01 Sep 2008

Parametric Study of Alternative EV1 Powertrains

Adam Saplin

Andrew Meintz

Mehdi Ferdowsi
Missouri University of Science and Technology, ferdowsi@mst.edu

Recommended Citation

A. Saplin et al., "Parametric Study of Alternative EV1 Powertrains," *Proceedings of the IEEE Vehicle Power and Propulsion Conference (2008, Harbin, China)*, Institute of Electrical and Electronics Engineers (IEEE), Sep 2008.
The definitive version is available at https://doi.org/10.1109/VPPC.2008.4677503

IEEE Vehicle Power and Propulsion Conference (VPPC), September 3-5, 2008, Harbin, China

Parametric Study of Alternative EV1 Powertrains

Adam Saplin, Andrew Meintz, and Mehdi Ferdowsi
Power Electronics and Motor Drives Laboratory
Missouri University of Science and Technology, Rolla, MO, USA
Email: adam.saplin@gmail.com, almdkc@mst.edu, and ferdowsi@mst.edu

***Abstract*—The General Motors (GM) EV1 is an electric vehicle originally powered by either a PbA or NiMh battery pack. This paper examines the possibility of alternative powertrain configurations. These alternatives include an ultracapacitor (UC) storage system, fuel cell system with UC storage, and a fuel cell system with a NiMh battery pack. The configurations were simulated using ADVISOR. Parametric tests were performed by varying the size of the energy storage systems. The study of these combinations is followed by an examination of the current art of the hybrid energy storage topologies used to combine battery and ultracapacitor storage. These topologies include passive parallel, active parallel, cascade parallel, and multi-input bi-directional converter.**

***Keywords*—Battery; electric vehicles, hybrid energy storage topologies; ADVISOR**

I. INTRODUCTION

The General Motors (GM) EV1 is an all-electric vehicle that operates with a charge depleting control strategy. The energy storage of this vehicle is composed of a full battery system originally of lead acid batteries and later with NiMH batteries. This vehicle has been chosen as a framework to compare differing configurations of energy storage in all electric and fuel cell vehicles. This paper reports on the simulations of several EV1 powertrains in section I. Efficiency in miles per gallon equivalent, acceleration, and gradeability; are the main features that are discussed. Hybrid energy storage systems are presented in Section III. Section IV draws conclusions and presents an overall evaluation of how energy storage relates to performance.

II. POWERTRAIN SIMULATIONS

The GM EV1 has been simulated using ADVISOR with the normal charge depleting operation for the standard NiMH battery pack and a completely ultracapacitor design. Further simulation has been performed for a hydrogen fuel cell design with all battery and all ultracapacitor energy storage unit (ESU) sizes. The performance of the EV1 under these varying conditions has been summarized in Table I which is at the end of paper. Note that configuration 1 in table 1 is the standard configuration of the GM EV1 with NiMH batteries.

The connection topology for the multiple energy source simulations is a simple parallel connection. This turns out to be a very crucial design characteristic that is further explored in section II; however, different topologies were not simulated in this paper. The control strategy used in these combination configurations, excluding the battery only and ultracapacitor only design, is a rule-based charge sustaining method. The set points on the energy storage charge and discharge have not been changed between configurations to produce similarity.

A. Charge Depleteing Ultracapacitor Configuration

A parametric test to determine the optimum number of UC's to use; a plot of ten data points from 200 UC's to 600 UC's versus the mile per gallon gasoline equivalent (MPGGE) for the tested configurations suggests that 334 as a more efficient number of UC's to use in the EV1 (see Fig. 1). The EV1 simulation was run using 334 UC's and the results are summarized in Table I, configuration 2. Fig. 2 shows the performance of the UC powered EV1. Note that it was unable to finish a single 7.4 mile UDSS drive cycle after discharging the UCs at5.9 miles. This was not an unexpected result since ultracapacitors are high power storage devices.

B. Fuel Cell and Battery Configuration

The EV1 model was then modified to use a fuel cell and batteries. The ADVISOR auto-size function determined the size of FC and battery pack to start with. It also reduced the motor size to 79 kW, scaled from the

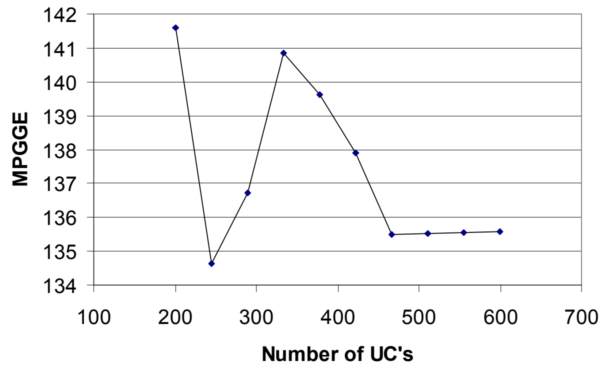

Figure 1. Parametric Test of UC's

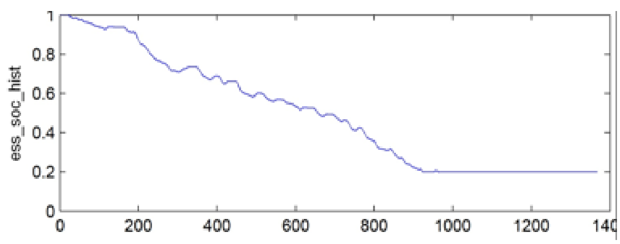

Figure 2. UC State of Charge during UDSS drive cycle

978-1-4244-1849-7/08/$25.00©2008 IEEE.

EV1 motor specifications. The first simulation used a 75 kW FC and 25 EV1 NiMh batteries. Table I, configuration 3 summarizes the results. The fuel cell size was reduced to 50kW for the next test, and the results are listed under configuration 4. Next, the battery pack was reduced to 10 batteries. The results of this simulation are in configuration 5. The auto-size function was used again, this time holding the motor size constant at 105kW. The resulting configuration used a 32kW FC and 17 batteries. Configuration 6 of Table I summarizes the results. Next, a parametric study of the number of batteries for fuel cell sizes 38kW, 50kW, and 75kW was done. Fig. 3 shows the MPGGE for the configurations. Fig. 4 shows the 0 mph to 60 mph acceleration time, and Fig. 5 shows the maximum gradeability at 55 mph.

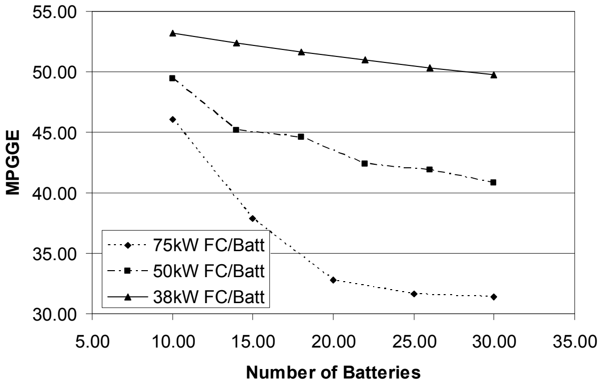

Figure 3. Parametric Test of MPGGE by number of batteries

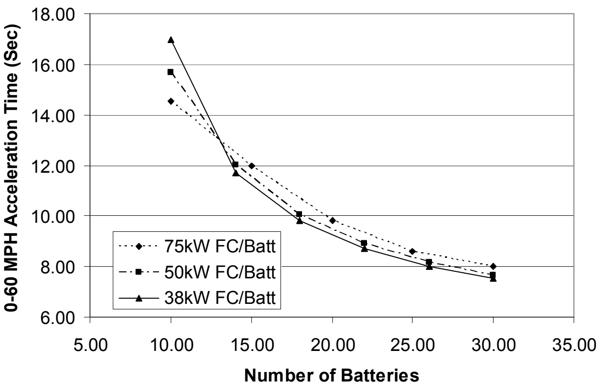

Figure 4. Parametric study of 0-60 MPH acceleration by number of batteries

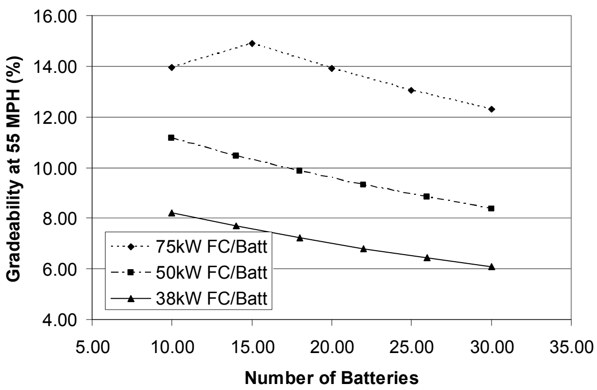

Figure 5. Parametric study of gradeability by number batteries

C. *Fuel Cell and Ultracapacitors*

The auto-size function was used to determine a reasonable starting point. The first configuration used a 38kW FC and 265 UCs. The results of this simulation are summarized in Table I, configuration 7. To further optimize the configuration, a parametric study varying the number of batteries for a 38kW FC was performed. Fig. 6 shows the MPGGE variation, Fig. 7 shows the 0 to 60 acceleration time variations, and Fig. 8 shows the variation in maximum gradeability at 55 mph. The parametric studies showed that 180 UCs made a good compromise between MPGGE, acceleration, and gradeability. A simulation using 180 UCs with a 38kW FC was run to check the performance of this configuration. The results of this test are included in Table I as Configuration 8.

To attempt to further optimize the vehicle, the powertrain control variables were adjusted. First, the high and low SOC boundaries were changed to 0.9 and 0.2, respectively. The results are shown in Table I, configuration 9. The SOC variables were reset to the default values and fc_init_state was changed. This meant that the fuel cell began the simulation on, instead of off. The UC SOC jumped to 1 quickly and maintained 1 through the drive cycle. Next, fc_init_state was changed back and a parametric study of cs_charge_pwr was performed. Fig. 9 shows the effect on the MPGGE. T0he acceleration and gradeability remained constant over the range.

All of the powertrain variables were returned to the

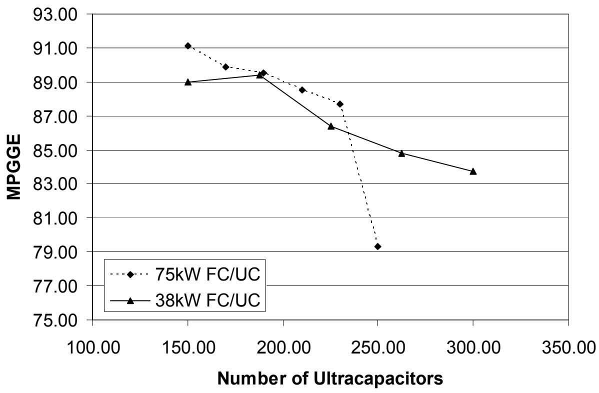

Figure 6. Parametric study of MPGGE by number of UCs

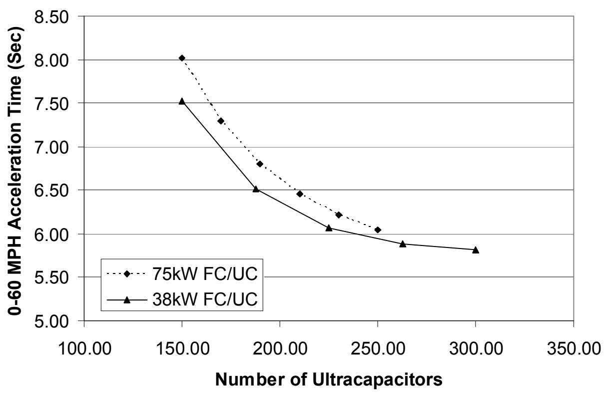

Figure 7. Parametric study of 0-60 MPH acceleration time by number of UCs

default values. The FC power was changed to 75kW and the number of UCs remained at 180. Configuration 10 of Table I shows the results of this simulation. The FC power was further increased to 100kW and the results are shown in configuration 11.

Another parametric study of the number of UCs was performed, this time using a 75kW FC. Fig. 6 shows the MPGGE variation, Fig. 7 shows the 0 to 60 acceleration time variations, and Fig. 8 shows the variation in maximum gradeability at 55 mph. The final vehicles simulated were vehicles included in ADVISOR. The model for the Honda FCX was used to form a comparison with the EV1 FC/UC configuration. The FCX uses a 78kW FC and 150 UCs to power a 61kW motor. The FCX was heavier than the EV1, at 1820 kg. Its performance is shown in Table I under configuration 12. FC_full_compact_r1 was tested on the UDSS drive cycle to form a comparison with the EV1 FC/battery configuration. It is a compact 1500 kg vehicle with lithium batteries and a 70kW FC. Configuration 13 of Table I summarizes its performance. In order to further compare the efficiency of the FC/UC configuration with the original EV1, longer tests were performed using the UDSS and US06_HWY driving cycles. All long drive cycle tests were done with the 75kW FC and 180 UCs. Its performance is shown in Table I under configuration 12.

FC_full_compact_r1 was tested on the UDSS drive cycle to form a comparison with the EV1 FC/battery configuration. It is a compact 1500 kg vehicle with lithium batteries and a 70kW FC. Configuration 13 of Table I summarizes its performance. In order to further

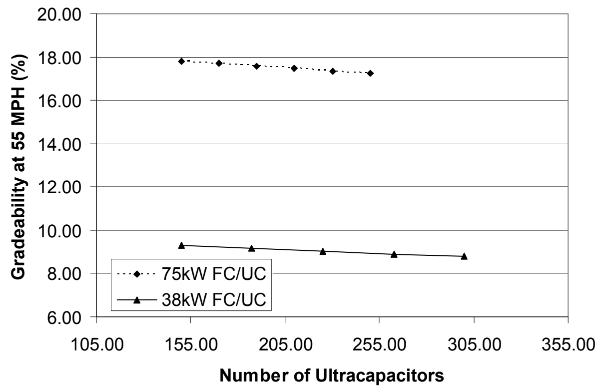

Figure 8. Parametric study of gradeability by number of batteries

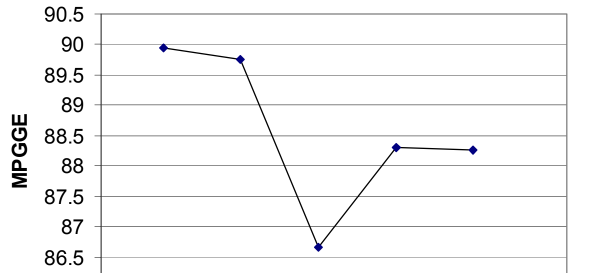

Figure 9. Parametric study of MPGGE by CS charge power

compare the efficiency of the FC/UC configuration with the original EV1, longer tests were performed using the UDSS and US06_HWY driving cycles. All long drive cycle tests were done with the 75kW FC and 180 UCs. Table II shows the drive cycles tested and the respective results.

III. HYBRID ENERGY STORAGE SYSTEMS

The energy storage systems of hybrid electric vehicles are ideally required to provide both high energy and power densities. However, this is difficult because batteries used to supply higher power must sacrifice energy capacity and battery life to provide energy at higher rates. To meet these requirements with pure battery systems more cells are needed to reduce the power load and provide more energy. These added batteries result in higher weight, volume, and cost. A possible compromise is to add ultracapacitors which are characterized by high power density but low energy density to high energy density batteries. The vehicle should benefit from increased fuel economy, acceleration, gradeability, maximum speed, and emissions over a battery only HEVs. The combination can be shown to reduce current flow from the batteries which would improve their life [3].

When designing a hybrid energy system the ratio of batteries to ultracapacitors is critical to improving the efficiency of the system. A method for determining the proper balance for use in HEVs and EVs has been presented in [7]. The power demands for a vehicle during a given driving cycle are used with the energy requirements to make determination on the proper ratio. It should be noted that for the vehicle selected a hybrid battery and ultracapacitor system was optimized to weigh 40% less than the equivalent battery only system and the volume was also reduced by 21%.

Hybrid battery systems may also improve the performance of fuel cell vehicles. An ultracapacitor-fuel cell system can perform better than a battery-fuel cell system because ultracapacitors are more capable of supplying transient power needs. However, ultracapacitors tend to be unable to provide enough energy for the fuel cells at start up. A system of ultracapacitors combined with batteries provided the benefits of the ultracapacitors while having the specific energy necessary for startup [4]. The efficiency of any hybrid power system is highly dependent on the connection topology used. These systems vary in the complexity of their control, cost, and possible efficiency. The following sections outline a review of current topologies.

TABEL II. LONG DISTANCE SIMULATION RESULTS

EV1 Powertrain	Cycle	Number of Cycles	MPGGE	Distance
FC/UC	UDSS	10	90.2	74.5
Original	UDSS	10	130.7	74.5
FC/UC	US06HWY	10	87.9	62.4
Original	US06HWY	10	120.8	62.4
FC/UC	UDSS	15	90.7	111.8
Original	UDSS	15	130.7	111.8

A. Passive Parallel Connection

The passive parallel topology is the simplest implementation in which ultracapacitors are added in parallel with the battery system, see Fig. 10. The simple parallel arrangement provides little benefit since the voltage of the battery pack and ultracapacitor are tied and thus the current drawn from each is proportional [9]. This topology has been shown to provide nearly 3 times more power for a 10 second pulse; however this improvement is strongly tied to the ultracapacitor and battery characteristics [1].

B. Active Parallel Connection

The active parallel topology, as seen in Fig. 11, uses a buck-boost conversion to either inject power into the battery bus (motor) or to remove it by charging the ultracapacitors. This topology puts the motor drive on the variable battery bus which would require the motor drive and its control to be designed in such away that it could operate under the voltage swing imposed by the batteries. This topology is advantageous because it allows for the charge of the ultracapacitor to be controlled and results in only the efficiency loss of one DC/DC conversion; however it complicates the motor drive.

This topology has been used to combine a lead acid battery pack with an ultracapacitor bank in [5]. This configuration using a heuristic control based on the state of charge improved efficiency by 24.4% and using an optimal neural network improved efficiency by 28.7%. The UC's system kept the battery current under 30 A where the battery only system saw battery currents in excess of 80 A. Matlab Simulink testing of this topology in [6] concluded that the system reduced the average energy consumption by 77% compared to a battery ESU.

C. Cascaded Parallel Connection

The cascaded connection topology, a seen in Fig. 12, is an extension of the active topology. This topology includes an additional DC/DC converter to stabilize the motor voltage. The position of the ultracapacitors has been moved so that the current to the batteries can be better regulated [1]. This position allows for better efficiency when the ultracapacitor is used to regulate transient power demands since only one conversion between the motor and ultracapacitor bank is required.

D. Multi-input Bi-directional DC DC Converter

The multi-input bidirectional topologies, seen in Fig. 13 and 14 respectively, allow for both the battery and the ultracapacitor voltage and currents to be independently controlled. The combination of the two converters into one allows for a reduction in the component weight and implementation cost. The structure of this topology allows for an increase in efficiency and stability over the cascaded parallel topology with the benefits of that topology [1]. In [8] the generic dc-dc converter or this topology is represented with a half bridge converter and modeled using Matlab Simulink. The topology allowed for a reduction in weight by 21% over the battery only design while maintaining the driving characteristics of the full battery design. A comparison of the effectiveness between the passive parallel connection and this one

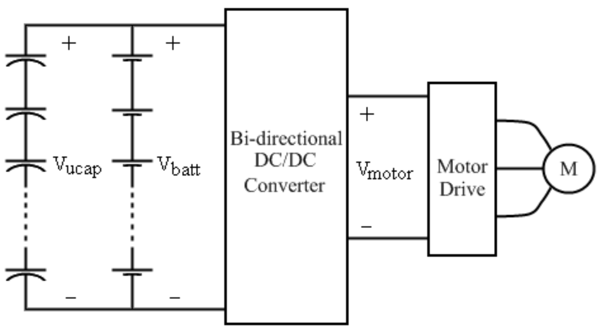

Figure 10. Passive Parallel Topology

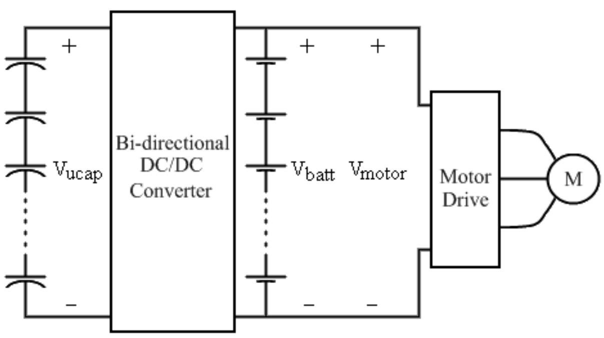

Figure 11. Active Parallel Topology

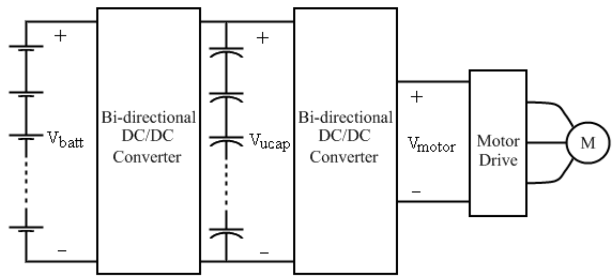

Figure 12. Cascaded Parallel Topology

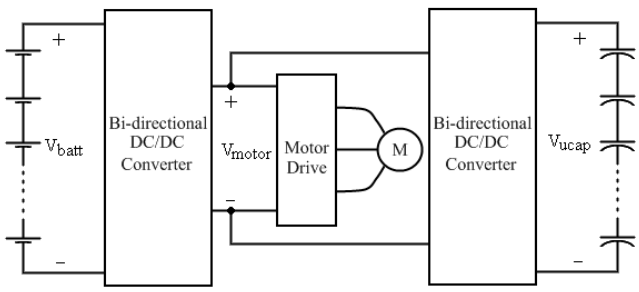

Figure 13. Two Converter Topology

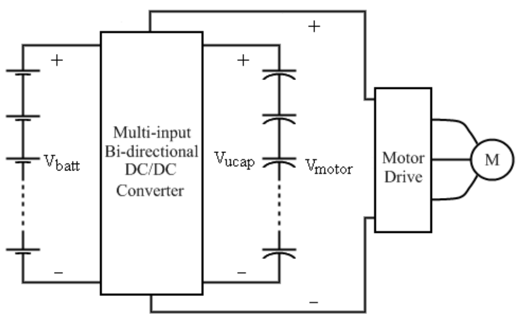

Figure 14. Combined Topology

showed a reduction in mass, volume, and cost of the energy storage unit with a simple active control strategy [9].

IV. CONCLUSION

The simulation results from the variation of EV1 powertrains were not much better than the original design. The addition of the fuel cell actually decreased its MPGE from the original design. Interestingly the combination of high-energy low-power fuel cell with a low-energy high-power device ultracapacitor performed very well and was still fairly efficient.

These results underline the need for a control strategy that has been modified and tuned for the different energy storage systems. More importantly, it should be noted that the parallel connection of the energy sources would make it difficult for any control strategy to adequately control the power flow between the fuel cells, energy storage, and traction motor.

This leads to concept that a hybridized energy storage system as discussed in section III would result in an overall improvement of the system. This hybridized system would allow for a much better management of both the power and energy requirements from the energy storage. The simulation and comparison of the hybridized energy storage systems is left for a future paper.

REFERENCES

[1] S. M. Lukic, S. G. Wirasingha, F. Rodriguez, Jian Cao, and A. Emadi, "Power management of an ultracapacitor/battery hybrid energy storage system in an HEV," Vehicle Power and Propulsion Conference, 2006. VPPC '06. IEEE , vol., no., pp.1-6, 6-8 Sept. 2006

[2] J. A. Hicks, R. Gruich, A. Oldja, D. Myers, T. T. Hartley, R. Veillette, and I. Husain, "Ultracapacitor energy management and controller developments for a series-parallel 2-by-2 hybrid electric vehicle," In Vehicle Power and Propulsion Conf., 2007, Dallas TX

[3] A. C. Baisden and A. Emadi, "ADVISOR-based model of a battery and an ultra-capacitor energy source for hybrid electric vehicles," IEEE Transactions on Vehicular Technology, vol.53, no.1, pp. 199-205, Jan. 2004

[4] W. Gao, "Performance comparison of a fuel cell-battery hybrid powertrain and a fuel cell ultracapacitor hybrid powertrain," Power Electronics in Transportation, pp. 143-150, 21-22 Oct. 2004

[5] M. Ortuzar, J. Moreno, and J. Dixon, "Ultracapacitor-based auxiliary energy system for an electric vehicle: implementation and evaluation," IEEE Transactions on Industrial Electronics, vol.54, no.4, pp.2147-2156, Aug. 2007

[6] N. Jinrui, W. Zhifu, and R. Qinglian, "Simulation and analysis of performance of a pure electric vehicle with a super-capacitor," IEEE Vehicle Power and Propulsion Conference, pp.1-6, 6-8 Sept. 2006

[7] R. M. Schupbach, J. C. Balda, M. Zolot, and B. Kramer, "Design methodology of a combined battery-ultracapacitor energy storage unit for vehicle power management," IEEE Power Electronics Specialist Conference, vol. 1, June 2003, pp. 88-93

[8] R. M. Schupbach and J.C. Balda, "The role of ultracapacitors in an energy storage unit for vehicle power management," IEEE Vehicular Technology Conference, vol.5, Oct. 2003, pp. 3236-3240

[9] D. Hoelscher, A. Skorcz, Y. Gao, and M. Ehsani, "Hybridized electric energy storage systems for hybrid electric vehicles," IEEE Vehicle Power and Propulsion Conference, Sept. 2006, pp.1-6

TABEL I SUMMARY OF SIMULATION RESULTS

Configuration.	Vehicle	FC Pow. (kW)	UCs	Batt.	MPGGE	0-60 mph (s)	40-60 mph (s)	0-85 mph (s)	Max Accel. (ft/s^2)	Max Speed (mph)	Max Grade at 55 mph (%)
1	EV1	X	X	26	130.8	9.1	3.8	18	11.3	89.2	21.80
2	EV1	X	334	X	141	9	3.8	X	11.3	66.4	18.7
3	EV1	75	X	25	31.7	9.4	4.1	17.8	11.5	108.5	12.6
4	EV1	50	X	25	42.2	9	4	16.9	12.1	108.4	8.7
5	EV1	50	X	10	50.1	15.7	7.6	30.5	14.9	109	10.9
6	EV1	32	X	17	44.7	10.4	5.4	22	15.3	108.8	10
7	EV1	38	265	X	85.1	5.9	2	23.3	15.3	101	8.9
8	EV1	38	180	X	89.8	6.7	2.8	35.1	15.3	100.5	9.2
9	EV1	38	180	X	82.9	7.2	3.3	40.2	15.3	100.1	9.2
10	EV1	75	180	X	90	7	3.1	20.9	15.3	108.7	17.6
11	EV1	100	180	X	82.2	7.3	3.4	18.5	15.3	108.5	21.1
12	FCX	78	150	X	46.5	12.7	6.6	28.3	12.3	92.2	X
13	FC	58	X	30	81.1	11.5	5.4	23.5	10.4	97.9	5.2