Battery Sizing for Plug-in Hybrid Electric Vehicles

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Abstract
Different types of hybrid electric vehicles (HEVs) are manufactured by some auto manufacturers or developed by some researchers to improve fuel economy and reduce emissions. HEVs reduce the vehicular emissions, however, they are not able to deliver zero local emissions. Plug-in hybrid electric vehicles (PHEVs) are new types of HEVs that have more batteries, more powerful traction motors and the plug-in capability such that they can be operated in all-electric mode for a given distance and the batteries can be charged from the power grid. PHEVs have the potential to further increase the fuel economy and reduce the vehicular emissions of HEVs. This paper evaluates the advanced batteries for HEV and PHEV applications and develops equations to calculate the performance requirements and costs of different subsystems in a vehicle.

Keywords
hybrid electric vehicle, pricing

1. INTRODUCTION
The demands for vehicles with substantially higher fuel economy and lower exhaust emissions have motivated the developments of HEVs, fuel cell electric vehicles (FCEVs) and battery electric vehicles (BEVs) for a number of years. Nowadays, HEVs are taking centre stage while electric vehicles are used in some niche area where fewer miles are traveled. The first production HEV available to the public was the Toyota Prius. The Prius sold successfully in Japan since late 1997 and in the United States since 1999. Nowadays, HEVs are manufactured by most auto manufacturers and they are becoming increasingly available [Kaizuka et al., 2005].

HEVs reduce the vehicular emissions, however, they are not able to deliver zero local emissions just like the BEVs do. PHEVs are new types of HEVs that have more batteries, more powerful traction motors and plug-in capability such that they can be operated in all-electric mode for a given distance and the batteries can be charged from the power grid. Figure 1 shows the energy flow in a PHEV.

With the fuel tank, PHEVs overcome the range limitations of the batteries, which is a major problem of BEVs. One key advantage of the PHEV is the ability of the vehicle to travel through congested area, pedestrian zones and typical day's mileage with zero local emission. In addition, the all-electric operations reduce the fuel consumption of the vehicle.

The basic principle of PHEVs design is the coordination of the electric propulsion system and the internal combustion engine (ICE) system. Each PHEV was conceptually designed to meet the performance of the baseline conventional vehicle (CV) in several performance categories, including acceleration performance, top speed, gradeability and minimum range target.

The success of existing HEVs and BEVs has proven the reliability and performance of electric drive systems and other hybrid components. However, similar to BEVs, the hurdles of commercialization of PHEVs are the cost

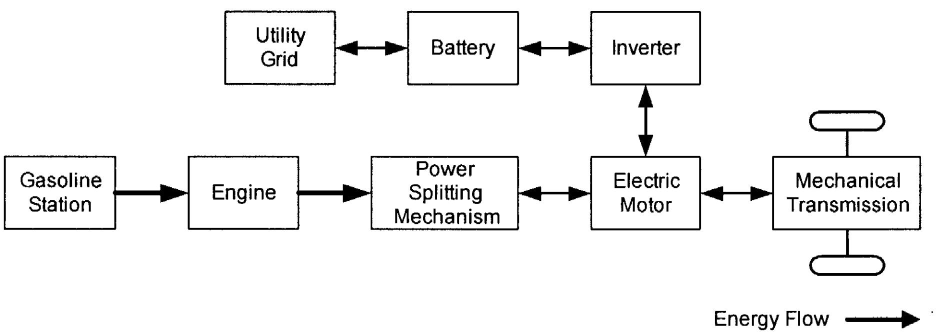

Fig. 1 Energy flow in a PHEV

and weight of the dual drive system and the batteries. The focuses of most research projects are in the analysis and optimization of the PHEV configuration and in the identification of the performance requirements of PHEV batteries. EPRI's electric transportation strategy is focused on establishing the value of PHEVs. DaimlerChrysler and EPRI have developed a limited number of plug-in Sprinter vans for demonstrations [EPRI, 2002 and 2004].

This paper aims to develop general equations for battery sizing and analysis of the lifecycle cost of PHEVs. Finally, a design strategy of PHEVs is proposed.

2. REVIEW OF BATTERIES FOR PHEV

The biggest challenge of PHEV commercialization is the cost of batteries. The design of PHEVs should be focused on the minimization of the onboard battery and the maximization of the hybrid efficiency. There are numerous secondary batteries for BEVs, HEVs and PHEVs applications. These batteries consist of valve-regulated lead-acid (VRLA), nickel-cadmium (Ni-Cd), nickel-metal hydride (Ni-MH), aluminum/air (Al/Air), zinc/air (Zn/Air), sodium/sulfur (Na/S), sodium/nickel chloride (Na/NiCl2), and lithium-ion (Li-Ion) types. Among them, VRLA, Ni-MH, Na/NiCl2 and Li-Ion batteries have demonstrated their applications in BEVs and HEVs. Table 1 shows their typical characteristics and Table 2 shows the possible battery suppliers and their applications [Graham, 2005; Kohler et al., 2005].

The specific energy of VRLA batteries is too low such that it is not attractive for PHEV applications. On the other hand, the specific power of Na/NiCl2 battery appears to be too low for HEV and PHEV applications. Ni-MH and Li-Ion batteries are mature batteries and they are commercially available. Hence, Ni-MH and Li-Ion batteries are being considered to be the near-term batteries of choice for PHEVs.

2.1 Ni-MH battery

Ni-MH battery is so attractive because it offers the highest specific energy among all nickel-based batteries (about 60 Wh/kg), high specific power (150-300 W/kg), very long cycle life (800-2000 cycles), environmental friendliness, rapid recharge capability, and maintenance-free operation. At present, the key drawback is its very high initial cost. Since this battery can potentially reduce to about $250/kWh on mass production, it is rapidly accepted for HEV and PHEV applications.

2.2 Li-Ion battery

Li-Ion battery exhibits both high specific energy and specific power (about 100 Wh/kg and 700 W/kg) as well

Table 1 Typical characteristics of BEV batteries

	Specific Energy [a] (Wh/kg)	Energy Density [a] (Wh/L)	Specific Power [b] (W/kg)	Cycle Life (Cycles)	Projected Cost (US$/kWh)
VRLA	30-50	60-100	200-400	400-600	120-150
Ni-MH	50-70	100-140	150-400	800-2000	150-200
Na/NiCl$_2$	86	149	150	1000	160-300
Li-Ion	120-140	240-280	700-950	1200	150-180

[a] At 80% depth-of-discharge

[b] At 3-hour discharge rate

Table 2 Possible BEV battery suppliers and recent applications

	Possible Suppliers	Recent Applications
VRLA	GS, Horizon, Panasonic, Sonnenschein, YUASA	Chrysler Voyager, Daihatsu Hijet, Ford Ranger, GM EV1, Mazda Bongo Friendee, Suzuki Alto
Ni-MH	GP, GS, Ovonic, Panasonic, SAFT, Varta YUASA,	Honda EV Plus, Mazda Demio, Peugeot 106, Solectria Force, Toyota RAV4L
Zn/Air	Electric Fuel	GM-Opel Corsa Combo, Mercedes-Benz MB410
Na/NiCl$_2$	Zebra	BMW AG, Mercedes-Benz Vito
Li-Ion	GS, SAFT, Sony, Varta	Nissan Prairie Joy

as long cycle life (about 1200 cycles). At present, the key drawback is its extremely high initial cost though the projected value is reasonable. Anyway, it has recently been applied for HEV and BEV applications.

3. SYSTEM DESIGN OF PHEV

PHEV design consists of seven main components, namely chassis design, engine and exhaust system design, transmission design, accessory subsystem design, electric traction system design, energy storage system design and on vehicle charging system design. These subsystems are closely linked together and all the interactions among them should be considered altogether for the design of PHEVs.

Home charging of PHEVs at home in the night is a very favorable characteristic. The cost of infrastructure to support home charging is manageable because of the low charging power.

The beauty of PHEVs is the all-electric range, utilizing only the batteries and the traction motor. The all-electric range is identified in this paper as the primary parameter in minimization of the lifecycle costs of PHEVs. In the iterative PHEV design, the characteristics of subsystems from vehicular drags to the mechanical transmission system were modeled using the ADVISOR computer program. The fuel economies of both the ICE system and the electric system are obtained from simulations in ADVISOR. General equations are developed to determine the requirements of the battery energy storage system and the electric and engine propulsion system.

3.1 System design of batteries

Battery is identified as the electrical energy storage device and the maximum battery energy storage is the core part of the PHEV system design. The maximum battery energy storage is calculated in Eq. (1)

$$E_{battery} = \frac{f_{electric} r_{electric}}{0.8} \quad (1)$$

where $E_{battery}$ is the maximum battery energy storage in kWh, $f_{electric}$ the electric fuel consumption of the all-electric operations in kWh/mile and $r_{electric}$ is the all-electric driving range in mile. Batteries in PHEVs will only be discharged to 80% degree-of-discharge (DOD), which is the highest DOD permitted in the interest of good battery cycle life.

According to the intrinsic characteristics of batteries, the maximum battery power is calculated in Eq. (2)

$$P_{battery} = E_{battery} R'_{p-e} \quad (2)$$

where $P_{battery}$ is the maximum battery power in kW and R'_{p-e} is the ratio of specific power to the specific energy of the battery in W/Wh

3.2 System design of powertrain

The acceleration and gradeability performance are determined by the powers of the electric motor and the engine. Most of the major vehicular drags are linearly proportional to the vehicle mass. The peak power requirement of the PHEV is assumed to be linearly proportional to the mass of the vehicle as stated in Eq. (3). The powers of traction motor and the engine affect each other

$$P_{engine} + P_{motor} = (1 + \frac{m_{battery}}{m_{cv}}) P_{cv} \quad (3)$$

where P_{engine} is the peak power of the engine in kW, P_{motor} the peak power of the motor in kW, $m_{battery}$ the mass of the battery, m_{cv} the vehicle mass of the baseline CV and P_{cv} is the peak engine power of the baseline CV.

The motor power is limited by the maximum battery power and the efficiencies of the inverter and the motor itself. It is calculated by

$$P_{motor} \le P_{battery} \eta_{inverter} \eta_{motor} \quad (4)$$

where $\eta_{inverter}$ is the efficiency of the inverter and η_{motor} is the efficiency of the motor.

Because of the exist of electric propulsion system, the power of the engine and the capacity of the gasoline tank can be reduced to reduce the mass of the vehicle. The capacity of the gasoline tank is determined by gasoline driving range, in which only the engine operates. The gasoline range is calculated in Eq. (5)

$$r_{gasoline} = r_{cv} - r_{electric} \quad (5)$$

where $r_{gasoline}$ is the gasoline driving range in mile and r_{cv} is the driving range of the baseline conventional vehicle by 90% of the full tank gasoline in mile.

The volume of the gasoline tank is calculated in Eq. (6)

$$V_{tank} = \frac{r_{gasoline}}{0.9 f_{gasoline}} \quad (6)$$

where V_{tank} is the capacity of the gasoline tank in gallon and $f_{gasoline}$ is the fuel economy of the ICE driving system in mile/gallon. The capacity of the gasoline tank is calculated by assuming that 90% of the full tank gasoline was used in a trip.

4. COST ANALYSIS

The lifecycle cost of PHEVs consists of both the retail price and the operating costs. General equations for the calculation of lifecycle costs are developed.

4.1 Retail price

The retail price is the sum of all component costs and it is calculated in Eq. (7)

$$c_{RP} = c_{chassis} + c_{engine} + c_{transmission} + c_{accessory} + c_{motor} + c_{battery} + c_{charger} \quad (7)$$

where c_{RP} is the retail price in US\$, $c_{chassis}$ is the cost of the chassis in US\$, c_{engine} the cost of the engine in US\$, $c_{transmission}$ the cost of the transmission system in US\$, $c_{accessory}$ the cost of the accessory systems in US\$, c_{motor} the cost of the traction motor in US\$, $c_{battery}$ the cost of the batteries in US\$ and $c_{charger}$ the cost of the grid charging system in US\$. The costs of the battery, motor and engine are calculated in Eq. (8), (9) and (10) respectively.

$$c_{battery} = E_{battery}\rho_{battery} \quad (8)$$

$$c_{motor} = P_{motor}\rho_{motor} \quad (9)$$

$$c_{engine} = P_{engine}\rho_{engine} \quad (10)$$

where $\rho_{battery}$ is the price of battery in US\$/kWh, ρ_{motor} the price of motor in US\$/kW and ρ_{engine} is the price of engine in US\$/kW.

4.2 Operating cost

Operating costs include costs for fuel and maintenance, which is estimated from the annual driving ranges of both gasoline and electricity. The annual operating cost will be calculated according to the daily mileage and the lifecycle operating cost will be calculated by net present value (NPV) analysis. The annual fuel costs of electricity and gasoline are calculated in Eq. (11) and (12) respectively.

$$c_{electricity} = 365.25\rho_{electricity}\frac{r'_{electric}f_{electric}}{\eta_{charging}} \quad (11)$$

$$c_{gasoline} = 365.25\frac{r'_{gasoline}}{f_{gasoline}}\rho_{gasoline} \quad (12)$$

where $c_{electricity}$ is the annual fuel cost of electricity in US\$, $r'_{electric}$ the daily electric driving range in mile, $\rho_{electricity}$ the price of electricity in US\$/kWh, $\eta_{charging}$ the efficiency of grid charging, $c_{gasoline}$ the annual fuel cost of gasoline in US\$, $r'_{gasoline}$ the gasoline driving range in mile and $\rho_{gasoline}$ is the price of gasoline in US\$/gallon.

The annual driving range and annual maintenance costs are calculated in Eq. (13) and (14) respectively.

$$r_{annual} = 365.25(r'_{electric} + r'_{gasoline}) \quad (13)$$

$$c_{maintanence} = r_{annual}\rho_{maintanence} \quad (14)$$

where r_{annual} is the annual driving range in mile, $c_{maintanence}$ the annual maintenance cost in US\$ and $\rho_{maintanence}$ is the price of maintenance in US\$/mile.

4.3 Lifecycle cost

The lifecycle cost of the PHEV is the sum of the retail price and the net present values (NPVs) of all the operating costs over the vehicle lifecycle. The total operating cost is calculated in Eq. (15) and the lifecycle cost is calculated in Eq. (16).

$$c_{OC} = (c_{electricity} + c_{gasoline} + c_{maintanence})\frac{1-\left(\frac{1}{1+i}\right)^{L_{vehicle}}}{1-\left(\frac{1}{1+i}\right)} \quad (15)$$

$$c_{lifecycle} = c_{RP} + c_{OC} \quad (16)$$

where c_{OC} is the total operating cost in US\$, $c_{lifecycle}$ the lifecycle cost in US\$, $L_{vehicle}$ the lifecycle of the vehicle in year and is the inflation rate over the vehicle lifecycle. Finally the lifecycle fuel economy can be calculated by Eq. (16) to compare the cost effectiveness of different types of vehicles.

$$\varepsilon_{lifecycle} = \frac{c_{lifecycle}}{r_{annual}L_{vehicle}} \quad (16)$$

where $\varepsilon_{lifecycle}$ is the lifecycle fuel economy of the vehicle in US\$/mile.

5. LIFECYCLE COST ANALYSIS

Lifecycle cost analysis of one baseline gasoline CV, one HEV and PHEVs is conducted. The baseline gasoline CV is a compact vehicle based upon a 2001 Saturn SL1 with a 1.9L I-4 engine. The HEV is assumed to be a parallel HEV. In a parallel hybrid, the engine and the traction motor provide power to the drive axle in parallel. There is only a small battery in the HEV for power assist and regenerative braking and there is no plug-in capacity and no all-electric range.

Advanced battery, Ni-MH, is identified as the near-term battery for PHEV application. Hence, Ni-MH battery is assumed to be the traction battery in this analysis. The lifecycle mileage is assumed to be 150,000 miles in 10 years. The driving cycle in this analysis is based upon FUDS and the lifecycles of the vehicle and the subsystems are assumed to be 10 years. Hence, there is no battery replacement in this analysis. PHEVs with different all-electric ranges are used in this analysis. The keys parameters for analysis are listed in Table 3 and the results are listed in Table 4. The lifecycle fuel economies of the vehicles are plotted in Figure 2.

In this analysis, the retail prices of the PHEVs and the HEV are higher than that of the CV. However, they also

Table 3 Design parameters

	CV	HEV	PHEV
Drag coefficient	0.315		
Frontal area (m^2)	1.974		
Coefficient of rolling resistance	0.008		
Cargo mass (kg)	136		
Wheel rolling radius (m)	0.282		
Average electrical accessory load (W)	400		
Average electrical system efficiency	0.85		
Average air conditioner load (W)	1000		
Typical day's mileage (mile)	41		
Minimum total range on FUDS (mile)	344		
Engine peak power (kW)	74	53	P_{engine}
Vehicle mass (kg)	1209	1221	$m_{vehicle}$
Motor peak power (kW)	NA	23.3	P_{motor}
Gasoline fuel consumption, FUDS (mpg)	31.6	48.5	$f_{gasoline}$
Electricity fuel consumption, FUDS (kWh/mile)	NA	NA	$f_{electric}$
Maximum battery energy storage (kWh)	NA	2.75	$E_{battery}$
Traction battery	NA	Ni-MH	Ni-MH
Specific power of the traction battery (W/kg)	NA	400	400
Specific energy of the traction battery (Wh/kg)	NA	60	60
Price of gasoline (US$/gallon)	1.65	1.65	NA
Price of electricity (US$/kWh)	NA	NA	0.06
Vehicle life (year)	10		
Lifecycle driving range (mile)	150,000		
Inflation rate (%)	3		

NA: Not applicable

Table 4 Lifecycle cost analysis

	CV	HEV	PHEV
Retail price (US$)	13,849	15,710	17,478 - 20,985
Operating cost (NPV) (US$)	9,658	7,260	4,419 - 6,827
Lifecycle cost (US$)	23,507	22,970	23,941 - 25404
Lifecycle fuel economy (US$/mile)	0.157	0.153	0.1596 – 0.1694

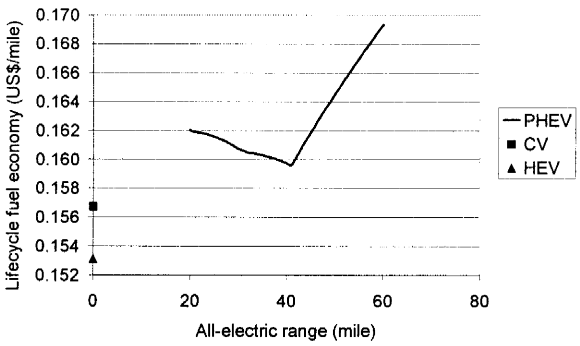

Fig. 2 Lifecycle fuel economies of CVs, HEV and PHEVs

offer significant efficiency improvements in the consumption of gasoline over the CV. The benefit of reduction in fuel consumption increases with all-electric range in PHEVs provided that battery stored energies are fully utilized. The costs of PHEVs are affected by the onboard battery, which is sized according to the all-electric range of the PHEV. As shown in Figure 2, the lifecycle fuel economy reaches the minimum at 0.1596 US$/mile when the all-electric range is designed at 41 miles.

The improvement of operating costs in HEV exceeds the extra money in retail price such that the lifecycle cost of the HEV is the lowest. HEV is found as the compelling vehicle in the near future to reduce the consumption of petroleum-based fuels and vehicular emissions. The critical challenge of PHEV commercialization is the cost of high energy batteries. The commercialization of PHEVs depends on the price of advanced batteries, price of electricity and any government fiscal subsidy policy to PHEVs.

6. CONCLUSIONS

Advanced batteries for HEV and PHEV applications are evaluated. To investigate the lifecycle costs of different types of vehicles quantitatively, general equations are developed to describe the performance requirements and costs of all subsystems in vehicles. The cost analysis results give methods for estimating the retail price, and operating costs of PHEVs.

Our conclusions suggest that Ni-MH batteries can be manufactured to meet the vehicle lifecycle requirements of HEVs and PHEVs. The price of batteries is the major challenge for PHEV commercialization. The lifecycle cost of HEVs is the lowest among CVs, PHEVs and HEVs. The batteries of PHEVs should be sized according to the driving habits of the drivers.

Acknowledgments

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