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High-power batteries for use in hybrid vehicles

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Abstract

The idea of hybrid vehicles is not a recent development; as early as the 1960s, several have companies attempted to develop bipolar lead/acid batteries for hybrid-electric vehicles [J.L. Arias, J.J. Rowlett, E.D. Drake, Journal of Power Sources, 40 (1993) 63–73.]. Hybrid vehicles have the potential to increase fuel economy by using a primary engine operating at a constant power to supply average power requirements and a surge power unit for peak power demands and to recover braking energy. To date, no detailed system optimization analysis has been performed for hybrid vehicles. This study combines a simplified version of the lithium-ion battery model developed by Doyle [C.M. Doyle, Design and simulation of lithium rechargeable batteries, Dissertation, Fall, 1995.] with a vehicle model that determines battery-power requirements for a given driving cycle. Batteries are designed for either the highest vehicle mileage or minimal acceptable battery dimensions. Hybrid vehicles have the potential to more than double mileage as compared to conventional vehicles, and have a limited electric vehicle range. The battery goals of the Partnership for a New Generation of Vehicles (PNGV) are investigated and often found to be differing with actual requirements. Specifically, PNGV overstates power and especially energy requirements for load-leveling devices and calls for unnecessary demands on the development of alternate technologies. The role of the driving cycle was investigated and found to be relatively unimportant as long as it contains several essential features. The important parameters in the driving cycle are the time of discharge and the maximum current (or power) level. This study suggests that a combination of both a vehicle model and a battery model is required to determine the complex interaction between hybrid-vehicle weight and battery power.

Keywords: Hybrid; Vehicle; Battery

1. Introduction

Increased worldwide energy use has led to multiple global environmental problems, one of which is the warming of the earth from an enhanced greenhouse effect due primarily to increased atmospheric concentrations of carbon dioxide. Transportation is a major contributor to greenhouse-gas emissions as well as urban pollution. Increased vehicle fuel efficiency will lessen both of these problems in addition to decreasing dependence on imported petroleum. The conventional vehicle design offers limited possibilities for improvements, and electric vehicles are expensive, lack a recharging infrastructure, and have limited range and long recharging times. A hybrid vehicle merges the benefits of conventional and electric-vehicle design.

A hybrid vehicle combines a primary power plant with an energy-storage device. The primary power plant supplies average power demands, and the load-leveling device cushions the vehicle power fluctuations and supplies power for peak demands (hill climbing and acceleration) and recovers braking energy. A conventional engine must respond quickly and supply adequate power, often over 80 kW, for rapid acceleration although highway cruising requires less than 8 kW. The average urban demand is less than 5 kW, and climbing a 3% grade at 90 km/h requires less than 20 kW. The variable load and rapid response requirements lower the overall thermal efficiency of the engine. The main advantage of hybrid vehicles is the high efficiency and low emissions of the power plant since it operates at optimized levels.

Additional advantages include the recovery of braking energy and the possibility of using slow-response power plants such as fuels cells, gas turbines, and stirling engines.

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Drawbacks of hybrid vehicles include increased cost and complexity. In addition, increased efficiencies must be greater than losses that occur in energy storage and recovery. Finally, reliability, component lifetime, and cost issues must be addressed.

2. Adjustable parameters and optimization study

The dissertation of Doyle [1] deals with the rigorous mathematical details of the lithium-ion battery computer simulation. Only minor modifications were made for this work, none of which alters the solution procedure. The battery studied in this research consists of the insertion electrodes Li_xC_6 and $Li_yMn_2O_4$. The separator is composed of the random copolymer, vinylidene fluoride and hexafluoropropylene swollen by a liquid electrolyte. The electrolyte is composed of a combination of 33 wt.% ethylene carbonate and 66 wt.% dimethylcarbonate. The addition of the salt $LiPF_6$ permits the transport of lithium. The porous medium is treated by the well-established macrohomogenous model, which ignores the detailed random geometry of the pores but accounts for the decrease of the effective conductivity and diffusion coefficient due to the porosity. The model is based on experimental data from the Bellcore lithium-ion battery [2].

Adjustable design variables in this study include salt (electrolyte) concentration, electrode thickness and porosity, active material particle radius, and electrode state of charge. To perform this study, the rigorous model uses a 1-min driving cycle. The cycle includes an initial acceleration, a cruising section, a braking section, and a stopped section. Current levels during each segment simulate 'typical' requirements for the 1-min driving cycle shown in Table 1. To begin this study and identify important battery design considerations for hybrid vehicles, parameters are adjusted one at a time to determine their individual influence on cell performance.

It is possible to optimize the initial salt concentration of the electrolyte for hybrid-driving conditions. During hybrid operation, the main use of the battery is for load-leveling, and the salt concentration should be near the maximum conductivity since little time exists for concentration gradients to develop. The cycling of positive and negative currents keeps the salt concentration near the original level. For this reason, it is important to minimize ohmic losses in the liquid phase by making the solution as conductive as possible. Electrolyte ohmic losses account for 23.5% of the losses in the original battery design.

Table 1
Representative 1-min driving cycle

Driving segment	Current level (A/m^2)	Segment time (s)
Acceleration	96.6	12
Cruising	−6.4	28
Braking	−135.91	5
Stopped	−20.7	15

Table 2
Summary of the inefficiencies that exist in the original battery design
The percentage losses are determined by setting the selected parameter to either a large or a small value to negate its effect in the model.

Anodic film resistance (%)	66.9
Electrolyte ohmic losses (%)	23.5
Solid-state diffusion (%)	8.3
Solid ohmic losses (%)	0.8
Kinetic overpotential (%)	0.2

The particle radius is the primary variable determining the performance of the battery. The impact of particle radius on the Li_xC_6 electrode is much more significant than for the $Li_yMn_2O_4$ electrode. Smaller particles provide a larger reaction surface per unit volume, lowering local current densities. A lower current density decreases ohmic losses in the anodic film, solid-state diffusion overpotentials, and kinetic overpotentials. Increased losses in the carbon electrode are partially explained by the smaller diffusion coefficient [2] of 3.9×10^{-14} m^2/s in the carbon electrode compared to 1×10^{-13} m^2/s for the manganese oxide electrode. Solid-state diffusion accounts for 8.3% of the losses in the cell. Almost 90% of these losses occurs in the carbon electrode.

Additional losses in the cell occur in the resistive anodic film, kinetic overpotentials, and solid-phase ohmic losses. Kinetic limitations account for only 0.2% of the cell losses and are not an important influence on cell performance. Solid-phase ohmic losses account for an insignificant 0.8% of cell losses. Almost all of the solid-state ohmic losses occur in the manganese oxide electrode. The remainder, and majority, of the losses occur from the irreversible anodic film that forms during the first cell cycle [3]. The film increases surface overpotential and accounts for 66.9% of cell losses. Table 2 shows a summary of the losses that occur in the original battery design.

3. Simplified lithium-ion battery model

A simplified battery model lessens the computer time required for the optimization procedure. In addition, the simplified model is general enough to evaluate the potential of generic load-leveling devices for use in hybrid vehicles. The first simplification is that the cell behaves as an ohmically limited system, and Ohm's law holds for short current pulses. The complete model determines best-fit linear relationships for the average overpotential (η) of a battery:

$$\eta = mi + n. \tag{1}$$

Ohmic relationships are determined uniquely for each particle size, electrode thickness, and length of current segment.

An additional consideration is that the state of charge affects the overpotential. All ohmic overpotentials are measured at a state of charge of $x = 0.4$ in Li_xC_6 and $y = 0.4199$ in $Li_yMn_2O_4$. An overpotential factor, normalized to unity at the measured conditions, adjusts the overpotential at various states of charge. The following functions fit the graphs of overpotential vs. state of charge:

$$F_C = ax^2 + bx + c, \tag{2}$$

$$F_{Mn} = d\left(\frac{1}{y+f}\right) + gy^4 + hy^3 + ry^2 + sy + t. \tag{3}$$

Equations for values for F_C and F_{Mn} are determined for each active-material particle size. The final overpotential (η') results from multiplication of the current overpotential by these factors:

$$\eta' = \eta F_C F_{Mn}. \tag{4}$$

The following equation calculates the battery power output (P_B):

$$P_B = iA(U - \eta'). \tag{5}$$

The battery power, current, and cell potential are all constant during a driving segment. Additional equations used in the battery model are to calculate the cell open-circuit potential [2], and the state of charge is determined by means of Faraday's law. The accuracy of the simplified battery model compared to the rigorous battery model in a 1-min cycle is within 0.25% of predicted battery output power.

4. Vehicle model

A vehicle model determines the power demands that a battery experiences in a hybrid vehicle. Required vehicle wheel power equals the power to overcome the various forms of friction present while driving an automobile. The resistive forces include rolling drag, aerodynamic drag, and elevation changes. The following basic equation determines cruising power requirements:

$$P_{resistance} = P_{rolling} + P_{aerodynamic} + P_{climb}, \tag{6}$$

$$P_{resistance} = C_1 mg v_C + \left(\frac{1}{2}\right)\rho_{air} C_2 A_C v_r^3 + mg v_C \sin\theta.$$

The simultaneous solution of Eq. (6) and Newton's law is required at each velocity to calculate acceleration power requirements as a function of time, mass and velocity. No analytic solution exists to this problem, and numerical integration of the vehicle model determines acceleration wheel-power requirements. During a single calculation step, the excess power determines the net amount of energy added to the vehicle system. Over the time step, constant engine and battery powers along with constant resistive forces occur. Eq. (7) calculates the change in kinetic energy:

$$\Delta E_{kinetic} = (P_{engine} + P_{battery} - P_{resistance})\Delta t. \tag{7}$$

The new amount of kinetic energy determines the vehicle velocity.

5. Combined model

The combination of the simplified battery model and the vehicle model allows for the design of the 'optimum' battery. 'Optimal' batteries in this study result in either maximum vehicle mileage or minimum battery size without regard to economic considerations. To simulate the power demands of a vehicle, it is necessary to account for efficiencies within the vehicle and select a driving cycle. Table 3 shows the representative vehicle design in this study. The electric-motor efficiency is the fraction of power from the battery delivered to the wheels, and the drive-train efficiency is the efficiency of power transfer directly from the engine to the wheels. The generator efficiency is the effectiveness of power transfer from the engine to the battery during recharging. Internal losses in the battery are not included in this value; the battery model accounts for these additional losses separately.

The following battery-design restrictions make the simulation as applicable as possible. First, the voltage range must stay within 3.375 to 4.5 V. The upper limit is to avoid electrolyte degradation [4], and the lower limit is set with the 0.75 voltage ratio specified by Partnership for a New Generation of Vehicles (PNGV). Next, the electrodes are required to stay within a limited state of charge. The amount of lithium in the manganese oxide electrode remains between 0.19 and 1.0 to avoid irreversible crystal phase changes. The maximum lithium value is 0.65 in the carbon electrode to avoid lithium plating. An additional design restriction, imposed to give greater battery capacity, is that the two electrodes have approximately equivalent

Table 3
Representative vehicle specifications for a midsize parallel-configuration hybrid-vehicle design
Mass for battery and its support is added for each battery design.

Vehicle base mass (kg)	1000
Passenger mass (kg)	135
Rolling drag coefficient	0.008
Front surface area (m^2)	1.75
Air drag coefficient	0.20
Electric motor efficiency (%)	85
Drivetrain efficiency (%)	80
Generator efficiency (%)	85
Power plant size (kW)	20
Engine thermal efficiency (%)	40
Power plant weight (kg)	55

lithium transfer capacities. This is equivalent to setting the $\Delta y / \Delta x$ ratio equal to 1.2. A zero net change in the state of charge during an urban cycle is the final requirement.

The first thing done in selecting a battery is the identification of parameters that can be optimized for the anticipated current levels and discharge periods of interest. Next, one identifies the critical design parameters that determine cell performance. Finally, less important variables are set at convenient and/or optimized levels. The initial salt concentration is the only parameter independently optimized for all load-leveling applications. It is set at 1 mol/l to minimize ohmic losses in hybrid load-leveling.

With the lithium-ion battery used in this study, the carbon active-material particle radius is the primary design criterion and region of greatest losses in the cell. After the particle sizes are set for both the carbon and manganese oxide, each electrode thickness and porosity can be determined. At each electrode thickness and particle size, the porosity is optimized for minimum overpotential using the 1-min cycle in Table 1. The optimal porosity is a balance between surface area for reaction and ohmic losses in the solution. The optimal electrode thickness is the one that results in maximum average mileage using a 1-min urban cycle. The 1-min cycle includes a 12-s acceleration to 100 km/h, a 28-s cruising segment at 100 km/h, a 5-s braking section, and a 15-s rest to include all driving elements. For particles 5 μm in diameter, the optimal battery design has a 40% porous carbon electrode with a thickness of 175 μm. The manganese oxide electrode is 200 μm thick with a porosity of 42%. The use of larger particles requires a thicker carbon electrode to provide more reaction surface area to minimize the anodic film and solid-state diffusion limitations. The optimum electrode porosity is relatively constant at 40% regardless of the selected particle sizes and depends primarily on the current levels.

This particular battery design is used in the vehicle simulation, and the separator cross-sectional area and state of charge of the electrodes are adjusted to give the maximum average miles per gallon or minimum battery size. Average miles per gallon is defined as 45% highway miles and 55% urban driving. A steady speed of 100 km/h on level ground with no head wind approximates highway driving. During highway cruising, the engine supplies all power directly to the wheels. Fig. 1 shows the urban driving cycle used in this study. The 6-min cycle approximates the simplified federal urban driving cycle (SFUDS). Maximum vehicle mileage results from a balance between battery efficiency and mass. A large and energy-efficient battery is important for urban driving, but the increase in battery mass increases urban and highway power requirements.

As the separator area increases, the vehicle model accounts for the additional mass. The battery mass and volume are composed of all the internal battery components including the current collectors. To account for external containment and for supporting material, including incremental vehicle structural support, the battery mass value is scaled by 1.5. A constant engine level supplies the average urban power demands, and the amount of battery current during each segment is adjusted to satisfy the power requirements of the vehicle. The battery discharges during times of high demand, and at times of surplus engine power, the excess charges the battery.

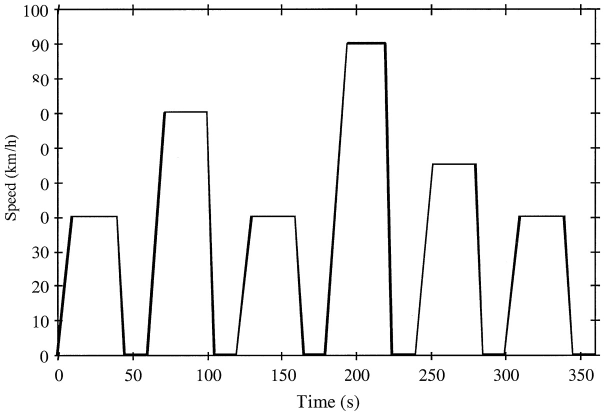

Fig. 1. Urban-driving cycles used in this study. The 6-min cycle is composed of six 1-min cycles, which contain three 10-s accelerations, two 12-s accelerations, and one 15-s acceleration. All braking segments are 5 s, and rests are 15 s.

6. Results

Similar trends result regardless of selected particle size. With small radii, the carbon-electrode performance improves greatly since reaction area doubles each time the particle radius is halved, and anodic film ohmic losses and diffusion limitations in the particles are minimized since surface reaction rates are lower. A particle size of 5 μm represents a high-power lithium-ion battery and is a compromise between performance, side reactions, and cost of manufacture.

The 6-min driving cycle performs a realistic study of the design and size of a load-leveling battery in a hybrid vehicle. The longer cycle introduces more error into the simplified battery model, but it is still within 0.5% of predicted power levels. Table 4 shows the results from the 6-min driving cycle for both maximum-mileage and minimum-size batteries. The maximum-mileage batteries result in the highest average vehicle mileage. The minimum-size batteries, the smallest batteries that satisfy all the design criteria, are essentially identical to the maximum-mileage batteries. This is strictly a consequence of the selected simulation parameters and should not be used as a general rule.

Battery cycle efficiency is the energy delivered by the battery divided by energy input measured at the battery leads. The initial state of charge of the battery is the

Table 4
Battery designs resulting in the maximum average mileage and minimum battery size using the 6-min driving cycle

	Maximum mileage			Minimum acceptable size		
	0% Brake recovery	33% Brake recovery	66% Brake recovery	0% Brake recovery	33% Brake recovery	66% Brake recovery
Average mileage (mpg)	66.70	71.34	77.38	66.7	71.31	77.21
Separator area (m^2)	55	70	100	55	65	95
Battery mass without scaling (kg)	62.0	78.9	112.8	62.0	73.3	107.1
Battery volume (m^3)	0.026	0.033	0.048	0.026	0.031	0.045
Battery cycle efficiency (%)	86.0	87.5	87.8	86.0	86.3	86.7
Initial x, Li_xC_6	0.65	0.60	0.45	0.65	0.55	0.40
Initial y, $Li_yMn_2O_4$	0.21	0.27	0.45	0.21	0.33	0.51
Initial OCP (V)	4.13	4.06	3.93	4.13	4.02	3086
Acceleration current (A/m^2)	155	126	94	155	138	101
Braking current (A/m^2)	−23	−100	−133	−23	−108	−140
Acceleration potential (V)	3.4	3.5	3.5	3.4	3.4	3.4
Braking potential (V)	4.3	4.5	4.5	4.3	4.5	4.5
Max power (3.375 V, kW)	30	35	40	30	31	34
Δy, $Li_yMn_2O_4$	0.019	0.016	0.012	0.019	0.015	0.011
Cycle energy (kW h)	0.13	0.14	0.16	0.13	0.13	0.14
Energy (kW h), 3.375 V	4.2	4.7	4.3	4.2	3.9	3.3
Heat generated (W)	433	425	468	433	467	512
Maximum power (2.8 V, kW)	43	53	68	43	48	61
Energy (kW h), 2.8 V	4.7	5.7	6.5	4.7	5.0	5.5

amount of lithium intercalated in each electrode at the beginning and end of each 6-min driving cycle. The maximum power is the maximum battery output for a 15-s discharge subject to the 3.375 V lower voltage limit. A 1-h constant current discharge from the initial state of charge to a cutoff voltage of 3.375 V calculates the battery energy. A cutoff voltage of 2.8 V is also included to demonstrate the benefits of operating over a larger voltage range. The depth of discharge (Δy) is the extreme amount of lithium that moves from one side of the battery to the other during the 6-min driving cycle. The cycle energy is the largest amount of energy delivered by the battery before recharging occurs. The heat-generation rate is an approximated average amount of heat dissipated by the battery over a single 6-min cycle. Regenerative braking is the recovery of the vehicle's kinetic energy during deceleration for storage as chemical energy in the battery.

The percent regenerative braking is the first variable studied. Values used include no regenerative braking, 33% regenerative braking, and 66% regenerative braking. The percent regenerative braking refers to the percentage of the kinetic energy of the vehicle sent to the battery as a constant 5-s pulse. The actual amount of energy retained in the battery is less since the battery model accounts for battery losses separately. The clear benefit of regenerative braking is substantially increased mileage. Regenerative braking values of 66% increase mileage 15%, but the battery increases by 80% in size to accommodate the large power spikes. The state of charge of the electrodes decreases with the amount of regenerative braking. This is to accommodate the large current pulses and is set in combination with battery size to balance battery mass, performance, and the upper voltage limit. Cycle efficiency increases with lower-overpotential batteries, but is less than 88% for maximum-mileage designs. The PNGV goal of 95% [5] may be too high and add cost, weight, and decrease efficiency for hybrid vehicles. An arbitrary efficiency value should not be stated ahead of time, but should result from the particular vehicle and battery technology selected.

The maximum available battery power is an important practical design consideration. A certain minimum power requirement will satisfy the consumer's desire for a vehicle that responds rapidly to acceleration demands. The vehicle design used in this study requires approximately 40 kW of wheel power to accelerate from 0 to 100 km/h in 12 s. Table 4 shows that optimizations done for maximum mileage result in maximum battery powers acceptable for moderate accelerations. It should be recalled that the primary power plant is capable of delivering an additional 20 kW. The vehicle used in this study is heavier than the 900 kg PNGV vehicle, and acceleration power requirements for that vehicle should be less than 40 kW. The minimum PNGV power requirement of 65 kW [5] may be almost double what is actually required. The voltage range is critical in determining maximum battery power. If the voltage range expands to 2/3, maximum power may increase over 50%. Maximum battery power, almost double the 3.375 V power, occurs at approximately 2 V. Optimizations done for minimum separator area with a voltage range of 4.5 to 2.8 V result in batteries 3/4 the size of the maximum mileage batteries with a 1% to 2%

decrease in mileage. However, the main disadvantage is that maximum powers are too low for practical consideration.

Heat generation is not considered in detail, and it is assumed that the battery design will have a thermal management system to deal with heat problems as they arise. The heat calculation includes internal losses of joule heating and local electrode overpotentials, but neglect that the open-circuit potential is not the same as the effective cell potential, which calculates the actual heat generated [6]. The error in including only ohmic overpotentials and neglecting the reversible entropy change in the cell is not significant in a load-leveling application since the concentration of lithium will be nearly uniform [2] because the current pulses are short and of alternating direction. The overall adiabatic temperature rise is less than 3°C during a single 6-min cycle for all battery designs. The batteries designed for large amounts of regenerative braking actually have a lower adiabatic temperature increase because of their larger mass.

The significant excess energy available is an added benefit of using high-energy-density batteries. A typical acceleration requires less than 0.2 kW h of battery energy to reach cruising speed. For practical design considerations, a load-leveling device should have a minimum of about 1 kW h of available energy. This contradicts the PNGV minimum goal [5] of 3 kW h of available energy. This excessive energy goal excludes lower energy density batteries and flywheels where safety and energy are directly related. The several times excess capacity of lithium-ion batteries provides the opportunity for point-source emission-free driving. Approximately 1 kW h of battery energy is required for each 10 km of zero-emission vehicle (ZEV) cruising at 100 km/h. For lithium-ion batteries, the ability to maintain a sustained current is dependent upon the initial salt concentration of the battery. During sustained high rates of discharge, the salt concentration depletes in the manganese oxide electrode and concentrates in the carbon electrode. The end-of-discharge mechanism is often not capacity limitation but limitation by severe salt-concentration polarization. With range-optimized initial salt concentration, ZEV ranges increase between 5 and 25%. For electric driving in urban conditions, salt concentration will not be as important an issue since the current will be periodically switching direction with acceleration and deceleration. This, combined with periods of rest, will give diffusion time to maintain a uniform salt concentration throughout the cell.

In addition, an electric start will give time for the catalyst to heat resistively to light-off temperature. Most pollutants form in the first few minutes, before the catalyst warms and begins to work effectively. An advantage of a hybrid is that no additional battery is required, and regardless of the length of the planned trip, initial driving is in the pure electric mode. Engine ignition does not occur until the catalyst and engine are warm. During shorter trips and heavy traffic, the ZEV range decreases vehicle emissions. In addition, fuel-cell vehicles may require a warm-up time before the reformer and stack are ready to produce power.

7. Design considerations

Mass has an important influence on vehicle performance, and the reduction of vehicle mass by 40% is an important goal of the PNGV [7]. This section examines the importance of vehicle mass in determining vehicle performance and battery load-leveling requirements. The base vehicle mass is reduced, and the separator area and state of charge of the battery are optimized for maximum mileage with 66% regenerative braking. Hybrid-vehicle mileage increases dramatically as vehicle mass decreases. For each 100 kg decrease in vehicle driving mass, mileage increases 4.5 mpg. This is roughly double that for a similar conventional vehicle design. Additionally, the required battery mass decreases at 8% of the rate of vehicle driving mass because of lower power requirements with decreased vehicle mass [8]. An interesting result is that the ratio of total vehicle driving mass to the base battery mass is a constant ratio of 12. This is valuable for design considerations. A battery designed for a particular vehicle scales linearly to approximate the required size for use in a different vehicle design.

The smaller batteries result because lower vehicle mass has a considerable effect on acceleration power requirements and a less important, but still significant, effect on highway cruising power requirements. For the vehicle design chosen for this study, acceleration power requirements for 12 s from 0 to 100 km/h decrease 3 kW per 100 kg, and cruising power decreases 0.2 kW per 100 kg. Weight is more important an issue during urban driving, and the urban mileage increases at twice the rate of highway mileage as weight is reduced.

The responsiveness of the primary engine to changes in load is not examined since a variable engine may compromise the assumed high thermal efficiency and low emissions. If the thermal efficiency of a responsive engine is close to that of a slow-response engine, the idea of a hybrid vehicle has limited applications, although an engine that shuts off during braking and when the vehicle is stopped has the potential to increase mileage 2 to 3% for conventional vehicle designs. Decreased battery heat generation is a potential benefit of the variable-engine design.

8. Selection of driving cycle

The driving cycle need only be approximate and not exact since the battery design changes only slightly. A battery too small will give less urban mileage and maximum power, but result in increased highway performance and decreased cost. A larger battery will have the benefits of urban efficiency and high maximum power, but will cost more, take up more car volume, and decrease highway performance. The selection of electrode thickness was studied, and it was found that there exists a complex relationship between porous electrode kinetics and vehicle efficiency to give essentially equivalent battery mass and similar mileage results for electrode thickness values within 25% of each other. For a strict load-leveling application, economics will play a crucial role in selecting the electrode thickness since separator costs can be much greater than electrode material. Since batteries do not change state of charge to a great degree in a hybrid cycle, the order of speeds within the cycle is not highly important. The important issues in selecting a driving cycle are approximating the length of discharge and the maximum and average power along with a range of vehicle power demands. In the 6-min driving cycle, batteries with a separator area within approximately 25% of the optimum area result in average mileage estimates that are within 1% of the optimal value. The states of charge of the batteries are different, but the final mileage results are similar.

9. Conclusions

This analysis identifies several important battery design considerations. For optimum performance, the salt concentration should be near the maximum conductivity. The short current pulses present during load-leveling do not allow time for salt concentration gradients to develop in the cell. The carbon electrode is the limiting factor in battery design because the resistive anode film contributes a significant portion of the cell losses. Smaller particles enhance performance by lowering local current density and thereby decreasing ohmic and diffusion limitations. This design criterion neglects consideration of possible design problems including increased corrosion, side reactions, and loss in initial cell capacity to form the anodic film.

During hybrid-vehicle load-leveling, batteries are generally cycled through only a low depth of discharge. Short current pulses cannot efficiently use the additional battery capacity. Losses become too large when the battery runs at higher current densities. The additional energy in the cells provides significant energy for driving without the engine. An additional finding is that optimum cycle efficiencies occur near 88% for maximum-mileage batteries. This value results from the optimization procedure, and not from a predetermined value. The higher PNGV target of 95% may actually decrease fuel efficiency because the extra weight added to the vehicle increases power demands. In addition, a larger battery is more expensive and takes up more volume. The minimum power and energy requirements are also overstated for unrevealed reasons. This study finds that the minimum power and energy requirements are roughly 40 kW and 0.2 kW h, respectively. If enhanced performance and a ZEV range are desired, this should be stated as a separate consideration.

The selection of an exact driving cycle is not a critical element in the design of a battery for use in a hybrid vehicle, but it must have all the elements of a typical urban driving condition. This includes an acceleration segment, a cruising segment, a regenerative braking segment, and a stopped segment. A battery designed for typical driving conditions still performs well for a cycle that is significantly different. The important design parameters are the duration of discharge and current density. From this, the electrode thickness and porosity can be determined. If more power is required for a larger vehicle, a battery with more electrode area is appropriate.

It should be noted that this study does not address several important factors in practical battery design. A major barrier to the use of batteries in hybrid and electric vehicles is cost. Other issues include component lifetime, manufacturing, and recycling.

10. List of symbols

A	separator area (m^2)
A_C	vehicle frontal surface area (m^2)
a, b, c	carbon state of charge correction parameters
C_1	rolling drag coefficient
C_2	air drag coefficient
d, f, g, h, r, s, t	manganese oxide state of charge correction parameters
F_C	carbon state of charge correction factor
F_Mn	manganese oxide state of charge correction factor
g	gravitational constant ($9.81\ \mathrm{m/s^2}$)
i	current ($\mathrm{A/m^2}$)
m	overpotential vs. current graph slope
n	overpotential vs. current graph intercept
m	vehicle mass (kg)
P_B	battery power (W)
t	time (s)
U	open-circuit potential (V)
v_C	vehicle velocity (m/s)
v_0	relative wind speed (m/s)
v_r	vehicle velocity relative to wind ($v_\mathrm{r} = v_\mathrm{C} + v_0$)
ρ_air	air density ($1.202\ \mathrm{kg/m^3}$)
η	ohmic overpotential (V)
η'	final overpotential (V)
θ	angle of climb

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