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Life-Cycle Cost Sensitivity to Battery-Pack Voltage of an HEV

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ABSTRACT*

A detailed component performance, ratings, and cost study was conducted on series and parallel hybrid electric vehicle (HEV) configurations for several battery pack and main electric traction motor voltages while meeting stringent Partnership for a New Generation of Vehicles (PNGV) power delivery requirements. A computer simulation calculated maximum current and voltage for each component as well as power and fuel consumption. These values defined the peak power ratings for each HEV drive system's electric components: batteries, battery cables, boost converter, generator, rectifier, motor, and inverter. To identify a superior configuration or voltage level, life cycle costs were calculated based on the components required to execute simulated drive schedules. These life cycle costs include the initial manufacturing cost of components, fuel cost, and battery replacement cost over the vehicle life.

INTRODUCTION

An HEV has a range of electrical power requirements usually supplied by a battery-pack or a fuel cell stack. The battery-pack is more common and is therefore a key component of today's HEVs. There is currently no standardization of the battery-pack voltage. This affects the material and manufacturing costs of the battery, electric motor, and controller.

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A criterion for standardizing the battery-pack voltage would help the battery and traction motor vendors to optimize their products and lower their initial costs. During the HEV's lifetime, however, other life-cycle costs such as fuel costs and maintenance costs contribute significantly to the overall vehicle ownership cost. One consumer-friendly way to evaluate HEV voltage sensitivity is by comparing estimated life-cycle costs.

This study examines simulation data from Southwest Research Institute's Performance Assessment Toolbox for Hybrid Systems (PATHS) for series and parallel HEV configurations of 8 sets of drive system components operating with dc battery-pack voltages of 50, 163, 250, 325, and 450 volts and with ac electric traction motor voltages of 115, 230, and 320 volts. Life-cycle costs include the initial manufacturing cost of components, lifetime fuel cost, and maintenance cost. In this study, maintenance is limited to battery replacement every 2 years over the 10 year life of the HEV.

HEV SIMULATION

The series hybrid configuration receives its motive force from an electric traction motor, which receives its power only from a battery-pack. Its battery-pack is charged by a generator driven by an Internal Cobpustion (IC) engine, which fires when the state of charge (SOC) falls below 60% and stops when the SOC reaches 80%. The series configuration is shown in Fig. 1.

The parallel hybrid configuration employs a more complex control strategy and may be driven by its electric traction motor and/or its IC engine. The control for the parallel configuration adds its own intelligence such as deciding if the drive system can meet the road load and energizing the IC engine if it cannot. The parallel configuration is shown in Fig. 2.

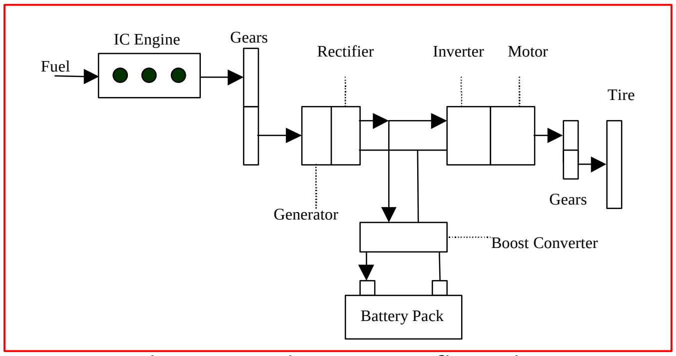

Figure 1. Series HEV Configuration

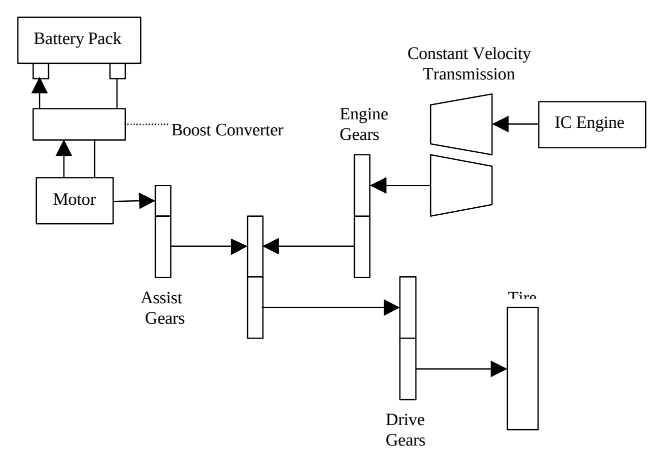

Figure 2. Parallel HEV Configuration

For both the series and parallel configurations studied the prime mover was a generic IC engine whose torque speed curves at full throttle were adjusted to deliver 40 kW.

The number of batteries connected in series in one string depends upon the voltage level selected for the battery-pack. The number of strings was determined by PNGV requirements The battery-pack of a series HEV should provide a peak power of 53 kW for two 23.4 second intervals of full power acceleration and deceleration over a time interval of 3 minutes. Similarly, the battery-pack of a parallel HEV should provide a peak power of 30 kW for two 23.4 second intervals of full power over a time interval of 3 minutes. For example, a 50 V battery-pack must supply 1060 A to provide 53 kW. For a maximum current of 275 A from using a 12 V battery with a maximum current of 275 A, requires a total of (1060/275) 4 parallel strings to supply the series HEV power. The battery size was selected to provide 275 A and was not charged when less current could still meet PNGV requirements. Consequently, all battery packs except those for Case 1 and 4 are oversized.

Lead acid batteries were modeled to be 80% efficient during charge and 100% efficient during discharge and were represented as a constant internal resistance in series with polarization and terminal resistance. Each battery in a string was assumed to have the same open circuit voltage and SOC. The SOC at the end of the run was always brought back to its initial value by running the generator (series HEV) or by backdriving the motor in regenerative mode with the wheels declutched (parallel HEV).

Three motor models were tailored so that their torque-speed curves and efficiency maps were identical to assure that, for a given configuration, the power delivered to the wheels would not depend on motor size. The peak power of the series HEV motors was 75 kW, while the peak power of the parallel HEV motors was 37 kW.

In addition to the drive inverter for the traction motor, several cases used a model of a boost converter to drive a high voltage motor with a low voltage battery-pack. The three components of a boost converter are a single-phase dc-ac high frequency inverter, a high frequency transformer, and a single-phase ac-dc rectifier. The efficiencies of the boost converter as well as the drive inverter (1,2) were calculated as a function of load factor, which is the fraction of full load power for use in the simulation.

PARAMETRIC VOLTAGE STUDY

Eight sets of HEV drive components were devised to study the effects of battery-pack voltage variations on vehicle performance and life-cycle costs. Table 1 summarizes the experiments.

Table 1. Battery-Pack Voltage Variation Study Cases

Case	Battery Pack Volts	Boost Conv.	AC Motor Volts	Series HEV #B/S	Series HEV #S	Parallel HEV #B/S	Parallel HEV #S
1	50	Yes	320	4	4	4	3
2	250	Yes	320	20	1	20	1
3	453	No	320	36	1	36	1
4	50	Yes	115	4	4	4	3
5	163	No	115	13	2	13	1
6	325	No	230	26	1	26	1
7	125	Yes	230	10	2	10	1
8	325	Yes	320	26	1	26	1

#B/S is the number of batteries in series forming a string.
#S is the number of strings forming parallel connections.

Cases 1,2,3, and 8 explore the effect on performance of a high voltage traction motor by replacing batteries connected in series with a boost converter to match the battery pack voltage with that of the dc link to the inverter. In Case 3, 36 batteries eliminated the need for a boost converter, which consumes additional energy, but were heavy enough to reduce the maximum speed and affect other performance parameters. Cases 4 and 5 explored the effect of using a low voltage traction motor with different numbers of batteries and similarly Cases 6 and 7 explored the effect of using an intermediate voltage traction motor.

FUEL CONSUMPTION

A useful way to evaluate the simulated performance is to examine the average energy deposited in each drive component divided by the energy content of the fuel, which gives the kg of fuel lost to inefficiencies in that component. The energy content of the fuel chosen for this study is 43,378 kJ/kg. The energy lost in a drive component is the product of the time interval and the difference between the time averaged power in and out. These values were provided by the simulations.

Tables 2 and 3 compare the fuel lost in the components of a series HEV and a parallel HEV as they traverse the urban route. Tables 4 and 5 compare the fuel lost in the components of a series HEV and a parallel HEV as they traverse the official highway route.

Early examination of simulated power flowing bi-directionally through the boost converter revealed that the efficiency was quite low. Further examination revealed that much of the time the boost converter does not operate near its design limit, which means that its load factor is low explaining its low efficiency. The impact of this on overall performance may be determined by examining the boost converter columns in Tables 2 through 5.

The urban (12 km) and the highway (16.5 km) schedules may be viewed as two energy sinks, each of which consume from the drive wheels a bounding minimum energy when a "properly" configured and controlled HEV traverses it. When the simulations are examined to determine the least fuel delivered to the drive wheels, that value may be considered an estimate of the bounding minimum. Estimates of the minima for the urban and highway schedules are 0.075 (Table 2) and 0.152 kg fuel (Table 4) respectively. The difference between the fuel actually delivered to the drive wheels and the estimate of the bounding minimum is a penalty characteristic of the control system's ability to efficiently move the vehicle through the schedule's accelerations and decelerations. We define this as the control penalty, i.e., the control penalty for the Case 1 parallel HEV (Table 3) traversing the urban schedule is 0.036 kg fuel

Likewise, the fuel consumption of all components except for the drive wheels has a bounding minimum, which may be estimated from data in Tables 2 through 5. We define the difference between these values and their estimated minimum as the configuration penalty. There may be more components to consume energy or excessive energy may be consumed in certain components. Estimates of the minima for the urban and highway schedules are 0.693 and 0.602 kg fuel respectively. The configuration penalty for the Case 1 parallel HEV (Table 3) configuration traversing the urban schedule is 0.186 kg fuel.

The sum of the penalties is a performance indicator for each case within a schedule. The smallest sum implies that a case is operating closest to optimum control and configuration from a fuel consumption perspective.

For the urban schedule, Case 6, which drives an intermediate voltage motor and uses no boost converter, is the clear winner for the series HEV and a good performer for the parallel HEV with total configuration plus control penalty values of 0.002 kg and 0.182 kg respectively. Case 3, which drives the highest voltage

Table 6. Fuel Consumption Penalties
Total kg Urban Fuel = 0.693 + 0.075 = Configuration Penalty + Control Penalty
Total kg Highway Fuel = 0.602 + 0.152 + Configuration Penalty + Control Penalty

Case	Configuration	Control	Sum	Configuration	Control	Sum	Sum of Sums, kg Fuel
Series							
1	.402	0	.402	.665	.001	.666	1.068
2	.370	.002	.372	.593	.003	.596	.968
3	.052	.010	.062	.402	.014	.416	.478
4	.242	0	.242	.716	0	.716	.958
5	.279	.003	.003	.658	.008	.666	.948
6	0	.002	.002	.431	.005	.436	.438
7	.411	.001	.001	.603	.003	.606	1.018
8	.438	.004	.004	.709	.007	.716	1.168
Parallel							
1	.186	.036	.222	.004	.012	.016	.238
2	.669	.033	.702	1.250	.086	1.336	2.038
3	.267	.025	.292	.926	.020	.946	1.238
4	.261	.031	.292	0	.006	.006	.298
5	.271	.031	.302	.554	.032	.586	.888
6	.163	.019	.182	.529	.007	.536	.718
7	.252	.010	.262	.353	.003	.356	.618
8	.569	.023	.592	.695	.011	.706	1.298

The highway data exhibit more scatter. Cases 1 and 4 are clear winners, for the parallel HEV with total penalty values of 0.016 and 0.006 kg respectively, but not for the series HEV, whose values were near 0.7 kg. Both cases use a boost converter but Case 1 drives the highest voltage motor while Case 4 drives the lowest voltage motor. Case 3 was the winner for the series HEV with a total penalty of 0.416 kg.

For equal mileage driven in both urban and highway schedules the overall winner is parallel HEV Case 1.

For the parallel configuration, significant energy comes directly from the IC engine, which is in parallel with the traction motor. Consequently, this energy is not involved in any battery regeneration with its attendant losses. For this reason, the average energy consumed by the battery packs in the series HEV, 0.095 kg fuel, was greater than that for the parallel HEV, 0.036 kg fuel by a factor of 2.6.

HEV COMPONENT RATINGS

The computer simulation calculates the voltage and current in the drive components of eight sets of series HEVs and parallel HEVs as they traverse Federal Urban and Highway Driving Schedules. The initial component costs depend upon the power that must pass through them. Battery-pack and inverter dc bus voltages do not change significantly. Table 7 summarizes the important voltages and maximum currents for the drive components in the series HEV. Each component must survive the maximum current it will conduct, which is extracted from the simulation output. Table 8 summarizes the important voltages and maximum currents for the parallel HEV.

Table 7. Voltage and Maximum Currents in Drive of Series HEV

	Battery-Pack		Boost Conv.		Gen./ Rect.	Inv./Mot./Gen.	
Case	Avg. Volts	Max Amps	Max Amps In	Max Amps Out	Max Amps	DC Link Volts	Max Amps
Urban							
1	53	262	1048	190	39	453	190
2	251	221	221	159	39	453	159
3	447	142	N/A	N/A	38	453	142
4	53	267	1068	118	107	163	273
5	163	197	N/A	N/A	105	163	394
6	323	193	N/A	N/A	52	325	193
7	128	214	428	213	54	325	213
8	323	177	177	159	28	453	159
Highway							
1	57	231	924	106	39	453	73
2	252	174	174	104	39	453	76
3	448	125	N/A	N/A	38	453	125
4	57	217	866	248	107	163	220
5	164	143	N/A	N/A	126	163	285
6	324	161	N/A	N/A	48	325	161
7	129	171	342	144	54	325	104
8	324	141	141	118	39	453	156

Some judgement was required to determine the power rating of each component. The rating was dictated by catalog availability of each component.

The maximum power that must be delivered by the generator is the product of the maximum current through the generator (and rectifier) and the inverter bus voltage.

The voltage rating of the series HEV rectifier depends upon the next higher catalog rating. For example, the next higher rectifier rating above an inverter bus voltage of 453 V is 600 V and the next higher inverter rating above a bus voltage of 325 V is 450 V. The product of the catalog rectifier voltage rating and the maximum current through the rectifier determines its rated peak power.

Because the boost converter and the drive inverter are attached to the inverter bus, which sees voltages from 163 to 453 V, it seemed reasonable to fix the rated voltage of their devices at 600 V. For the boost converter, the current ratings on the low and high side were the next higher catalog current rating for an IGBT. For example, the next higher current rating above 1048 A is 1200 A on the low side and the next higher current rating above 190 A is 200 A on the high side. The maximum current rating of the boost converter is the sum of its maximum high and low side current ratings. The product of the maximum current rating of the boost converter and 600 V is the peak rated power of the boost converter. Similarly, the inverter's peak power is the product of its maximum current and 600V. The peak power of the motors was modeled at 75 kW and 37 kW for the series and parallel HEV respectively.

LIFE-CYCLE COST ESTIMATES

This life-cycle cost analysis considers the initial component costs, the fuel costs, and the primary maintenance cost, which is replacement of the battery pack every two years over the life of the vehicle. The HEV wheels travel 12 km during the Federal Urban Driving Schedule and 16.5 km during the Federal Highway Driving Schedule representing a one-way trip to work. If this drive is made twice a day for 365 days each year over the 10 year life of the vehicle, the total distance is 129,000 miles. Fuel is assumed to be $1 per gallon (0.352 $/kg) for the estimates of lifetime fuel costs.

The initial component manufacturing costs for the series replacement costs, and the total life-cycle costs. The winner appears to be the arrangement for the parallel configuration that uses no boost converter and the smallest motor.

Table 9. Initial HEV Battery-Pack, Generator, and Rectifier Costs

	Battery Cables		Battery-Pack		Generator		Rectifier		
Case	Length, ft	Cost, $	No. Bats.	Cost, $	Peak Power, kW	Cost, $	Rated Current Amps	Peak Power, kW	Cost, $
Series									
1	22	$15	16	$1,282	17.7	$221	50	30.0	$150
2	23	$16	20	$1,603	17.7	$221	50	30.0	$150
3	39	$27	36	$2,885	17.2	$216	50	30.0	$150
4	22	$15	16	$1,282	17.4	$218	150	67.5	$338
5	30	$21	26	$2,083	20.5	$251	150	67.5	$338
6	29	$20	26	$2,083	16.9	$212	75	33.8	$169
7	24	$17	20	$1,603	17.6	$220	75	33.8	$169
8	29	$20	26	$2,083	17.7	$221	50	30.0	$150
Parallel									
1	17	$12	12	$962					
2	23	$16	20	$1,603					
3	39	$27	36	$2,885					
4	17	$12	12	$962					
5	16	$11	13	$1,042					
6	29	$20	26	$2,083					
7	13	$9	10	$801					
8	29	$20	26	$2,083					

Table 10. Initial HEV Boost Converter, Inverter, and Three-Phase Traction Motor and Total Drive System Costs

	Boost Converter				Inverter/ Controller		3-phase Motor		
	600 V IGBT Current Rating, Amps		Rated Input plus Output Power, kW	Cost, $	600 V IGBT Rated Current, Amps	Cost, $	Peak Power, kW	Cost, $	Total Drive System Cost, $
Case	Low Side	High Side							
Series									
1	1200	200	840	$6,624	200	$1,330	75	$828	$10,451
2	300	200	300	$2,520	200	$1,330	75	$828	$6,668
3					150	$1,102	75	$828	$5,208
4	1200	150	810	$6,396	300	$1,786	75	$828	$10,863
5					400	$2,242	75	$828	$5,763
6					200	$1,330	75	$828	$4,643
7	600	300	540	$4,344	300	$1,786	75	$828	$8,966
8	200	200	240	$2,064	200	$1,330	75	$828	$6,697
Parallel									
1	800	75	525	$4,230	75	$760	37	$426	$6,389
2	200	100	180	$1,608	100	$874	37	$426	$4,526
3					100	$874	37	$426	$4,212
4	800	200	600	$4,800	200	$1330	37	$426	$7,529
5					300	$1786	37	$426	$3,264
6					100	$874	37	$426	$3,403
7	400	150	330	$2,748	150	$1102	37	$426	$5,086
8	100	75	105	$1,038	75	$760	37	$426	$4,327

Table 11. Life-cycle Costs to Evaluate Battery-Pack Voltage Sensitivity in HEVs

Case	Initial Drive System Cost, $	Fuel Cost, $	Cost of 4 Battery-Pack Changes, $	Life-Cycle Cost, $
Series				
1	$10,451	$6,654	$5,128	$22,243
2	$6,668	$6,398	$6,412	$19,478
3	$5,208	$5,139	$11,540	$21,887
4	$10,863	$6,373	$5,128	$22,364
5	$5,763	$6,346	$8,332	$20,442
6	$4,643	$5,036	$8,332	$18,011
7	$8,966	$6,527	$6,412	$21,905
8	$6,697	$6,887	$8,332	$21,916
Parallel				
1	$6,389	$4,522	$3,848	$14,759
2	$4,526	$9,148	$6,412	$20,086
3	$4,212	$7,092	$11,540	$22,844
4	$7,529	$4,677	$3,848	$16,054
5	$3,264	$6,193	$4,168	$13,625
6	$3,403	$5,756	$8,332	$17,491
7	$5,086	$5,499	$3,204	$13,789
8	$4,327	$7,246	$8,332	$19,905

CONCLUSIONS

1. Analysis of configuration and control penalties indicated that the series HEV Case 6 driven by the intermediate voltage motor with no boost converter was the best performer on the urban schedule. The parallel HEV Case 4 driven by the lowest voltage motor with the least number of batteries was the best performer on the highway schedule. The parallel HEV Case 1 driven by the highest voltage motor with the least number of batteries was the best overall performer.
2. The battery pack in the series configuration consumes 2.6 times the energy in the parallel configuration. This will have an impact on its lifetime and possibly on battery replacement costs.
3. Drive system costs indicate that the parallel HEV Cases 5 and 6 with low and medium voltage motors are winners by over $800 because they have no boost converter costs.
4. Fuel costs indicate that the parallel HEV Cases 1 and 4 with a boost converter and the least number of batteries capable of meeting PNGV requirements are winners regardless of the motor voltage levels.
5. Life-cycle costs indicate that the overall winner is the parallel HEV operating the lowest voltage motor with only 13 batteries connected in series and no boost converter.

CONTACT

John W. McKeever received the B.S. degree in physics from Case Institute of Technology, Cleveland, Ohio, and the M.S. and Ph.D. degrees in physics from the University of Tennessee, Knoxville. He has 39 years of work experience, serving in both technical and project management capacities. From 1960 to 1985, he developed uranium enrichment processes at the Oak Ridge Gaseous Diffusion Plant. From 1985 to the present, he has been involved in technology transfer and program development as part of the Engineering Technology Division, Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee. He is currently involved with the Power Electronics and Electric Machinery Research Center managing HEV research projects for DOE and collaborative projects to commercialize ORNL's inverter technology. John's e-mail address is ttl@ornl.gov.

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ACRONYMS

AIPM – Automotive Integrated Power Module

ANL – Argonne National Laboratory

HEV – Hybrid Electric Vehicle

IC – Internal Combustion

PATHS – Performance Assessment Toolbox for Hybrid Systems

PNGV – Partnership for a New Generation of Vehicles

PVC – Polyvinyl chloride

SOC – State of Charge

SWRI Southwest Research Institute