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Energy Management Strategies for Plug-In Hybrid Electric Vehicles

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) differ from hybrid vehicles (HEVs) with their ability to use off-board electricity generation to recharge their energy storage systems. In addition to possessing charge-sustaining HEV operation capability, PHEVs use the stored electrical energy during a charge-depleting operating period to displace a significant amount of petroleum consumption. The particular operating strategy employed during the charge-depleting mode will significantly influence the component attributes and the value of the PHEV technology. This paper summarizes three potential energy management strategies, and compares the implications of selecting one strategy over another in the context of the aggressiveness and distance of the duty cycle over which the vehicle will likely operate.

INTRODUCTION

PHEVs have the potential to reduce fuel consumption to levels even lower than those achieved by the commercially-available HEVs now manufactured by many major automakers. Current HEVs deliver efficiency improvements through means such as enabling the engine to shut off rather than idle, recapturing a portion of normally wasted braking energy, and permitting engine downsizing to improve average in-use efficiency. While such hybridization benefits do improve the fuel economy of these vehicles, all of the available energy still comes from the fuel tank. PHEVs enjoy the same hybridization benefits as HEVs and also provide an opportunity for fuel switching—obtaining some of the vehicle's usable energy in the form of electricity through a charging plug, which displaces some of the energy that would otherwise be obtained by burning fuel in the vehicle's engine.

Fuel switching provides an operating cost benefit as well as a national security benefit by reducing the amount of petroleum required by the nation's vehicle fleet. Full electric vehicles (EVs) also enjoy these benefits, but have very large batteries and motors, limited range, and require several hours to recharge before reaching full-range capability. The onboard fuel converter helps PHEVs mitigate these drawbacks and allows them to fall back on charge-sustaining (CS) HEV operation. However, until the PHEV exhausts the stored electrical energy obtained through its charging plug, an energy management strategy must decide how to best use both energy sources (fuel and stored electricity) in a charge-depleting (CD) operating manner.

One possibility is to allow the driver to manually select between a CS HEV and a full EV operating mode. This could be useful if the vehicle operates in a region that restricts use of the onboard combustion engine (such as in a city center or in a tunnel). In order to ensure that the vehicle possesses sufficient charge to operate in the use-restricted region, the driver would command CS HEV operation prior to reaching the region and CD EV operation within the region. Further consideration of this example reveals that the choice of energy management strategy dictates vehicle component design decisions. Specifically, the energy content of the vehicle battery must be sufficient to operate the vehicle through the full distance of the anticipated use-restricted zone. The power of the battery and motor must also be sufficient to provide full operating capability without using the vehicle's engine. The strategy also influences the value proposition of the PHEV technology. Not only does this example vehicle benefit from fuel switching, but it also receives the special privilege to operate where other vehicles cannot. Realizing this benefit, however, requires the vehicle to effectively possess a fully redundant powertrain, which requires increased cost, mass, and volume as compared to designs without full EV operating capability [1].

While the previous example represents a particular niche application, PHEVs in more widespread use may rely upon a single 'normal' operating mode rather than various driver-selected modes. In such cases, the vehicle will use the stored electrical energy during initially CD operation, and eventually switch to CS operation after exhausting the energy obtained during charging. The remainder of this paper will examine three different energy management approaches for this initial CD operating period, and discuss their implications for component design and the delivered benefit from the PHEV technology. The strategies discussed are an all-electric-range (AER) or AER-focused strategy, an engine-dominant blended strategy, and an electric-dominant blended strategy.

AER-FOCUSED STRATEGY

Similar to the example discussed in the Introduction, an AER-focused strategy seeks to operate the PHEV all-electrically during roughly the full range of CD operation. During continued driving, the vehicle switches to CS HEV operation.

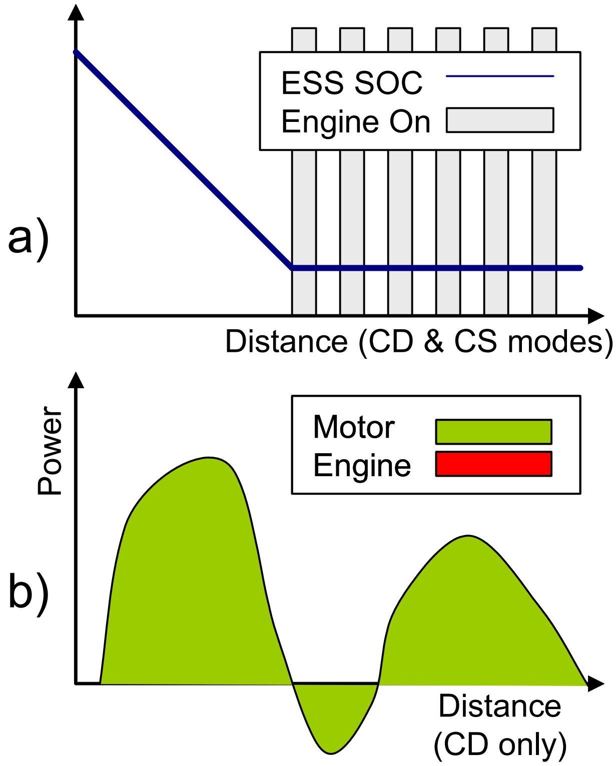

Figure 1. Example illustration of the AER-focused strategy: a) engine and SOC usage (CD & CS modes); b) power split in CD mode.

Figure 1 provides an example illustration of the AER-focused strategy operation. Before driving, the vehicle's fully charged energy storage system (ESS) begins at its maximum state-of-charge (SOC) as shown in Figure 1a. The SOC drops during the CD operating distance as the vehicle drives electrically without assistance from the engine. Once reaching the CS SOC level, the SOC remains roughly steady while the engine and motor work together during CS HEV operation. Figure 1b emphasizes that during CD operation, the motor satisfies the full vehicle power demand, and the engine remains off.

In order to achieve all-electric CD operation, the AER-focused strategy dictates sizing the motor and ESS power capability to at least match the maximum power requirement of the expected cycle. As in the driver-selected EV-mode operating example, the effectively redundant powertrain that results will be larger and more costly than if lower-power electric drive components were selected. Even so, a high-power electric drive capability does have some advantages. Drivers who enjoy the feel of quiet and smooth all-electric operation will appreciate a vehicle that can complete a full drive cycle without needing the engine. If the engine never turns on during a moderate-distance drive cycle, the vehicle will also emit zero tailpipe pollutants. This potential emissions benefit led the California Air Resources Board (CARB) to designate that PHEVs achieving at least 10 miles of AER would receive a much larger credit weighting towards the state's zero-emission-vehicle (ZEV) regulation as compared to PHEVs not employing an AER-focused strategy [2].

Discussion of the advantages and disadvantages accompanying a particular energy management strategy would be incomplete without consideration for how the actual drive cycle driven by the vehicle might vary from the cycle for which it was designed. The drive cycle can vary with respect to its intensity and with respect to its distance—specifically the distance driven between vehicle recharge events. An AER-focused PHEV driving more aggressively than the cycle for which it was designed will have to utilize its engine during CD operation or else fail to meet the higher-power road load demand. For instance, CARB awards zero emission range credit based on the distance a PHEV can drive all-electrically over repetitions of the U.S. Environmental Protection Agency's (EPA's) standard Urban Dynamometer Driving Schedule (UDDS). A midsize sedan platform PHEV weighing 1700 kg requires roughly 45 kW to meet the peak driving demand of the UDDS. However, an AER-focused PHEV designed to just satisfy the mild UDDS cycle intensity will fail to achieve its AER rating when driven more aggressively in the 'real world.' This detracts from the actual in-use experience of the anticipated benefits mentioned above. To help avoid this problem, the vehicle could instead be designed to provide all-electric operation on more aggressive driving such as the EPA's US06 cycle, which was introduced to measure vehicle emissions over higher driving speeds and acceleration rates. Such a change, however, would lead to even larger and costlier electric drive requirements (the peak power requirement for the same midsize PHEV on the US06 cycle would be over 100kW). The alternative would be to allow engine assistance when the vehicle drives more aggressively than the AER-designed cycle (such as with the electric-dominant blended approach described later in this paper).

The driving distance between vehicle recharges will also influence the impact of a PHEV as compared to a conventional or hybrid vehicle. Driving distance will particularly influence the relative amount of petroleum displacement provided by the PHEV. For driving distances equal or less than the AER (assuming a vehicle designed for the type of driving experienced), the AER-focused strategy provides maximum petroleum displacement—the engine remains off and uses no fuel. For longer driving distances, the fuel consumed during

CS HEV operation is divided into the full CD plus CS distance to determine the average petroleum fuel economy for that particular driving. If driven far enough, a strategy optimally blending engine and battery/motor operation could save more fuel than the AER-focused strategy. This would result from using the engine to efficiently power the larger driving demands during CD operation. The energy saved from not powering those driving demands electrically can instead be used to extend the boosted-efficiency CD operating period.

For instance, Figure 2 provides an example of a load-leveled CS engine operating range. Note that the region of most efficient engine operation is narrower than the CS operating region, but that the vehicle cannot remain charge neutral when controlling to this narrower range. For driving longer than the AER distance, an AER-focused PHEV will enter the CS operating mode sooner than will a PHEV using a blended control strategy. The blended PHEV will be able to operate longer in the boosted-efficiency CD mode, giving it slightly higher average engine efficiency over long driving distances. The next section will describe a blended strategy in more detail and discuss some of the implications for its use.

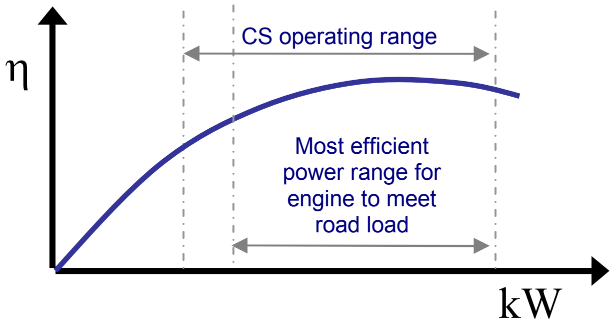

Figure 2. Example engine efficiency curve and operating ranges.

ENGINE-DOMINANT BLENDED STRATEGY

An engine-dominant blended strategy uses the stored electrical charging energy to supplement engine operation, but spreads out its utilization so as to maximize system efficiency (which is typically dominated by the engine operating efficiency). Figure 3 provides an example illustration of this strategy. In Figure 3a the vehicle again begins driving with the ESS at its maximum SOC level. The vehicle may operate all-electrically during initial CD operation (as indicated in Figure 3a by the declining SOC with initially no engine operation). However, the engine eventually turns on during the CD mode as soon as the driving demand becomes high enough to either exceed the power capability of the battery and motor or to be satisfied by efficient engine operation as described above. After the engine turns on, the battery supplements the engine power in a way that both consumes electrical energy from the ESS but also maximizes engine (or system) efficiency. Figure 3b demonstrates this operating characteristic where efficient engine operation provides the basis for meeting the driving power demand and the electric drive supplements for demands greater than the power capability or efficient operating region of the engine. The electric drive operates alone during negative power demands (to recapture regenerative braking energy) and during low power demands that would be inefficient for the engine to satisfy. Because the engine-dominant blended strategy draws on the engine earlier and more frequently as compared to the AER-focused strategy, it will spread out utilization of a given amount of electrical recharge energy over more miles of CD operation. This is reflected by the more gradual slope of the ESS SOC line in Figure 3a as compared to that in Figure 1a.

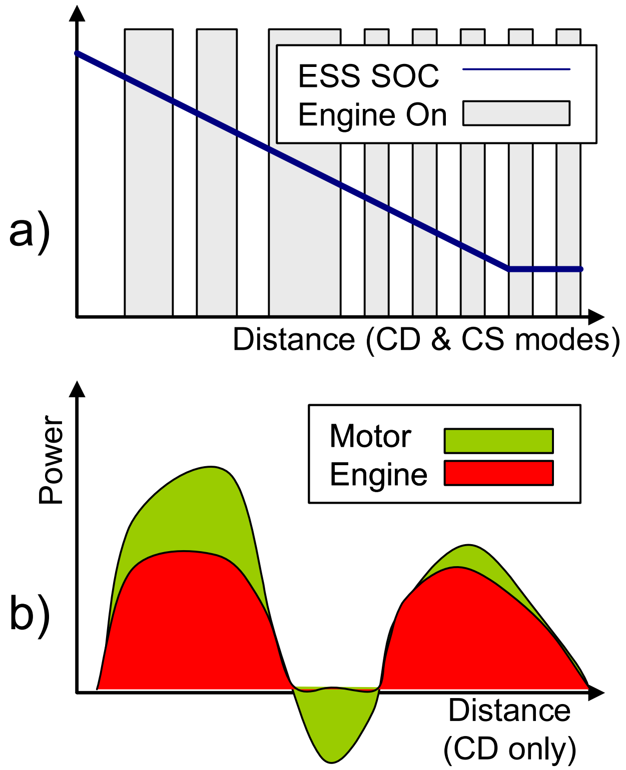

Figure 3. Example illustration of the engine-dominant blended strategy: a) engine and SOC usage; b) power split in CD mode.

Because it lacks a full EV-capability requirement, an engine-dominant blended PHEV can utilize much smaller and less expensive electrical components. The strategy can actually operate very similarly to present-day HEVs, simply making more liberal use of electrical assist during CD operation. Therefore, the power capability of the electric drive need not exceed that of existing HEV components. In order to achieve a significant amount of driving in CD mode, the energy content of the ESS needs to be greater than that in current HEVs, however, the cost increase should be less than proportional to the increase in energy content. This results from achieving economies of scale, a likely widening of the allowable

SOC usage window, and the fact that a higher-energy, constant-power ESS can be constructed from batteries with a lower power-to-energy ratio that are less expensive on a $/kWh basis [3].

The trade-off for using smaller electric drive components is that an engine-dominant blended PHEV will have a much lower petroleum displacement rate during CD operation. Such a PHEV will also not receive the considerable credit boost from meeting the CARB zero emission range criteria. The impact of cycle intensity on the PHEV benefit is considerably lessened for this strategy because the engine already operates at significant power levels. However, the total amount of petroleum savings will depend significantly on the driving distance between vehicle recharges. If the vehicle is driven a long distance, a considerable fuel savings will be achieved from spreading out use of the electrical recharge energy so as to supplement fuel consumption and maximize system efficiency. On the other hand, if the vehicle drives less than the CD distance, the vehicle will consume more fuel and under-utilize the ESS electrical storage capacity (as compared to strategies that do not rely so much on engine operation during the CD mode). Another study has suggested that the fuel use penalty for under-utilizing the ESS will likely be greater than the additional savings from spreading out electrical energy use to maximize system efficiency, making the engine-dominant blended strategy (from a petroleum displacement standpoint) less than ideal if the vehicle driving distance is uncertain [4].

ELECTRIC-DOMINANT BLENDED STRATEGY

An electric, ESS/motor-dominant blended strategy operates similarly to the AER-focused strategy. The key difference is that the control and component sizing do not prioritize achieving a substantial all-electric driving distance during CD operation. Figure 4 provides an example illustration of this strategy. As in Figure 3a, the ESS SOC declines from an initial maximum at the far left of Figure 4a, with the vehicle operating all-electrically only until the driving demand exceeds the power capability of the ESS and electric motor. In contrast to the engine-dominant blended strategy, the electric-dominant blended strategy only uses the engine to satisfy the transient load demand beyond the power capabilities of the ESS and motor. As Figure 4b illustrates, the ESS and motor supply most of the power demand during CD operation, with the engine providing a small amount of additional assistance. Even though the engine may not operate at its maximum efficiency point, its small power demand will require very little fuel. For a comparable amount of electrical recharge energy, the CD distance for the electric-dominant blended strategy will be greater than that for the AER-focused strategy (engine fuel use spreads out electrical energy utilization) and less than that for the engine-dominant blended strategy (only a small amount of engine assistance takes place).

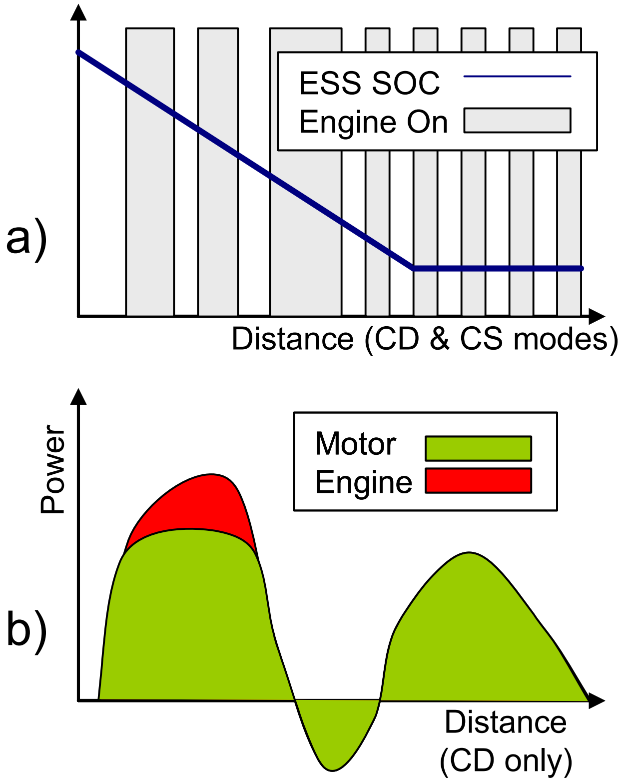

Figure 4. Example illustration of the electric-dominant blended strategy: a) engine and SOC usage; b) power split in CD mode.

As with the engine-dominant blended case, relaxation of the full EV-power requirement allows an electric-dominant blended PHEV to use smaller and less expensive components. The electric drive could possess greater power capability than a comparable engine-dominant blended PHEV, but need not be sized to satisfy very large power demands that occur infrequently during a drive cycle. However, the resulting intermittent low-power engine operation will present unique emissions control system challenges for these vehicles.

Intermittent engine operation during the CD mode would also prevent electric-dominant blended PHEVs from receiving the credits for satisfying CARB's zero emission range criteria. However, the rate of petroleum displacement during the CD mode will still be nearly as great as that for AER-focused PHEVs. Increased cycle aggressiveness should not have a particularly large impact on electric-dominant blended PHEVs, since these vehicles will already be designed to accommodate large intermittent power demands. Sensitivity to cycle distance will be similar to the discussion for AER-focused PHEVs: relative to HEVs and conventional vehicles the percentage petroleum displacement will be greatest for driving less than the CD distance. The percentage savings will be diluted for longer distances as more miles of CS HEV operation become included. Compared with the engine-dominant blended strategy for driving greater than that strategy's CD distance, the electric-dominant blended strategy will consume slightly more fuel due to focusing less on maximizing engine efficiency throughout all driving modes. However, for driving much less than the engine-dominant blended strategy's CD distance, the electric-dominant blended strategy will consume significantly less fuel due to its greater utilization of electrical recharge energy.

CONCLUSION

The choice of CD operating strategy directly influences PHEV design decisions and the benefit derived from the technology. The AER-focused strategy requires larger and more expensive electric components, but offers all-electric cycle operational benefits, including receiving greater credits towards satisfying CARB's ZEV regulation. The engine-dominant and electric-dominant blended strategies do not achieve as great all-electric operation benefits, but are able to utilize smaller and less expensive electric components. The AER-focused strategy is particularly sensitive to increased cycle aggressiveness because it will be unable to satisfy significant power demands during the CD mode all-electrically as designed. The engine-dominant blended strategy is particularly sensitive to driving distance, as the vehicle must exceed the CD distance in order to benefit from the efficiency maximization approach. For shorter driving distances, the engine-dominant blended strategy will have a significant fuel use penalty as compared to the other strategies due to under utilization of the electrical recharge energy.

If the vehicle could make intelligent predictions about the upcoming cycle, the greatest fuel savings strategy would be to adaptively switch between the engine-dominant and electric-dominant blended approaches. If the vehicle will definitely travel a long distance, the controller could select the engine-dominant blended strategy to realize the fuel savings provided by the efficiency maximization approach. If the vehicle might drive a shorter distance before recharging, the controller would select the electric-dominant blended strategy in order to maximize use of the electrical recharge energy. In the absence of future driving information and provided an effective emissions control system could be designed, the electric-dominant blended strategy would deliver effective utilization of the electrical energy during CD operation, and could have a relatively small fuel efficiency opportunity loss for longer driving distances. A PHEV manufacturer designing such a vehicle for electric-dominant blended CD operation over real-world driving could still size the electric drive large enough to meet the peak power requirement on the UDDS. Although cost remains a major challenge for PHEVs (and is examined more closely in other studies), the additional cost increment for this extra power capability could be worthwhile, particularly since the increased electric power would improve the vehicle's acceleration capability, which in turn increases its consumer appeal. The vehicle produced by such a design approach could realize real-world petroleum savings, capture consumer attention, and achieve clean vehicle certification that would award substantial ZEV regulation credits under the current CARB rules.

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