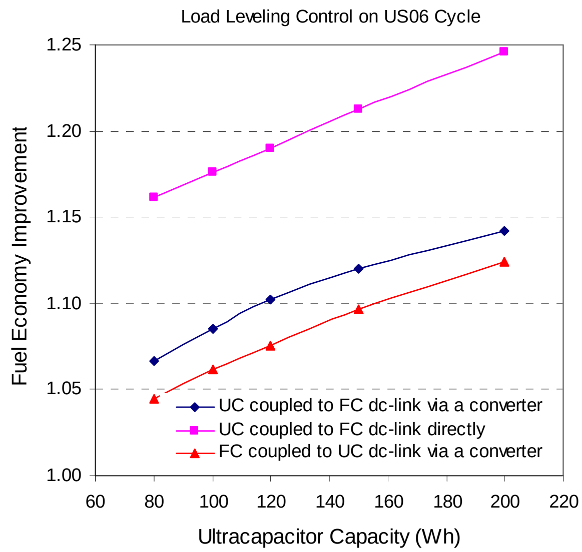

Figure 6 Fuel Economy Improvement of Various Fuel Cell-Supercapacitor Hybrid Vehicles on the US06 cycle

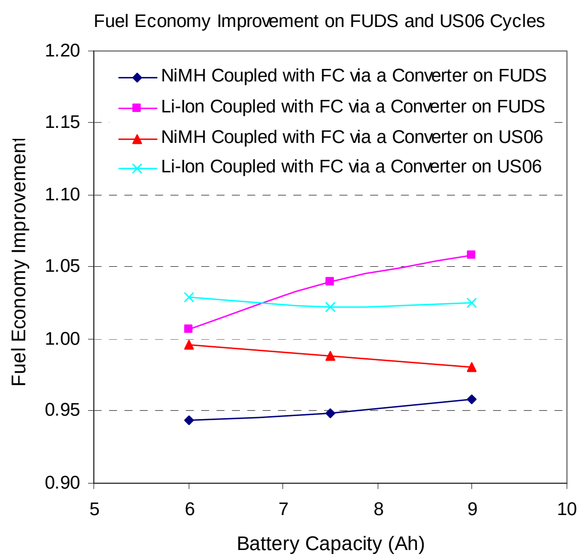

Figure 7 Fuel Economy Improvement of Various Fuel Cell-Battery Hybrid Vehicles on the FUDS and US06 cycles

The improvement in fuel economy of hybrid fuel cell vehicles using supercapacitors and batteries with 60sec load leveling control over the FUDS and US06 cycles are shown in Figure 5-7 compared with fuel cell vehicles without energy storage. The fuel cell-supercapacitor hybrid configurations result in fuel economy improvement of 11-28% on the FUDS cycle and of 4-24% on the US06 cycle, even with small supercapacitors. Fuel cell/Li-ion battery hybrids achieved improvement of fuel economy of less than 6% due to the efficiency losses in the batteries. NiMH batteries are not suitable for fuel cell hybrids with load leveling control because the improvement of fuel cell system efficiency and the recaptured regenerative energy are completely offset by the efficiency losses in the batteries.

Fuel cell vehicles with supercapacitors connected directly in parallel with fuel cell achieved the highest fuel economy improvement due to elimination of losses in the DC/DC converter. Fuel economy improvements for the FUDS and US06 cycles increased with an increase of the supercapacitor Wh capacity because the larger supercapacitor unit can capture more regenerative braking energy. However, this improvement for the FUDS cycle tapers off for fuel cell vehicles having a DC/DC converter when the Wh capacity of supercapacitor reaches 120 Wh. Therefore, sizing the supercapacitor should consider both meeting the transient acceleration power demand and maximizing regenerative braking energy recovery for improving fuel economy.

The simulation results for the current, cathode back pressure and air mass flow rate of the fuel cell stack with/without supercapacitors and power electronics, are given in Figure 8, 9, and 10, respectively, for the US06 driving cycle. The results of fuel cell vehicles having NiMH or Li-ion batteries coupled to the fuel cell dc-link via a DC/DC converter are also plotted for comparison. A 60 second load leveling control was used in fuel cell hybrids with a DC/DC converter. Comparison of the simulated results indicated that the supercapacitors significantly load-leveled the fuel cell operation mitigating the stresses on the fuel cell electrically and mechanically. In addition, load leveling makes downsizing the fuel cell stack feasible. Fuel cell-battery hybrids achieved limited load leveling due to battery power limitations. The profiles of the supercapacitor/battery *SOC* in Figure 10 show that compared to the fuel cell-supercapacitor hybrid vehicles without power electronics, fuel cell vehicles having power electronics can utilize a large fraction of the energy stored in the capacitors. .

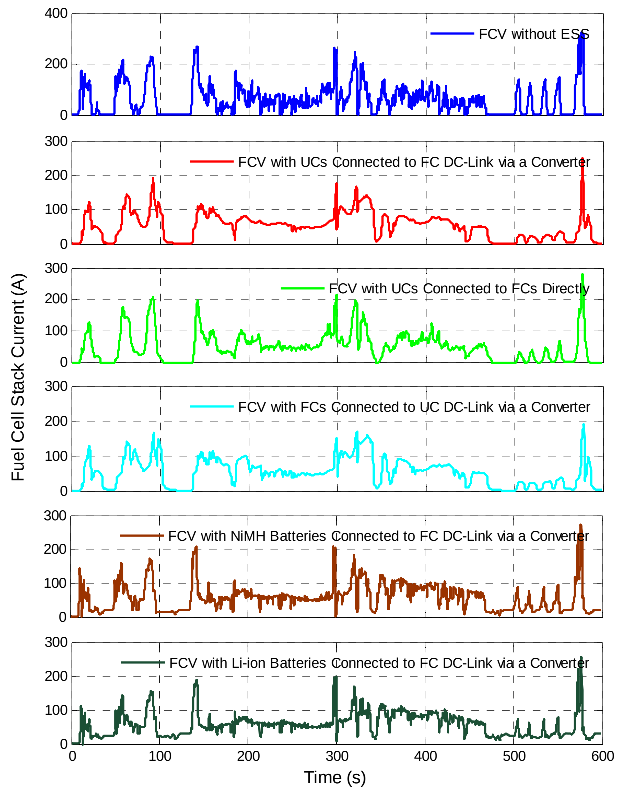

Figure 8 Comparison of the fuel cell stack current of fuel cell vehicles with different powertrain arrangements on the US06 Cycle (60s load leveling)

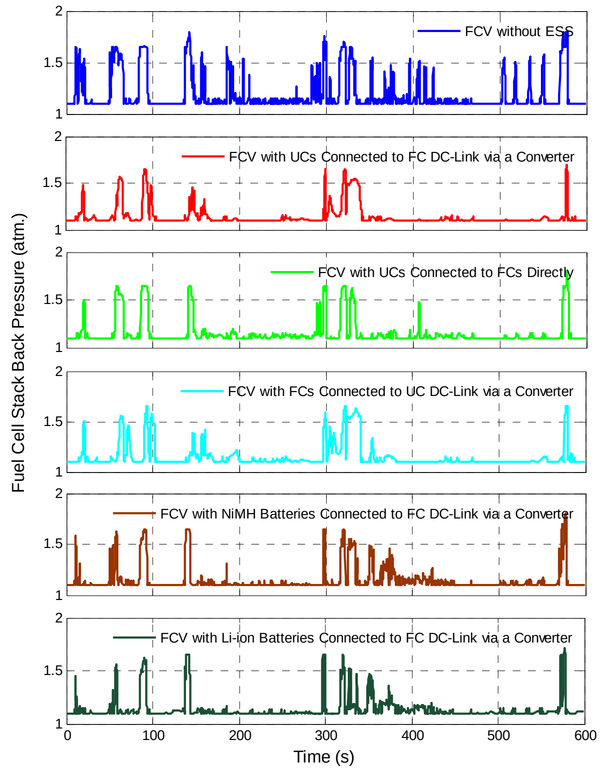

Figure 9 Comparison of the fuel cell cathode back pressure of fuel cell vehicles with different powertrain arrangements on the US06 Cycle (60s load leveling)

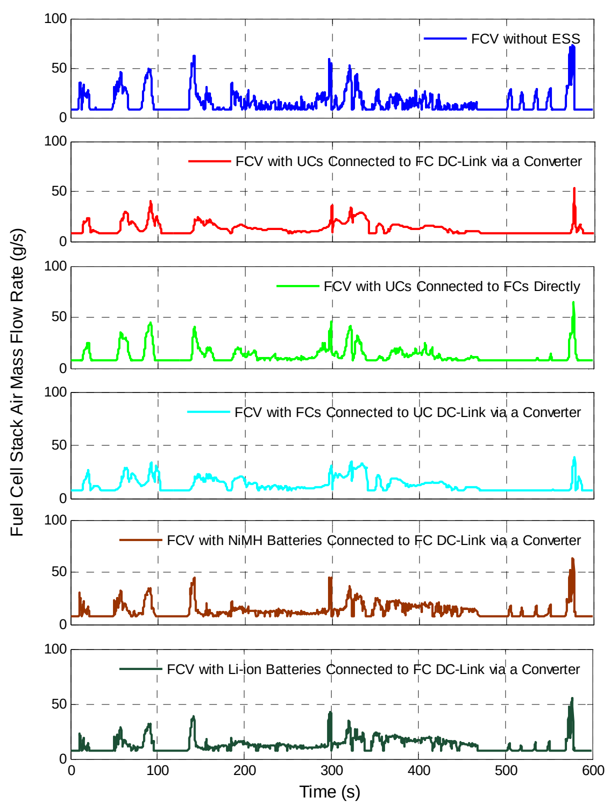

Figure 10 Comparison of the fuel cell air mass flow rate of fuel cell vehicles with different powertrain arrangements on the US06 Cycle (60s load leveling)

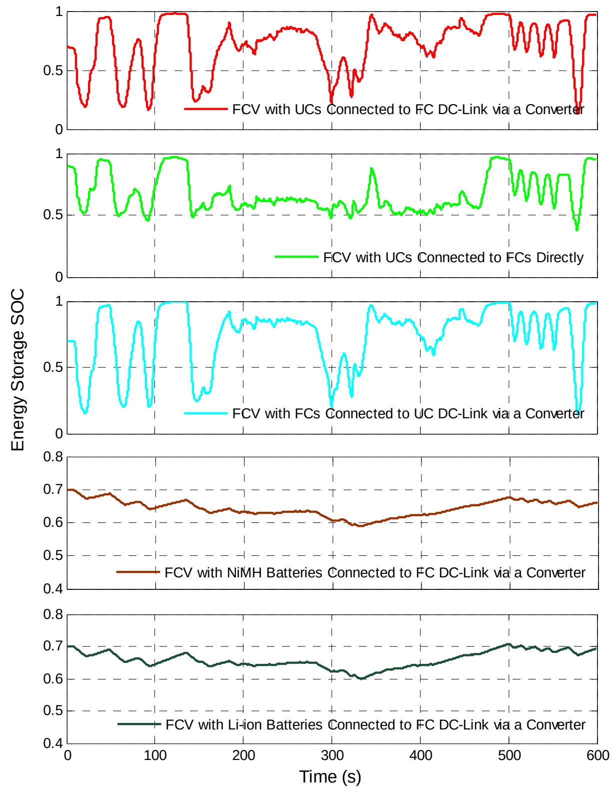

Figure 11 Comparison of the Supercapacitor/battery SOC of fuel cell vehicles with different powertrain arrangements on the US06 Cycle (60s load leveling)

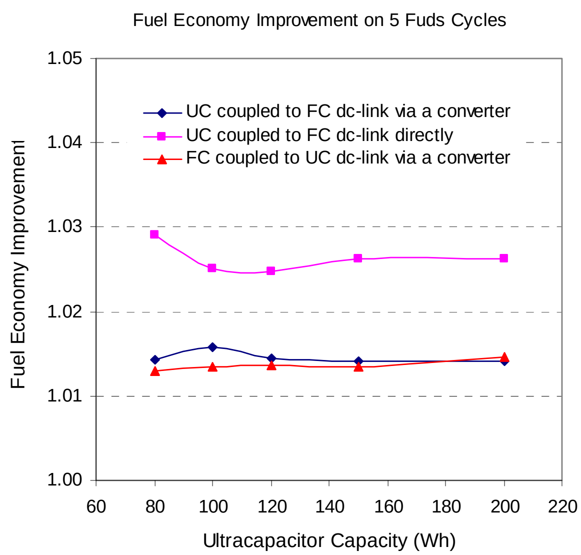

Figure 12 Fuel economy improvement on the FUDS cycle by downsizing the fuel cell system (60s load leveling)

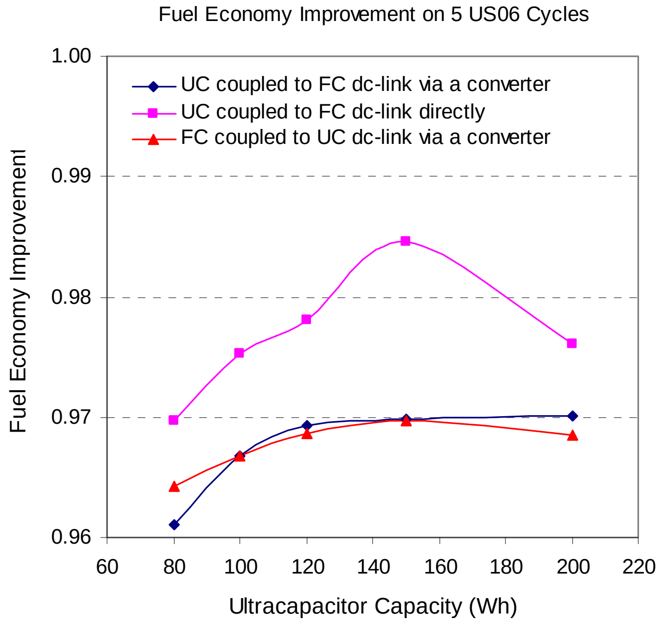

Figure 13 Fuel economy improvement on the US06 cycle by downsizing the fuel cell system (60s load leveling)

The above simulations show that hybridization with supercapacitors/batteries can significantly reduce the fuel cell peak current requirement. This indicated that potential downsizing of the fuel cell system was possible. Downsizing fuel cell will shift the system peak efficiency to lower load region, which can potentially improve the average system efficiency for low power driving cycles, but decrease it over more aggressive driving cycles like the US06. Simulations with a lower power fuel cell were performed for the FUDS and US06 cycles. A fuel cell stack of 440 cells with active area of 340 cm^2 was utilized in the simulation. Simulation parameters are given in Table 3 (case 2). Compared to fuel cell vehicles with a larger fuel cell (case 1), the improvement of fuel economy for the FUDS and US06 cycles by downsizing the fuel cell system is given in Figure 12-13, respectively. The figures show that implementation of downsizing the fuel cell results in an improvement of 2-4% in fuel economy for the FUDS cycle and approximately 3% deterioration for the US06 cycles. Therefore, fuel cell system downsizing from 75 kW to 50 kW in a fuel cell-supercapacitor hybrid does not necessarily improve fuel economy like conventional hybrid vehicles. However, the main reason for downsizing the fuel cell is cost rather than fuel economy.

Vehicles with supercapacitors, NiMH and Li-ion batteries coupled with fuel cells via a DC/DC converter were also simulated using a power assist control strategy. The detailed simulation results for power assist control over 5 FUDS and US06 cycles are given in Appendix II. Figure 14-16 show the fuel economy improvements for hybridization with supercapacitors, NiMH batteries and Li-ion batteries, respectively. Compared to load leveling control, power assist control can significantly improve fuel economy for battery hybrids over the FUDS and US06 cycles due to less power losses in batteries using the power assist strategy. The results indicate that increasing the size of energy storage units slightly benefits fuel economy for both load level and power assist control. Table 4 lists some simulation results for comparison of different powertrain configurations and power splitting strategies. Fuel cell vehicles having supercapacitors coupled with fuel cells via a DC/DC converter with load leveling control is the best approach in term of improving fuel economy and mitigating the stress on the fuel cell.

Power assist control is well suited for the fuel cell-battery hybrids in terms of fuel economy improvement.

Table 4 Comparison of different powertrain configurations and power splitting strategies

Powertrain Configuration	Fuel Economy FUDS/US06	Comments
Supercapacitors Connected to Fuel Cells Directly (120 Wh)	85.9/60.3	Highest fuel economy; Less costly; Moderate reduction in stress on fuel cells
Supercapacitors Coupled with Fuel Cells via a Converter (120 Wh)	79.7/55.8 (Load Leveling, 60sec) 80.1/57.9 (Power Assist)	Suitable power splitting strategy: Load leveling; High fuel economy and lowest stress on fuel cells
Li-ion Batteries Coupled with Fuel Cells via a Converter (7.5 Ah)	70.6/51.8 (Load Leveling, 60sec) 77.0/54.5 (Power Assist)	Suitable power splitting strategy: Power Assist High fuel economy and low stress on fuel cells

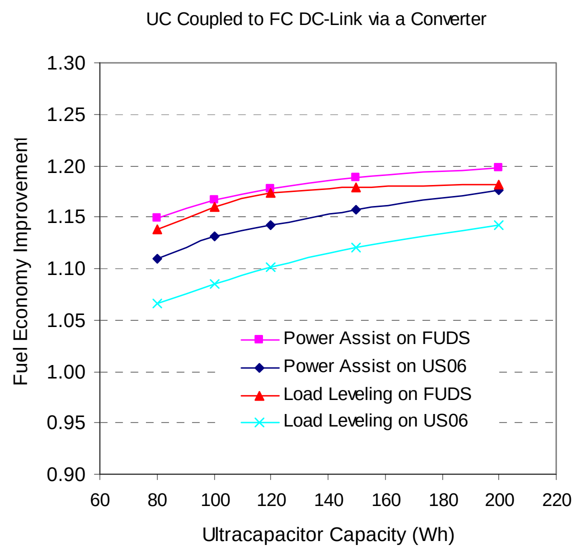

Figure 14 Comparison of fuel cell-supercapacitor battery hybrids with load leveling (60sec) and power assist control over the FUDS and US06 cycles

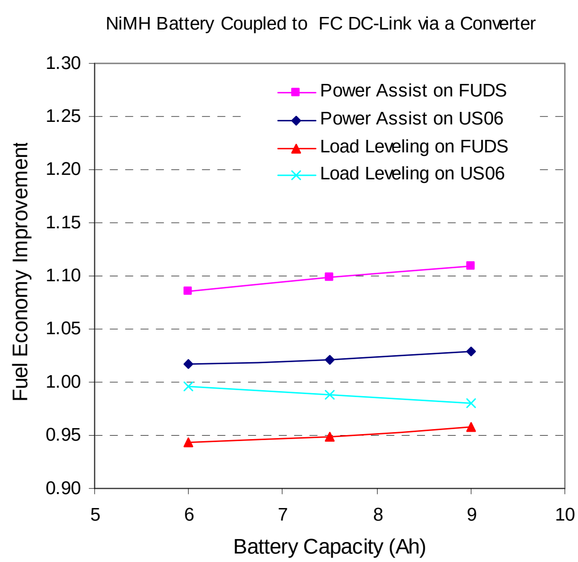

Figure 15 Comparison of fuel cell-NiMH battery hybrids with load leveling (60sec) and power assist control over the FUDS and US06 cycles

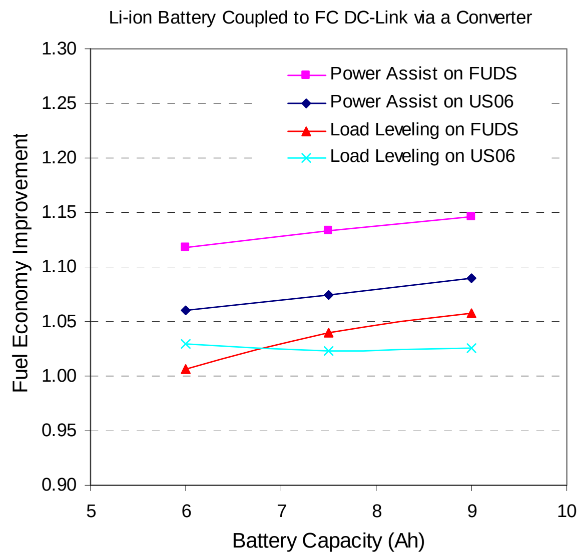

Figure 16 Comparison of fuel cell/Li-ion battery hybrids with load leveling (60sec) and power assist control over the FUDS and US06 cycles

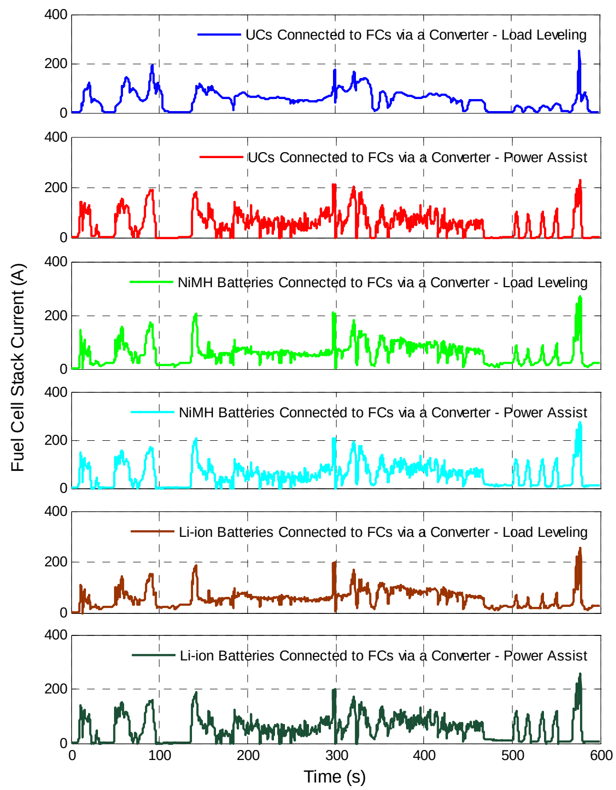

Figure 17 Comparison of fuel cell stack current for fuel cell hybrid vehicles with load leveling (60sec) and power assist control

The profile of the fuel cell stack current in Figure 17 shows that supercapacitor hybridization with load leveling control significantly smoothes fuel cell current. Since a longer averaging time in load leveling control leads to higher fraction of transient power passing through energy storage, this increases losses and lower fuel economy. The fuel cell vehicles having a 120 Wh supercapacitor and 7.5 Ah NiMH and Li-ion batteries coupled to the fuel cell via a DC/DC converter were run with different averaging times. The simulation results for FUDS and US06 cycles are summarized in Appendix III. The effect of the averaging time on fuel economy improvement on the FUDS and US06 cycles are given in Figure 18 and Figure 19, respectively. The simulation shows that increasing the averaging time increases fuel economy for fuel cell-supercapacitor hybrids due to the improvement of fuel cell system efficiency and the increase of captured regenerative energy, and will slightly decreases the fuel economy for fuel cell-battery hybrids. However, the averaging time has little effect on fuel economy when the averaging time is larger than 60 seconds.

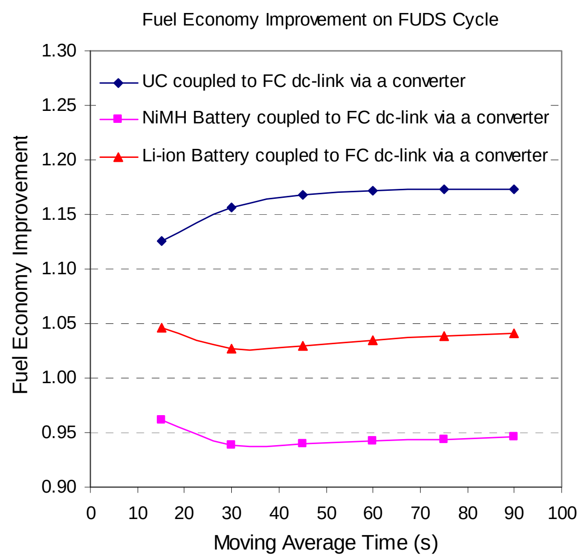

Figure 18 Effect of moving average time on fuel economy improvement over the FUDS cycle

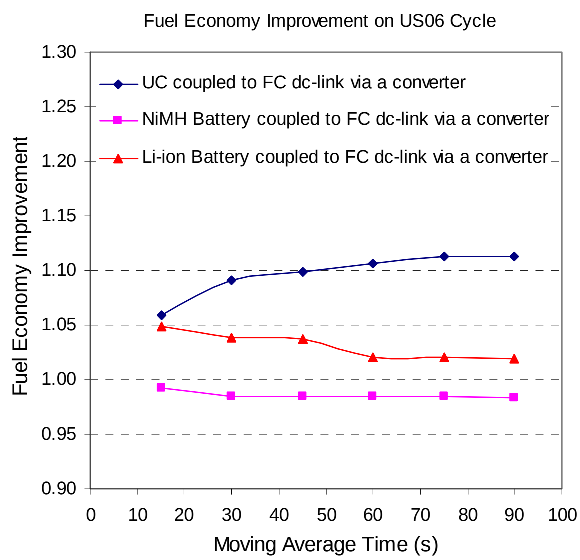

Figure 19 Effect of moving average time on fuel economy over the US06 cycle

5. Summary

Fuel cell hybrid vehicles with different powertrain configurations have been simulated on the FUDS and US06 cycles. Hybridization with supercapacitors can significantly reduce the stress on fuel cells through load leveling control. Compared to fuel cell vehicles without energy storage, fuel cell-supercapacitor hybrid vehicles can achieve a fuel economy increase of up to 28% on the FUDS cycle and up to 24% on the US06 cycle depending on the Wh capacity of the supercapacitor unit. Fuel cell vehicles with supercapacitors directly coupled in parallel with the fuel cell achieved the highest fuel economy improvement due to elimination of losses in the power electronics. Fuel cell vehicles having a DC/DC converter coupling the fuel cell and supercapacitors can utilize a large fraction of the energy stored in the supercapacitors for load-leveling the fuel cell. Power assist control is well suited for the fuel cell-battery hybrids in terms of fuel economy improvement because that mode of control reduces the losses in the DC/DC converter electronics and batteries. For both supercapacitors and batteries, the load leveling control strategy results in a greater mitigation of stress on the fuel cell than the power assist strategy. Fuel cell vehicles with supercapacitors coupled to fuel cells via a DC/DC converter is likely to be the best approach considering mitigating the stress on the fuel cell and achieving high fuel economy for optimal fuel cell system operation.

Acknowledgements

The work presented in this paper was supported by the STEPS program and the PHEV Center of the Institute of Transportation Studies of the University of California, Davis. Please refer to http://www.its.ucdavis.edu for further details about the STEP program, the PHEV Center, sponsors, and previous reports/papers.

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Appendix I

Fuel cell hybrid vehicles with load leveling control (60sec) over five FUDS and US06 cycles (con'd)
Case 1 (cell number: 440; cell active area: 510 cm^2)

Powertrain Configuration		FCVs w/o ESS	FCVs Having Ultracapacitors Connected to Fuel Cell DC-Link via a DC/DC Converter (APowerCap)					FCVs Having Fuel Cells Connected to Ultracapacitor DC-Link via a DC/DC Converter (ApowerCap)				
ESS	Capacity		80 Wh	100 Wh	120 Wh	150 Wh	200 Wh	80 Wh	100 Wh	120 Wh	150 Wh	200 Wh
FUDS: 5 cycles												
Fuel Economy	mpgge	68.0	77.3	78.8	79.7	80.1	80.3	75.4	77.7	78.2	78.7	79.2
Wheel	Regenerative	0.000	-2.693	-2.887	-3.003	-3.063	-3.124	-2.452	-2.771	-2.859	-2.952	-3.041
Energy	Accelerating	7.141	7.168	7.179	7.192	7.211	7.244	7.171	7.177	7.188	7.206	7.240
(kWh)	Mech. Brake	3.267	0.560	0.372	0.263	0.215	0.172	0.804	0.486	0.403	0.322	0.251
DCDC & ESS	Loss (kWh)	0	0.65	0.65	0.64	0.64	0.64	0.72	0.73	0.72	0.72	0.71
Motor	Regenerative	0.000	0.805	0.814	0.817	0.817	0.818	0.801	0.815	0.816	0.816	0.817
Efficiency	Accelerating	0.784	0.770	0.770	0.771	0.771	0.771	0.770	0.770	0.771	0.771	0.771
FCS	Efficiency	0.572	0.583	0.584	0.586	0.586	0.587	0.585	0.586	0.586	0.587	0.588
DCDC	Charge eff		0.941	0.941	0.941	0.941	0.941	1.000	1.000	1.000	1.000	1.000
Converter	Discharge eff		0.949	0.950	0.951	0.952	0.952	0.934	0.929	0.928	0.926	0.925
Efficiency	Round-trip eff		0.893	0.894	0.895	0.896	0.896	0.934	0.929	0.928	0.926	0.925
Energy	Charge eff		0.988	0.990	0.992	0.994	0.995	0.989	0.990	0.992	0.994	0.995
Storage	Discharge eff		0.987	0.989	0.991	0.993	0.995	0.987	0.990	0.991	0.993	0.995
Efficiency	Round-trip eff		0.975	0.980	0.983	0.987	0.990	0.976	0.980	0.984	0.987	0.990
US06: 5 cycles												
Fuel Economy	mpgge	50.7	54.0	55.0	55.8	56.8	57.9	52.9	53.8	54.5	55.6	57.0
Wheel	Regenerative	0.000	-1.685	-1.905	-2.091	-2.281	-2.492	-1.503	-1.690	-1.851	-2.065	-2.352
Energy	Accelerating	11.418	11.443	11.452	11.462	11.474	11.520	11.461	11.471	11.483	11.488	11.529
(kWh)	Mech. Brake	3.462	1.756	1.540	1.357	1.170	0.992	1.958	1.774	1.618	1.401	1.140
DCDC & ESS	Loss (kWh)	0	0.58	0.59	0.59	0.59	0.57	0.74	0.71	0.69	0.66	0.61
Motor	Regenerative	0.000	0.846	0.850	0.857	0.865	0.874	0.857	0.853	0.853	0.859	0.873
Efficiency	Accelerating	0.870	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860	0.860
FCS	Efficiency	0.542	0.558	0.561	0.563	0.566	0.569	0.557	0.560	0.562	0.564	0.568
DCDC	Charge eff		0.957	0.959	0.959	0.959	0.960	1.000	1.000	1.000	1.000	1.000
Converter	Discharge eff		0.958	0.960	0.960	0.961	0.964	0.964	0.965	0.965	0.965	0.965
Efficiency	Round-trip eff		0.917	0.920	0.921	0.921	0.925	0.964	0.965	0.965	0.965	0.965
Energy	Charge eff		0.972	0.977	0.980	0.983	0.987	0.969	0.975	0.979	0.982	0.986
Storage	Discharge eff		0.970	0.975	0.978	0.982	0.986	0.971	0.976	0.979	0.983	0.987
Efficiency	Round-trip eff		0.943	0.952	0.958	0.965	0.973	0.941	0.951	0.958	0.965	0.973

Powertrain Configuration		FCVs with Ultracapacitors Connected to Fuel Cell DC-Link Directly (APowerCap)					FCVs Having NiMH Batteries Connected to Fuel Cell DC-Link via a DC/DC Converter			FCVs Having Li-Ion Batteries Connected to Fuel Cell DC-Link via a DC/DC Converter (ElGNiCo)		
ESS	Capacity	80 Wh	100 Wh	120 Wh	150 Wh	200 Wh	6 Ah	7.5 Ah	9 Ah	6 Ah	7.5 Ah	9 Ah
FUDS: 5 cycles												
Fuel Economy	mpgge	83.4	85.0	85.9	86.7	87.6	64.1	64.4	65.1	68.4	70.6	71.9
Wheel	Regenerative	-2.805	-2.985	-3.096	-3.212	-3.267	-1.149	-1.305	-1.492	-1.689	-2.008	-2.195
Energy	Accelerating	7.107	7.122	7.135	7.156	7.191	7.235	7.282	7.326	7.148	7.161	7.174
(kWh)	Mech. Brake	0.412	0.242	0.138	0.035	0.001	2.127	2.002	1.842	1.545	1.234	1.054
DCDC & ESS	Loss (kWh)	0.06	0.06	0.06	0.05	0.04	1.42	1.39	1.34	1.20	1.16	1.11
Motor	Regenerative	0.807	0.814	0.820	0.824	0.825	0.555	0.589	0.629	0.654	0.706	0.729
Efficiency	Accelerating	0.769	0.770	0.770	0.770	0.770	0.772	0.773	0.773	0.771	0.771	0.771
FCS	Efficiency	0.572	0.574	0.576	0.578	0.582	0.599	0.598	0.598	0.597	0.599	0.599
DCDC	Charge eff	1.000	1.000	1.000	1.000	1.000	0.918	0.925	0.929	0.927	0.934	0.936
Converter	Discharge eff	1.000	1.000	1.000	1.000	1.000	0.950	0.950	0.950	0.949	0.950	0.950
Efficiency	Round-trip eff	1.000	1.000	1.000	1.000	1.000	0.872	0.879	0.883	0.880	0.887	0.889
Energy	Charge eff	0.992	0.993	0.994	0.995	0.996	0.957	0.959	0.963	0.965	0.967	0.971
Storage	Discharge eff	0.991	0.992	0.993	0.994	0.995	0.880	0.896	0.908	0.923	0.933	0.942
Efficiency	Round-trip eff	0.983	0.985	0.987	0.988	0.991	0.842	0.859	0.874	0.891	0.903	0.914
US06: 5 cycles												
Fuel Economy	mpgge	58.9	59.6	60.3	61.4	63.2	50.5	50.1	49.7	52.1	51.8	52.0
Wheel	Regenerative	-1.991	-2.193	-2.363	-2.583	-2.873	-0.894	-0.814	-0.743	-1.113	-0.965	-1.018
Energy	Accelerating	11.362	11.384	11.400	11.421	11.454	11.483	11.533	11.583	11.356	11.376	11.389
(kWh)	Mech. Brake	1.396	1.211	1.051	0.843	0.572	2.539	2.651	2.756	2.241	2.403	2.358
DCDC&ESS	Loss (kWh)	0.14	0.14	0.14	0.13	0.12	0.80	0.90	0.99	0.78	0.84	0.92
Motor	Regenerative	0.847	0.859	0.869	0.880	0.894	0.608	0.595	0.583	0.653	0.617	0.628
Efficiency	Accelerating	0.859	0.859	0.859	0.859	0.859	0.860	0.860	0.861	0.860	0.860	0.860
FCS	Efficiency	0.553	0.555	0.557	0.559	0.562	0.560	0.564	0.567	0.565	0.570	0.573
DCDC	Charge eff	1.000	1.000	1.000	1.000	1.000	0.933	0.945	0.957	0.953	0.966	0.967
Converter	Discharge eff	1.000	1.000	1.000	1.000	1.000	0.963	0.964	0.963	0.963	0.963	0.963
Efficiency	Round-trip eff	1.000	1.000	1.000	1.000	1.000	0.898	0.910	0.921	0.918	0.930	0.931
Energy	Charge eff	0.981	0.984	0.986	0.988	0.990	0.950	0.951	0.951	0.955	0.954	0.956
Storage	Discharge eff	0.981	0.983	0.984	0.986	0.989	0.861	0.864	0.867	0.902	0.906	0.909
Efficiency	Round-trip eff	0.963	0.967	0.970	0.974	0.979	0.818	0.822	0.824	0.861	0.864	0.869

Appendix II

Fuel cell vehicles with power assist control over five FUDS and US06 cycles

Case 1 (cell number: 440; cell active area: 510 cm^2)

Powertrain Configuration		FCVs Having Ultracapacitors Connected to Fuel Cell DC-Link via a DC/DC Converter (APowerCap)					FCVs Having NiMH Batteries Connected to Fuel Cell DC-Link via a DC/DC Converter			FCVs Having Li-Ion Batteries Connected to Fuel Cell DC-Link via a DC/DC Converter (ElGNiCo)		
ESS	Capacity	80 Wh	100 Wh	120 Wh	150 Wh	200 Wh	6 Ah	7.5 Ah	9 Ah	6 Ah	7.5 Ah	9 Ah
FUDS: 5 cycles												
Fuel Economy	mpgge	78.1	79.2	80.1	80.8	81.4	73.8	74.6	75.4	76.0	77.0	77.9
Wheel Energy (kWh)	Regenerative	-2.6853	-2.8684	-3.0014	-3.1205	-3.237	-2.1476	-2.2688	-2.3863	-2.328	-2.4752	-2.6064
	Accelerating	7.1644	7.1752	7.1872	7.2063	7.2387	7.2578	7.297	7.3358	7.1536	7.1664	7.1796
	Mech. Brake	0.5652	0.3878	0.2611	0.1527	0.0546	1.1517	1.0531	0.9579	0.9115	0.7717	0.6482
DCDC & ESS	Loss (kWh)	0.32	0.33	0.34	0.34	0.34	0.27	0.26	0.26	0.26	0.27	0.27
Motor Efficiency	Regenerative	0.8042	0.8117	0.816	0.8198	0.8232	0.7149	0.7331	0.7488	0.7454	0.7644	0.7784
	Accelerating	0.77	0.7702	0.7703	0.7706	0.7711	0.7717	0.7722	0.7726	0.7702	0.7704	0.7705
FCS	Efficiency	0.5677	0.5677	0.5677	0.568	0.5685	0.5725	0.5725	0.5725	0.5725	0.5725	0.5725
DCDC Converter Efficiency	Charge eff	0.9452	0.9476	0.9499	0.9522	0.9551	0.8985	0.9116	0.9206	0.9179	0.9281	0.9355
	Discharge eff	0.869	0.8742	0.8768	0.8787	0.8802	0.8663	0.8666	0.867	0.8674	0.8671	0.8666
	Round-trip eff	0.8213	0.8285	0.8329	0.8367	0.8407	0.7783	0.79	0.7982	0.7962	0.8048	0.8107
Energy Storage Efficiency	Charge eff	0.9909	0.9925	0.9936	0.9948	0.9959	0.9644	0.9665	0.968	0.9721	0.9739	0.9753
	Discharge eff	0.9966	0.9971	0.9975	0.998	0.9985	0.9611	0.9688	0.9739	0.9788	0.9834	0.9863
	Round-trip eff	0.9875	0.9896	0.9912	0.9927	0.9944	0.9269	0.9363	0.9428	0.9515	0.9578	0.9619
US06: 5 cycles												
Fuel Economy	mpgge	56.2	57.3	57.9	58.7	59.6	51.6	51.7	52.1	53.7	54.5	55.2
Wheel Energy (kWh)	Regenerative	-2.1201	-2.3563	-2.5085	-2.6893	-2.9351	-1.0773	-1.1652	-1.3365	-1.4918	-1.6862	-1.8851
	Accelerating	11.4419	11.4547	11.4661	11.4847	11.5163	11.4898	11.5395	11.5818	11.3742	11.3962	11.4164
	Mech. Brake	1.3205	1.0915	0.9451	0.7744	0.5461	2.3628	2.3069	2.1598	1.8806	1.7025	1.518
DCDC&ESS	Loss (kWh)	0.28	0.28	0.27	0.27	0.28	0.48	0.47	0.47	0.41	0.40	0.40
Motor Efficiency	Regenerative	0.864	0.8805	0.8859	0.8946	0.9011	0.631	0.6495	0.6753	0.7069	0.74	0.7709
	Accelerating	0.8593	0.8594	0.8594	0.8594	0.8595	0.86	0.8601	0.8602	0.8594	0.8594	0.8595
FCS	Efficiency	0.5505	0.5513	0.5514	0.552	0.5528	0.5554	0.5568	0.5574	0.5566	0.5577	0.5584
DCDC Converter Efficiency	Charge eff	0.947	0.9501	0.9498	0.9528	0.9559	0.9029	0.9115	0.919	0.9198	0.9319	0.9417
	Discharge eff	0.9293	0.9323	0.9355	0.9381	0.9399	0.9355	0.9374	0.9385	0.9374	0.9386	0.9375
	Round-trip eff	0.8801	0.8858	0.8885	0.8938	0.8985	0.8447	0.8544	0.8625	0.8623	0.8747	0.8828
Energy Storage Efficiency	Charge eff	0.9796	0.983	0.9855	0.9882	0.9909	0.9621	0.964	0.9654	0.9657	0.9664	0.9662
	Discharge eff	0.9889	0.9906	0.9916	0.993	0.9946	0.9017	0.9132	0.9222	0.9361	0.9445	0.9533
	Round-trip eff	0.9687	0.9738	0.9773	0.9813	0.9855	0.8675	0.8803	0.8903	0.904	0.9127	0.9211

Appendix III

Fuel cell vehicles with load leveling control over one FUDS and US06 cycles

Case 1 (cell number: 440; cell active area: 510 cm^2)

Powertrain	Configuration	FCVs Having Ultracapacitors Connected to Fuel Cell DC-Link via a DC/DC Converter (APowerCap) (120 Wh)						FCVs Having Fuel Cells Connected to Ultracapacitor DC-Link via a DC/DC Converter (ApowerCap) (120 Wh)					
ESS	Capacity	15s	30s	45s	60s	75s	90s	15s	30s	45s	60s	75s	90s
FUDS: 1 cycle													
Fuel Economy	mpgge	76.5	78.5	79.4	79.6	79.8	79.7	74.4	77.0	78.1	78.4	78.3	78.1
Wheel	Regenerative	-0.5333	-0.576	-0.5938	-0.5973	-0.5978	-0.5947	-0.4451	-0.5225	-0.5637	-0.5763	-0.5747	-0.5637
Energy	Accelerating	1.4379	1.4385	1.4386	1.4386	1.4387	1.4386	1.4374	1.4379	1.4379	1.4378	1.4383	1.4382
(kWh)	Mech. Brake	0.1194	0.0774	0.0596	0.0561	0.0557	0.0588	0.2071	0.1303	0.0891	0.0764	0.0783	0.0893
DCDC & ESS	Loss (kWh)	0.12	0.13	0.13	0.13	0.13	0.13	0.11	0.12	0.14	0.14	0.15	0.14
Motor	Regenerative	0.7973	0.8098	0.8153	0.8165	0.8169	0.8169	0.7785	0.8018	0.8138	0.8166	0.8176	0.8172
Efficiency	Accelerating	0.7705	0.7705	0.7705	0.7705	0.7705	0.7705	0.7707	0.7706	0.7705	0.7705	0.7705	0.7705
FCS	Efficiency	0.5778	0.5829	0.5848	0.5856	0.5863	0.5868	0.5804	0.5854	0.5861	0.5865	0.5874	0.5872
DCDC	Charge eff	0.9466	0.9462	0.9435	0.9422	0.9418	0.9418	1	1	1	1	1	1
Converter	Discharge eff	0.94	0.9499	0.9505	0.9502	0.9501	0.9505	0.9481	0.9405	0.9319	0.9287	0.9272	0.9289
Efficiency	Round-trip eff	0.8898	0.8988	0.8967	0.8953	0.8948	0.8951	0.9481	0.9405	0.9319	0.9287	0.9272	0.9289
Energy	Charge eff	0.9929	0.992	0.9917	0.9919	0.992	0.9921	0.9933	0.9928	0.9919	0.9919	0.9917	0.9923
Storage	Discharge eff	0.9925	0.9911	0.9909	0.991	0.9908	0.9908	0.9924	0.9912	0.991	0.9911	0.9909	0.9909
Efficiency	Round-trip eff	0.9854	0.9832	0.9826	0.983	0.9828	0.983	0.9858	0.9841	0.9829	0.9831	0.9827	0.9833
US06: 1 cycle													
Fuel Economy	mpgge	53.6	55.3	55.7	56.1	56.4	56.4	52.3	54.2	54.5	54.9	55.3	55.4
Wheel	Regenerative	-0.3617	-0.4103	-0.4221	-0.4341	-0.4461	-0.4472	-0.3035	-0.3705	-0.3772	-0.3941	-0.411	-0.4148
Energy	Accelerating	2.2931	2.2926	2.2924	2.2923	2.2918	2.2909	2.2953	2.2954	2.2952	2.2963	2.297	2.297
(kWh)	Mech. Brake	0.3287	0.2795	0.2675	0.2554	0.243	0.2411	0.3892	0.3222	0.3154	0.2997	0.2835	0.2798
DCDC&ESS	Loss (kWh)	0.13	0.13	0.12	0.12	0.12	0.12	0.14	0.14	0.14	0.14	0.14	0.14
Motor	Regenerative	0.8302	0.8558	0.8573	0.8616	0.8661	0.867	0.8359	0.852	0.859	0.8612	0.8664	0.8724
Efficiency	Accelerating	0.8594	0.8595	0.8595	0.8595	0.8595	0.8595	0.8598	0.8599	0.8599	0.86	0.86	0.8599
FCS	Efficiency	0.5542	0.5604	0.5619	0.563	0.5634	0.563	0.5511	0.5591	0.5607	0.5618	0.5627	0.5623
DCDC	Charge eff	0.9566	0.9591	0.9594	0.9591	0.9586	0.9585	1	1	1	1	1	1
Converter	Discharge eff	0.9582	0.9592	0.9602	0.9591	0.9597	0.96	0.9675	0.9647	0.9646	0.9646	0.9646	0.9645
Efficiency	Round-trip eff	0.9167	0.92	0.9212	0.9199	0.92	0.9201	0.9675	0.9647	0.9646	0.9646	0.9646	0.9645
Energy	Charge eff	0.9782	0.9793	0.9795	0.9794	0.9797	0.9796	0.9745	0.9783	0.978	0.9781	0.9783	0.9776
Storage	Discharge eff	0.9787	0.9771	0.9772	0.9776	0.9771	0.9776	0.9791	0.978	0.9781	0.9784	0.9779	0.9783
Efficiency	Round-trip eff	0.9573	0.9569	0.9571	0.9574	0.9572	0.9577	0.9542	0.9568	0.9566	0.957	0.9567	0.9564

Powertrain Configuration		FCVs Having NiMH Batteries (7.5 Ah) Connected to Fuel Cell DC-Link via a DC/DC Converter						FCVs Having Li-Ion Batteries (7.5 Ah) Connected to Fuel Cell DC-Link via a DC/DC Converter (ElGNiCo)					
ESS	Capacity	15s	30s	45s	60s	75s	90s	15s	30s	45s	60s	75s	90s
FUDS: 1 cycle													
Fuel Economy	mpgge	65.3	63.7	63.9	64.1	64.1	64.3	71.1	69.8	70.0	70.3	70.5	70.8
Wheel	Regenerative	-0.3249	-0.2688	-0.2712	-0.2751	-0.2763	-0.2824	-0.4192	-0.3757	-0.3787	-0.3859	-0.3926	-0.3963
Energy	Accelerating	1.4566	1.4562	1.457	1.4571	1.4571	1.4572	1.4322	1.4322	1.4325	1.4325	1.4324	1.4326
(kWh)	Mech. Brake	0.3364	0.3921	0.3907	0.3868	0.3856	0.3795	0.2288	0.2723	0.2697	0.2625	0.2557	0.2521
DCDC & ESS	Loss (kWh)	0.23	0.27	0.28	0.28	0.28	0.28	0.19	0.22	0.23	0.23	0.23	0.23
Motor	Regenerative	0.6537	0.5939	0.5917	0.5999	0.6007	0.6063	0.7203	0.6864	0.6885	0.6956	0.7009	0.7045
Efficiency	Accelerating	0.7726	0.7725	0.7725	0.7725	0.7724	0.7725	0.7706	0.7706	0.7706	0.7706	0.7706	0.7706
FCS	Efficiency	0.5867	0.5938	0.5967	0.5981	0.599	0.5996	0.5867	0.5938	0.5966	0.5981	0.599	0.5996
DCDC	Charge eff	0.9302	0.925	0.922	0.9214	0.9215	0.9229	0.944	0.9366	0.9338	0.9332	0.9333	0.9344
Converter	Discharge eff	0.9451	0.9512	0.9501	0.9492	0.9491	0.9492	0.945	0.9512	0.95	0.9491	0.9491	0.9491
Efficiency	Round-trip eff	0.8791	0.8799	0.876	0.8746	0.8746	0.876	0.8921	0.8909	0.8871	0.8858	0.8857	0.8868
Energy	Charge eff	0.9575	0.9593	0.961	0.9611	0.9612	0.9606	0.965	0.9672	0.968	0.968	0.9678	0.9674
Storage	Discharge eff	0.901	0.8922	0.8943	0.8954	0.8949	0.8962	0.9382	0.931	0.9318	0.9329	0.9326	0.9335
Efficiency	Round-trip eff	0.8628	0.8559	0.8595	0.8606	0.8601	0.8609	0.9053	0.9004	0.902	0.903	0.9026	0.903
US06: 1 cycle													
Fuel Economy	mpgge	50.3	49.9	49.9	49.9	49.9	49.8	53.2	52.6	52.6	51.7	51.7	51.7
Wheel	Regenerative	-0.1846	-0.1641	-0.1622	-0.1622	-0.1626	-0.1632	-0.2448	-0.2024	-0.1992	-0.1926	-0.1951	-0.1975
Energy	Accelerating	2.3059	2.3064	2.3065	2.3065	2.3066	2.3064	2.2742	2.2748	2.2748	2.2751	2.2755	2.2752
(kWh)	Mech. Brake	0.5079	0.5289	0.5309	0.5309	0.5305	0.5298	0.4279	0.4707	0.4741	0.4809	0.4789	0.4762
DCDC&ESS	Loss (kWh)	0.17	0.18	0.19	0.19	0.19	0.19	0.15	0.17	0.17	0.17	0.17	0.17
Motor	Regenerative	0.6335	0.5956	0.5945	0.5947	0.5945	0.5936	0.7014	0.6323	0.6283	0.6155	0.618	0.6225
Efficiency	Accelerating	0.8604	0.8604	0.8604	0.8604	0.8604	0.8604	0.8598	0.8598	0.8597	0.8597	0.8597	0.8598
FCS	Efficiency	0.563	0.5632	0.5642	0.564	0.5639	0.5636	0.5648	0.57	0.5718	0.5685	0.5682	0.5677
DCDC	Charge eff	0.9458	0.9453	0.9468	0.9463	0.9457	0.9461	0.9642	0.9659	0.9666	0.9655	0.9646	0.9645
Converter	Discharge eff	0.9593	0.9621	0.9628	0.9632	0.964	0.9644	0.9588	0.9617	0.9628	0.9626	0.9633	0.9637
Efficiency	Round-trip eff	0.9073	0.9095	0.9116	0.9115	0.9117	0.9124	0.9246	0.9289	0.9307	0.9294	0.9292	0.9294
Energy	Charge eff	0.9497	0.9501	0.9496	0.9498	0.95	0.9499	0.9547	0.9531	0.9534	0.955	0.9554	0.9553
Storage	Discharge eff	0.8755	0.8656	0.8646	0.8639	0.8626	0.8624	0.9126	0.9085	0.9078	0.9041	0.9029	0.9029
Efficiency	Round-trip eff	0.8315	0.8224	0.821	0.8205	0.8196	0.8191	0.8713	0.8659	0.8655	0.8634	0.8626	0.8625