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Plug-In Hybrid Electric Vehicle Energy Storage System Design

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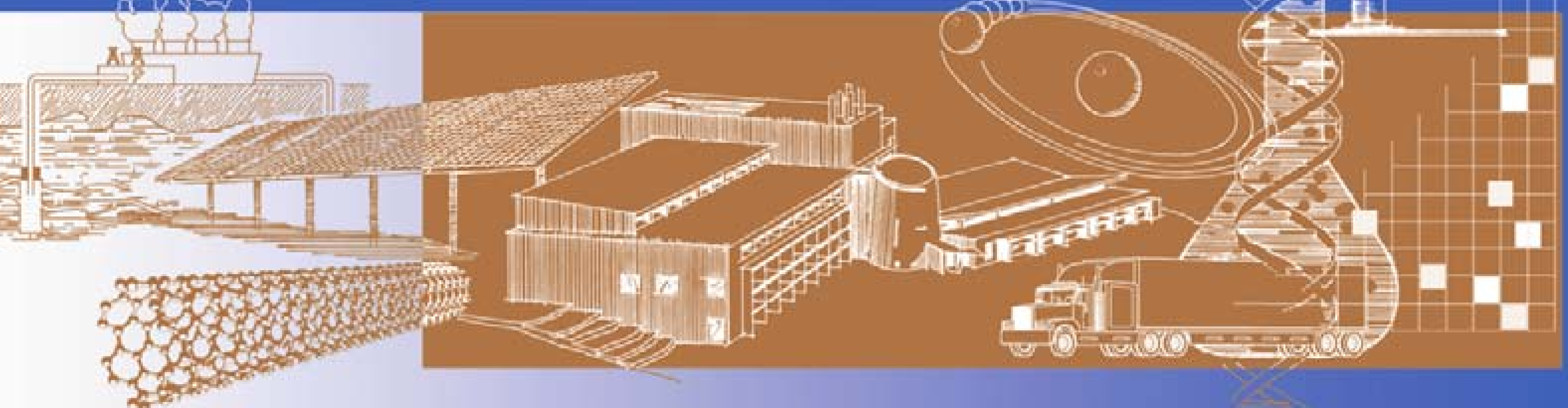

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Plug-In Hybrid Electric Vehicle Energy Storage System Design*

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ABSTRACT

Plug-in hybrid electric vehicle technology holds much promise for reducing the demand for petroleum in the transportation sector. Its potential impact is highly dependent on the system design and in particular, the energy storage system. This paper discusses the design options including power, energy, and operating strategy as they relate to the energy storage system. Expansion of the usable state-of-charge window will dramatically reduce cost but will likely be limited by battery life requirements. Increasing the power capability of the battery provides the ability to run all-electrically more often but increases the incremental cost. Increasing the energy capacity from 20-40 miles of electric range capability provides an extra 15% reduction in fuel consumption but also nearly doubles the incremental cost.

Introduction

The United States is faced with a transportation energy dilemma. The transportation sector is almost entirely dependent on a single fuel – *petroleum*. The continued role of petroleum as the primary transportation fuel should be questioned.

Today, nearly 60% of U.S. total petroleum consumption is imported and results in billions of dollars flowing to the economies of foreign countries. More than 60% of U.S. petroleum consumption is dedicated to transportation.[1] The domestic production of petroleum is steadily declining while our rate of consumption continues to increase; thus imports are expected to continue to increase. Meanwhile, petroleum consumption rates in the emerging economies of China and India are rapidly expanding. Furthermore, experts believe world petroleum production may peak within the next 5-10 years.[2] The combination of these factors will place great strain on the supply and demand balance of petroleum in the near future.

Hybrid electric vehicle (HEV) technology is an excellent way to reduce our petroleum consumption through efficiency improvements. HEVs use energy storage technology to improve vehicle efficiency through engine downsizing and by recapturing energy normally lost during braking events. A typical HEV will reduce gasoline consumption by about 30% over a comparable conventional vehicle.[1] Since introduced, HEV sales have grown at an average rate of more than 80% per year. However, after 5 years of availability, they represent only 0.1% of the total U.S. vehicle fleet. There are 237,000,000 vehicles on the road today and more than 16 million new vehicles sold each year.[3] New vehicles will likely be in-use for more than 15 years and the vehicle miles traveled (VMT) continues to grow.[4] It will be challenging to overcome the inertia of the vehicle fleet. For instance, if every new vehicle sold in 2011 and beyond was a petroleum-fueled hybrid, our petroleum consumption level 10 years from now would still be 6% greater than the current light-duty fleet consumption, and it would never drop below today's consumption level. Efficiency improvements of HEVs will be insufficient to overcome vehicle fleet and VMT growth expectations.

This presents a challenge of how to best displace as much petroleum consumption as soon as possible while incurring reasonable costs. Many industries, including polymer and pharmaceutical, have little choice but to use petroleum. There are several alternatives to petroleum for a transportation fuel source. These include hydrogen, ethanol, biodiesel, and electricity. Hydrogen and fuel cell technology has advanced rapidly but still faces significant cost, infrastructure, and technical challenges that could limit market penetration within the next 15-20 years. Both ethanol and biodiesel are used today

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[1] With additional improvements in aerodynamics and engine technology, hybrid vehicles today have demonstrated upwards of a 45% reduction in consumption as compared to a conventional vehicle.

and help displace petroleum. However, at current production levels and given future expectations on cellulosic production potential, biofuels have limited ability to end our oil addiction alone but may be more successful when combined with other displacement technologies.

Plug-in hybrid electric vehicle (PHEV) technology is an option with the potential to displace a significant portion of our transportation petroleum consumption. A plug-in hybrid vehicle is an HEV with the ability to recharge its energy storage system with electricity from the electric utility grid. With a fully charged energy storage system, the vehicle will bias towards using electricity over liquid fuels. A key benefit of PHEV technology is that the vehicle is no longer dependent on a single fuel source. The primary energy carrier is electricity generated using a diverse mix of domestic resources including coal, natural gas, wind, hydroelectric, and solar energy. The secondary energy carrier is a liquid fuel (e.g., gasoline, diesel, or ethanol).

PHEV technology is not without its own technical challenges. Energy storage system cost, volume, and life are major obstacles that must be overcome for these vehicles to be viable. The fuel displacement potential of a PHEV is directly related to the characteristics of the energy storage system. More stored energy means more miles that can be driven electrically. However, increasing energy storage also increases vehicle cost and can present significant packaging challenges. Finally, the energy storage system duty cycle for a PHEV is likely to be more severe from a life standpoint than electric vehicles or HEVs.

The purpose of this paper is to expand on the current understanding of the potential benefits, the design options, and the challenges related to PHEV technology.

PHEV and HEV Terminology

Charge-sustaining mode – An operating mode in which the state-of-charge of the energy storage system over a driving profile may increase and decrease but will by the end of the cycle return to a state with equivalent energy as at the beginning of the period.

Charge-depleting mode – An operating mode in which the state-of-charge of the energy storage system over a driving profile will have a net decrease in stored energy.

All-electric range (AER) – The total distance driven electrically from the beginning of a driving profile to the point at which the engine first turns on.

Electrified miles – Is the sum of all miles driven with the engine off including those after the engine first turns on.

PHEVxx – A plug-in hybrid vehicle with sufficient energy to drive xx miles electrically on a defined driving profile usually assumed to be urban driving. The vehicle may or may not actually drive the initial xx miles electrically depending on the control strategy and driving behavior.

SOC – State-of-charge of the energy storage system. The fraction of total energy capacity remaining in the battery.

Degree of hybridization – The fraction of total rated power provided by the electric traction drive components.

Utility factor – A measure of the fraction of total daily miles that are less than or equal to a specified distance based on typical daily driving behavior.

Potential Benefits of PHEVs

A key reason for exploring PHEV technology is its ability to achieve significant petroleum consumption reduction benefits. A PHEV has essentially two operating modes: a charge-sustaining mode and a charge-depleting mode. The total consumption benefits of a PHEV are a combination of the charge-depleting and charge-sustaining mode improvements.

Figure 1 highlights the relative importance of these two modes in achieving fuel displacement. It shows the total consumption benefit as a function of the improvement in charge-sustaining mode consumption for HEVs and PHEVs with several electric range capabilities. Several current model hybrid vehicles are included. Today's HEVs do not have a charge-depleting mode, so their total consumption benefits are derived solely from improvements in the charge-sustaining mode. The large dots on the plot present three scenarios that achieve 50% reduction in total petroleum consumption. A PHEV40 that consumed no petroleum (all-electric operation) in charge-depleting mode with a fuel economy in charge-sustaining mode equivalent to a conventional vehicle would consume 50% less petroleum because the first 40 miles of driving would be done electrically. Likewise, a PHEV20 that

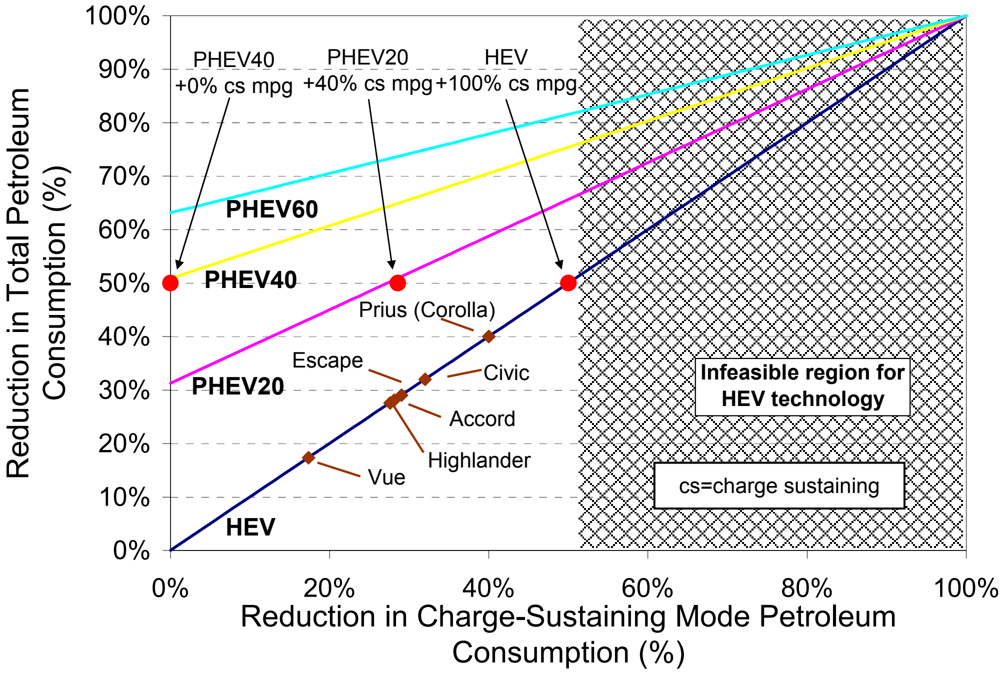

Figure 1: HEV and PHEV Fuel Consumption Benefits by Operating Mode

consumed 30% less petroleum in charge-sustaining mode would also consume 50% less total petroleum. An HEV would have to achieve 50% reduction in consumption in its charge-sustaining mode to have an equivalent total benefit. It is unlikely that the consumption reduction in charge-sustaining mode can be reduced beyond 50% cost effectively. Quantifying the relative costs of adding electric range capability versus improving charge-sustaining mode efficiency is important. Moving vertically in the figure at a given charge-sustaining mode consumption level results in more miles driven electrically. Electrification of miles through charge-depleting operation in a PHEV is expected to be a cost-effective way to continue to reduce fuel consumption beyond HEV technology capabilities.

The conclusions drawn from Figure 1 are based on national driving statistics shown in Figure 2. Figure 2 is a histogram showing the daily driving distance distribution and the resulting utility factor derived from the 1995 National Personal Transportation Survey (NPTS) data. The utility factor represents the fraction of total daily VMT that are less than or equal to the said distance. The utility factor is important for PHEVs because it can be used to effectively weight the value of the charge-depleting fuel consumption benefits versus the charge-sustaining fuel consumption benefits in a way that allows the results to be extrapolated and applied to the national fleet.

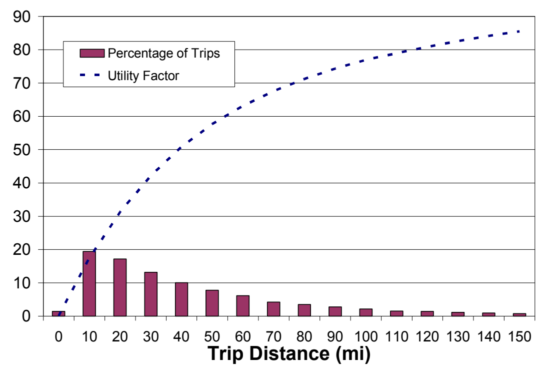

Figure 2: 1995 NPTS Data on Daily Driving Distance Distribution and Resulting Utility Factor

PHEVs take advantage of the fact that the typical daily driving distance is on the order of 30 miles. If most of these miles could be driven electrically, a large portion of our petroleum consumption would be eliminated.

Design Options and Implications

Determination of the energy storage system characteristics is a critical step in the PHEV design process. The energy storage system design variables include the power, energy, and usable state-of-charge (SOC) window. These three variables will affect cost, mass, volume, life, fuel economy, and vehicle operation.

The usable energy capacity of the energy storage system is defined by the desired electric range capability. The fuel displacement potential is directly related to the electric range capability. From Figure 2, a range capability of 20 miles (i.e., a PHEV20) would substitute electrical energy for petroleum consumption in 30% of total VMT. Likewise, a PHEV with 40 miles of range capability could displace 50% of total VMT. A typical midsize sedan will require ~300 Wh/mi for all electric operation. Thus a PHEV20 would require ~6 kWh, and a PHEV40 would require ~12 kWh of usable energy. It is possible to reduce the usable energy requirement through aerodynamic and lightweight vehicle designs but not substantially.

For design purposes, the usable SOC window relates the total energy capacity to the required usable energy capacity. A PHEV is likely to incur at least one deep discharge cycle per day and as a result will need to provide 4000+ deep discharge cycles in its 10-15 year lifetime. Figure 3 is a curve-fit to data presented by Rosenkranz showing the expected cycle life performance of lithium-ion (Li-ion) and nickel-metal hydride (NiMH) technology as a function of the discharge depth.[5] It shows that when a battery is discharged more deeply, the cycle life decreases. The horizontal, shaded box is the typical depth of discharge cycling that HEV batteries today incur while the vertical, shaded box is the range of cycles that a PHEV battery will need to endure for a 10-15 year vehicle life.

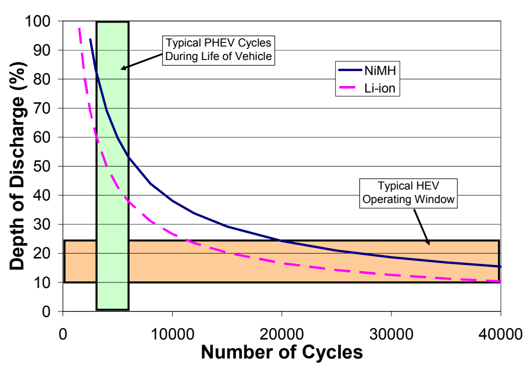

Figure 3: Cycle Life Characteristics of Varta Energy Storage Technologies [5]

The data indicate that NiMH can achieve 4000 cycles when discharged to 70% depth of discharge repeatedly. To achieve the same number of cycles, Li-ion technology could only be discharged to 50% depth of discharge on a daily basis. Assuming a 70% usable SOC window for a PHEV20 then requires 8.6 kWh of total energy capacity. This battery would have 5-10 times more energy capacity relative to that found in current hybrid vehicles. The PHEV40 will need 17.2 kWh. To minimize total energy storage capacity (and thus cost and volume), it will be important to maximize the usable SOC window for PHEVs while satisfying cycle life requirements.

The energy storage system cost, mass, and volume are strong functions of the energy storage system power to energy ratio. Representative specific power and power densities are provided for both Li-ion (based on Saft products [6]) and NiMH (based on Cobasys products [7]) technologies in Figures 4 and 5. Current and projected specific cost relationships are provided in Figure 6. The cost projections are those suggested by Electric Power Research Institute.[8] For fixed energy storage capacity, as power to energy ratio decreases so do cost, volume, and mass. The question is how does reducing the power capability affect the fuel consumption reduction potential?

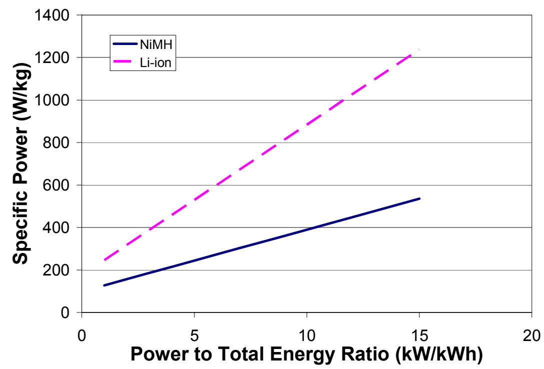

Figure 4: Typical Specific Power of Energy Storage Technologies

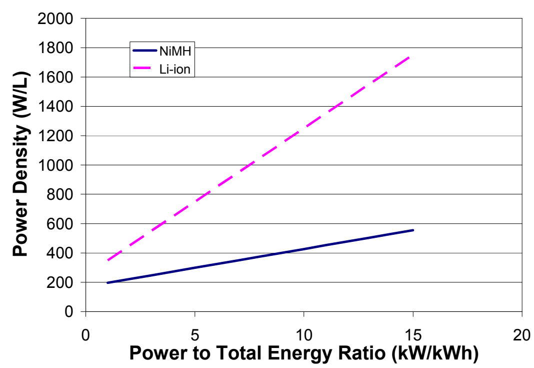

Figure 5: Typical Power Density of Energy Storage Technologies

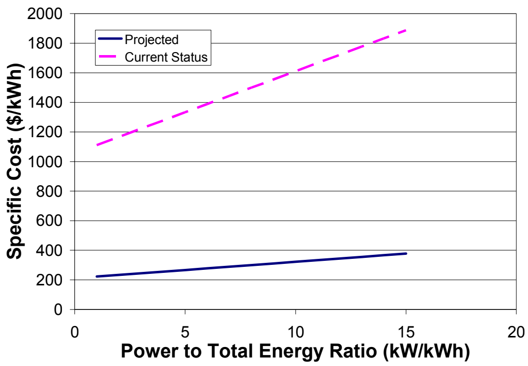

Figure 6: Typical Specific Cost of Energy Storage Technologies

To achieve a desired all-electric range (AER) capability, the energy storage system and motor will need to provide sufficient power to propel the vehicle without assistance from the engine. On an urban driving profile, the peak power is ~40 kW and the power is typically less than 15 kW as shown in Figure 7 for a typical light-duty vehicle.

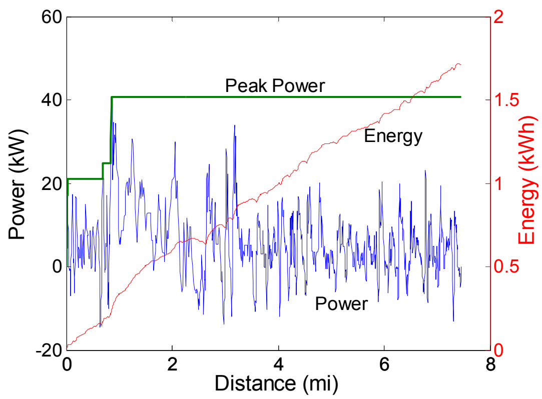

Figure 7: Power and Energy Requirements for All-Electric Range Capability on Urban Driving

In Figures 8 and 9, the power and energy required for all-electric range capability on several driving profiles is provided. The Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET) cycles are used by the U.S. Environmental Protection Agency to represent urban and highway driving behaviors in reporting the fuel economies of today's vehicles. The Unified Driving Cycle, also called LA92, and the US06 (part of the Supplemental Federal Test Procedure) are more aggressive urban and highway driving cycles respectively that are likely to be more representative of current driving behaviors. The energy to provide 20 miles of all-electric range on the UDDS and HWFET cycles only provides 10 and 15 miles of range capability on the US06 and LA92 cycles, respectively as shown by the dashed line in Figure 9. A PHEV on the UDDS would need 40 kW of battery power while it would require more than 60 kW on the LA92 cycle. Adding battery power beyond the peak power requirement is unlikely to provide additional value. Acceleration requirements will place additional constraints on the energy storage system power requirements depending on engine sizing.

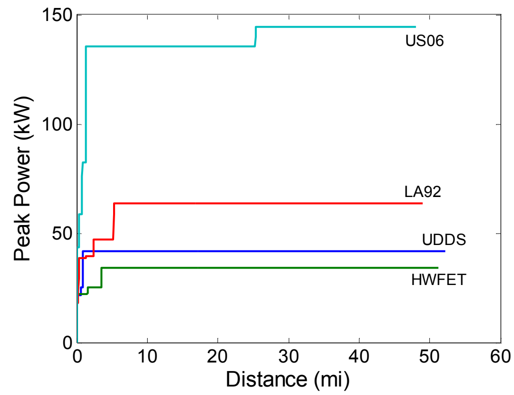

Figure 8: Peak Power Requirements for All-Electric Range Capability for Typical Mid-size Car on Several Duty Cycles

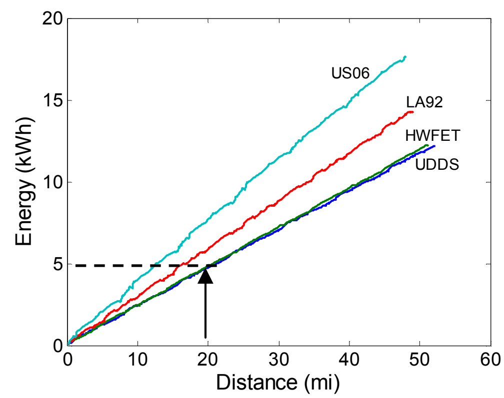

Figure 9: Usable Energy Requirements for All-Electric Range Capability on Typical Driving Profiles for a Mid-size Car

To maximize charge-sustaining fuel economy, it is desirable to minimize the power rating (downsize) the engine as much as possible. The engine in a PHEV will likely be sized to provide continuous performance capability. If it is assumed that the vehicle must achieve a continuous top speed of 110 mph and continuous gradeability at 55 mph on a 7.2% grade using 2/3 of peak engine power then the minimum engine would need to be 80-85 kW for a typical sedan. Now to achieve a 0-60 mph acceleration time of 8.0s or less, the energy storage system would need at least 45-50 kW of power capability at the low SOC operating point. As a result, with maximum engine downsizing, the power to energy ratio would be ~5 for a PHEV20 and 2.8 for a PHEV40.

The sizes described so far are only necessary to achieve large all-electric range capabilities. Significant fuel can be displaced without large all-electric range capability. As shown in Figure 7, the urban drive cycle power requirements are typically less than 15 kW. Since cost, mass, and volume of the energy storage system can be reduced by reducing the power to energy ratio, it is worthwhile to explore the fuel displacement potential of low power energy storage systems for PHEVs.

The lower bound on the energy storage power will be a function of the lowest power to energy ratio modules available. The lowest power to energy ratio for typical Li-ion or NiMH technology today is ~1. Therefore, the minimum power will be on the order of 10-15 kW.

Employing the low-power option limits the all-electric range capability of the vehicle. However, if, when the engine is on, it only provides supplemental power beyond the capabilities of the energy storage system; substantial fuel displacement can still be achieved via a strategy where energy storage and engine operate in a blended manner. The blended approach was proposed in an early paper [9] and will be referred to as a blended strategy in the remainder of the paper.

Figures 10 and 11 provide a comparison between operating characteristics for PHEVs with all-electric-range-focused versus blended operating strategies. In Figure 10, the battery and motor (dashed line) have sufficient power to propel the vehicle until about 22 miles at which time the engine (solid line) is turned on. In Figure 11, the engine turns on within the first mile but when on, it only provides supplemental power, and the battery still provides most of the power. Thus, the battery discharges over approximately the same distance and displaces nearly as much fuel.

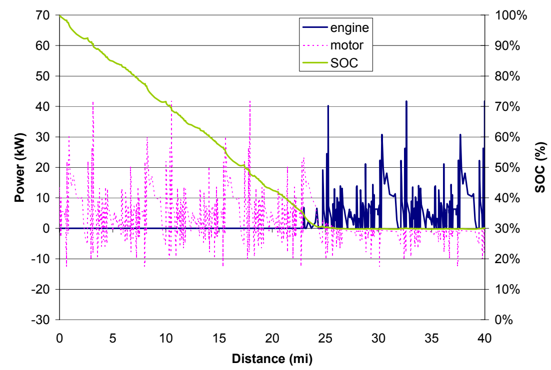

Figure 10: Urban Cycle Operating Characteristics of an All-Electric Range Focused PHEV20

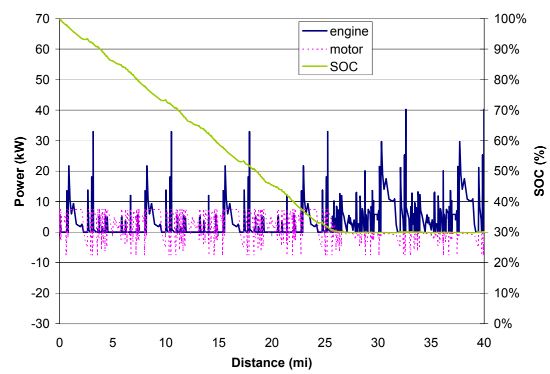

Figure 11: Urban Cycle Operating Characteristics of a PHEV20 with a Blended Strategy

The charts that follow summarize the tradeoffs of power, energy, SOC window, and operating strategy on the cost, efficiency, and fuel savings potential of a PHEV20 and a PHEV40. All components in each vehicle scenario were sized first for an all-electric range scenario and second for a blended scenario. And for each of these four scenarios, a 50% SOC window and a 70% usable SOC window were considered. To define the blended scenario, a power to energy ratio was chosen that was half that of the all-electric range scenario.

Figure 12 summarizes the energy storage system power and energy characteristics of the eight vehicles considered. The SOC window only slightly impacts the power requirement while the AER case needs twice as much power as the blended case as designed. Battery energy is slightly more than a factor of two due to mass compounding.

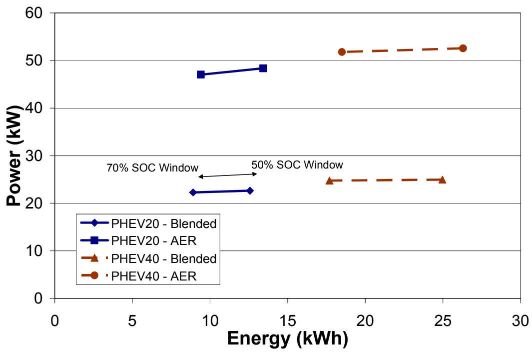

Figure 12: Power and Total Energy Characteristics of the Energy Storage System

Incremental cost of the vehicle is likely to be a significant barrier to PHEV technology acceptance. The main reason for trying to use a lower power to energy ratio energy storage system would be to reduce cost while providing the same amount of energy. Figure 13 shows that reducing power to energy ratio and moving from an AER to blended strategy reduced incremental cost. However, increasing the usable SOC window seemed to more strongly impact the incremental costs.

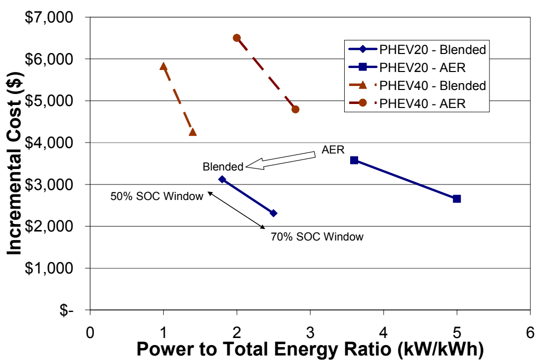

Figure 13: Relationship between Incremental Cost and Power to Energy Ratio

For a given range (e.g., PHEV20) and SOC window (e.g., 50%), moving to a lower power to energy ratio not only reduced the incremental cost but also reduced the fuel consumption reduction potential as expected. The fuel consumption benefits of the blended strategy are about 6% less than the AER strategy for both PHEV20 and PHEV40 cases as shown in Figure 14. Interestingly, expanding the usable SOC window has minimal impact on fuel consumption reduction potential but substantially reduces incremental cost and thus should be emphasized.

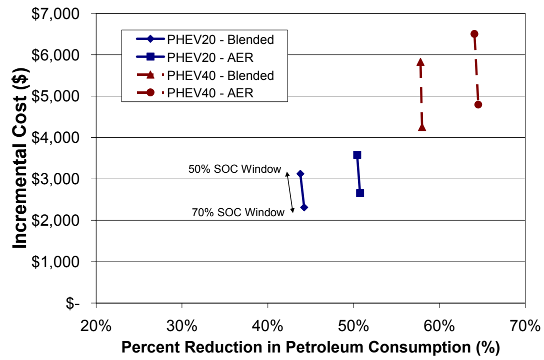

Figure 14: Cost-to-Benefit Relationship for PHEVs

As shown in Figure 15, there are efficiency tradeoffs between a blended and an all-electric range focused strategy. In the AER approach, the engine is as small as possible and when it is on, it will operate at higher load fractions which typically correlate to higher efficiencies. The energy storage system in the AER scenario is a higher power to energy ratio with lower internal resistance and thus less loss. On the other hand, the motor in the blended approach is smaller, and thus running at higher load fractions with higher efficiencies.

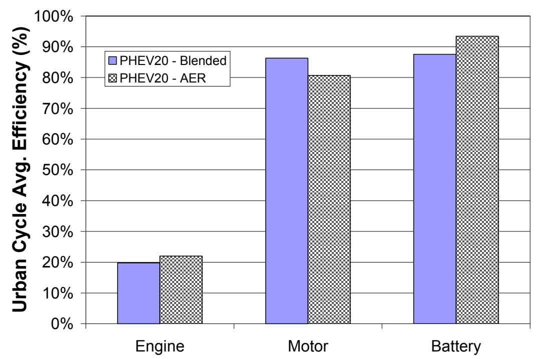

Figure 15: Component Efficiencies for AER and Blended PHEV Strategies

The purpose of these case scenarios is to demonstrate that there are many options in the design of a PHEV. Each of these options has associated tradeoffs. Ideally, the design should find a balance between petroleum consumption reduction potential and incremental costs if it is to be successful. Our results demonstrate that a blended approach combined with an expanded SOC window effectively reduced cost while displacing nearly as much fuel in comparison to an all-electric range focused PHEV. These cost reductions are critical for market viability.

Analysis Refinements

This analysis provides only a simplified view of the PHEV design space and challenges. There are many uncertainties associated with these conclusions. In particular, there is uncertainty associated with the life cycle data, the battery cost data, and the vehicle usage patterns. It will be important to identify how each of these uncertainties will affect the PHEV design and operation.

The life cycle data available at this time have been collected as constant discharge cycles to a specified depth of discharge repeatedly. The batteries in HEVs today can be expected to encounter tens of thousands of small depth of discharge cycles at a moderate to high SOC. PHEVs will on the other hand encounter at least one deep discharge cycle on a daily basis. In addition, a fully utilized energy storage system will also encounter shallow depth of discharge cycles both at high and low SOC levels. It has been assumed that the daily deep discharge cycle will be the overriding factor that will determine life cycle performance. It is unclear how the shallow cycling behavior may contribute to the degradation of the energy storage system.

Today, the cost of hybrid battery technology is high, and tax incentives are used to make hybrids cost competitive with comparable vehicle options. The energy storage system costs contributing to the incremental cost analysis presented earlier assume future high-volume production. Current costs are estimated to be 4-5 times higher than the long-term assumptions. Since this is a pivotal assumption, it is possible to turn the analysis around and look at what battery costs might need to be to provide a cost effective vehicle.

Figure 16, shows the specific costs that the energy storage technology would need to achieve for the fuel cost savings over 5 years to offset the initial incremental cost. The chart includes both a present fuel cost ($2.15/gallon gasoline and 9 ¢/kWh electricity case) and a future fuel cost scenario ($4.30/gallon and 9 ¢/kWh). At today's fuel costs, to be cost neutral, PHEV20 batteries would need to be at the projected long-term cost goals (labeled as Projected Battery Costs in Figure 16). However, in the future fuel price scenario, both PHEV20 and PHEV40 energy storage systems only need to reach the $750 to $500/kWh range to be cost neutral respectively.

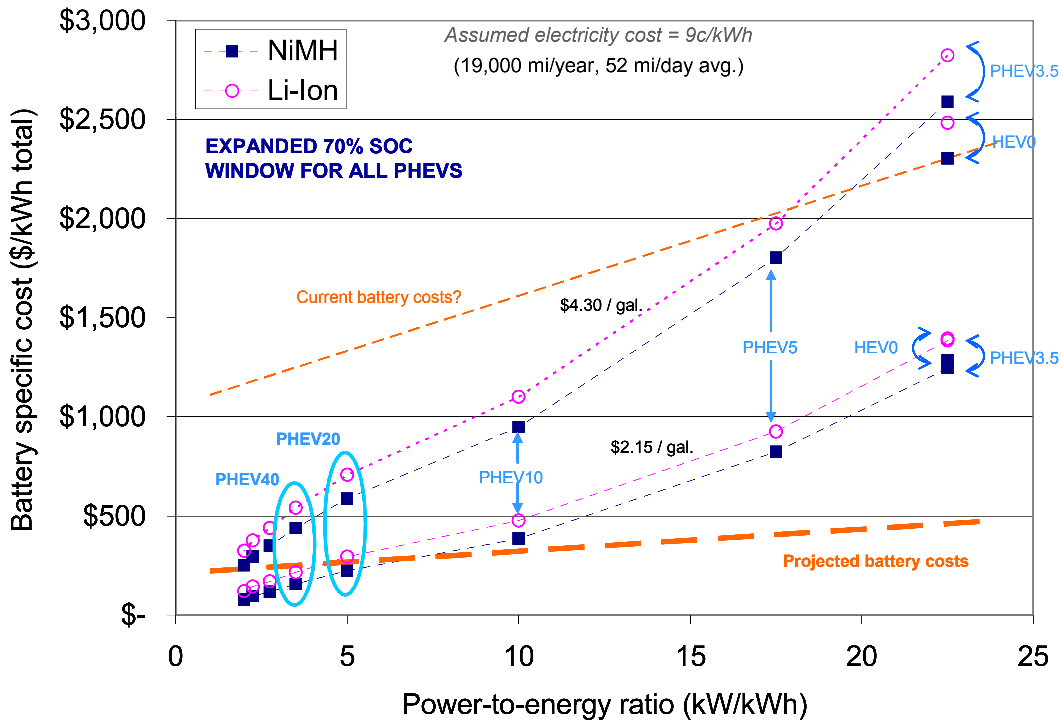

Figure 16: Battery Cost Requirements for Fuel Savings to Offset Incremental Cost within 5 Years

Additional research completed at the National Renewable Energy Laboratory clearly shows that there is a significant connection between the vehicle usage pattern and the consumption reduction benefits of a PHEV both over a conventional vehicle and an HEV. The analysis presented assumes utility factor weighted fuel economies based on the UDDS and HWFET driving profiles. It is fair to assume that neither of these driving profiles (developed in the 1970s) accurately represents typical driving habits of today. In addition, the utility factor is used to weight the relative value of the electric range capability of a PHEV. However, the utility factor is based on data from national personal travel surveys conducted in 1995. More recent data are available and need to be analyzed. It's likely that travel behavior is evolving. In addition, the existing survey data typically only represent a single day of the year and do not account for variation daily or seasonally. PHEV benefits are likely to be significantly influenced by these variations in driving habits.

Conclusions

PHEVs have the potential to dramatically reduce future U.S. transportation petroleum consumption. To overcome the implementation challenges of PHEV technology, a systems perspective should be employed. This study sheds light on the systems design tradeoffs as they relate to energy storage system technology for PHEVs. Specifically, it evaluates the impacts of reducing power to energy ratio and expanding the usable SOC window on incremental cost and fuel consumption reduction benefits.

Based on the analyses, we conclude that:

- Plug-in hybrids provide potential for reducing petroleum consumption beyond that of HEV technology.
- There is a spectrum of PHEV design options that satisfy performance constraints but with tradeoffs in incremental costs and fuel consumption reduction potential.
- Expansion of the usable SOC window while maintaining energy storage system life will be critical for reducing incremental costs of PHEVs.
- The fuel consumption reduction benefits are only slightly reduced while the battery size and cost are significantly reduced when a blended strategy is chosen relative to an all-electric range focused strategy.

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This paper discusses the design options for a plug-in hybrid electric vehicle, including power, energy, and operating strategy as they relate to the energy storage system.

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Plug-in hybrid electric vehicle; hybrids; PHEV; energy storage

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