01 Sep 2008

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Recommended Citation

D. Somayajula et al., "Study on the Effects of Battery Capacity on the Performance of Hybrid Electric Vehicles," *Proceedings of the IEEE Vehicle Power and Propulsion Conference (2008, Harbin, China)*, Institute of Electrical and Electronics Engineers (IEEE), Sep 2008.
The definitive version is available at https://doi.org/10.1109/VPPC.2008.4677504

IEEE Vehicle Power and Propulsion Conference (VPPC), September 3-5, 2008, Harbin, China

Study on the Effects of Battery Capacity on the Performance of Hybrid Electric Vehicles

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***Abstract*—Hybrid electric vehicles are gaining a significant presence in the auto market. However, the present day hybrid electric vehicles mostly use battery as a secondary source of power. If the battery were to be used as a primary source of power then the battery capacity is one of the important features in the design of a hybrid electric vehicle. Hybrid electric vehicles which are powered by more than one energy source have to follow a good energy management strategy to provide the best fuel economy in all situations. This paper presents a comprehensive study of the effect of variation of the energy storage system size on the fuel economy of a hybrid electric vehicle and the important design criteria involved in the design of the energy storage system. Simulations carried out using ADVISOR software show that increase in battery capacity alone cannot improve the fuel economy.**

***Keywords*—All electric range; Blended mode; Charge depleting mode; Energy storage system**

I. INTRODUCTION

The biggest challenge facing the world today is to reduce global warming and dependence on oil as emphasized in [1]. In this context, it is necessary for the countries of the world, especially United States, to improve the efficiency of cars which are mostly run by gasoline and which are a major contributor of the carbon emissions. The probable solution for this crisis, as stated in [1], is the mass production of hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV). A PHEV is a hybrid vehicle that could be charged from the grid. HEVs and PHEVs have better fuel efficiency. However, the biggest barrier in the mass production of these vehicles is energy storage system (ESS) cost. The performance of the ESS which consists of different battery modules is thus dependent on battery model, battery technology, cost, and performance. The parameters to be considered in ESS design are discussed in [2].

Since the vehicle is powered by two energy sources (fuel and battery) an energy management strategy which decides the best way to utilize the energy available from internal combustion engine (ICE) and battery is needed. Energy management strategy is one of the key parameters which can vary the efficiency of the vehicle considerably. Currently 2 strategies are being employed as shown in Fig.1. The first strategy is called the charge sustaining (CS) strategy. In this strategy, the state of charge (SOC) of the battery is regulated to be relatively constant over the drive cycle and the battery assists the engine. The second strategy is called charge depleting (CD) strategy. In this strategy the SOC of the battery is allowed to fall to a certain low value before the ICE starts to operate. The battery could be recharged either during the regenerative braking mode like in HEVs or from the grid like in PHEVs depending on the battery capacity and the amount of energy needed to charge it. The importance of the CD mode and its inherent advantages over CS mode are emphasized in [2].

The present HEVs mostly rely on CS strategy which has the following advantages 1) ICE is downsized, 2) ICE has to supply just the average power, and 3) Regenerative braking energy is captured in the battery. Thus there is considerable improvement in fuel economy and the emissions are also considerably less. The main drawback of CS strategy is that battery capacity is less and it is designed to store the energy available in regenerative braking without further charging from the grid; without the grid charging capability the battery cannot be used as the primary energy source to power the vehicle. This mode improves the fuel economy and reduces emissions to an extent. However, gasoline is still the primary energy source and dependence on it is not completely reduced. On the other hand, charge depleting CD strategy is used only in electric vehicles (EV) at present. The CD strategy has the following advantages 1) Zero emissions at the tail pipe, 2) reduced or no dependence on gasoline, and 3) cheaper energy source to power the vehicle. The main drawbacks of CD strategy are 1) the battery capacity is large, 2) the gasoline engine which acts as a backup in emergency situations is largely unutilized, 3) the batteries are costly thereby increasing the cost of the vehicle and 4) the batteries could be damaged during aggressive drive cycles.

Therefore, a possible trade off strategy called the CD blended strategy is defined. In this strategy, the battery pack capacity is larger than present HEVs though not as large as the battery packs in EVs [1]. In CD blended mode vehicle operates on both battery and the gasoline engine. The use of gasoline engine along with the battery reduces the battery size and cost considerably. The CD blended mode of operation could be implemented in HEVs only if they are grid charged i.e. they are PHEVs. In PHEVs the energy captured during regenerative braking is not sufficient to recharge the battery pack. [2]. In [1, 2], parameters affecting the design of ESS for HEVs and PHEVs are presented. In [3], different energy management strategies for PHEVs and the types of

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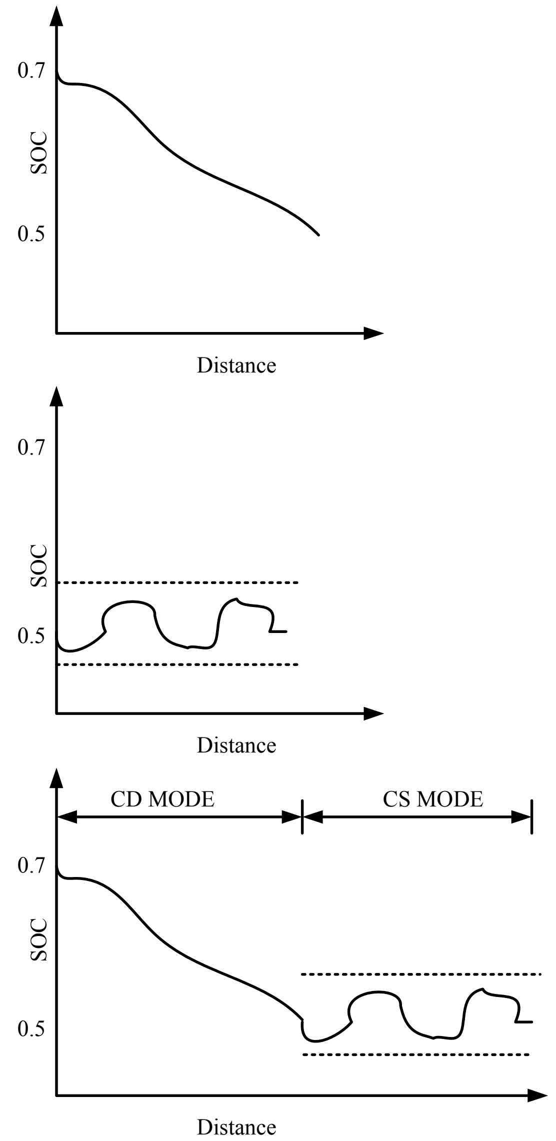

Figure 1. State of charge (SOC) vs. distance as shown in CD, CS, and CD blended modes

blended mode are discussed. The modeling of vehicles using the ADVISOR software is discussed in [4-7]. In [8-14], different types of onboard energy management strategies in HEVs are discussed. Cost comparison of PHEVs with HEVs and conventional vehicles is presented in [15, 16]. Current battery trends and the progress in PHEV conversion details can be obtained from [17, 18]. However, study on the effects of change in ESS size on the performance of a hybrid vehicle under CD blended mode of operation has not been reported. In this paper the effects of change in ESS size of a vehicle which is in CD blended mode of operation is carried out using ADVISOR simulation tool. Section II describes the different design considerations to be made in the selection of the battery, the simulation results are analyzed in Section III, and the conclusions that can be drawn from the simulation results are presented in Section IV.

II. Design Considerations

Battery capacity and cost determine the cost of an HEV; therefore, it is important to define the battery parameters correctly. One of the battery parameters is P/E which is defined as the ratio of battery power to battery energy [2]. Equation (1) shows how the P/E value can be determined for a given battery pack. P/E is a useful parameter and it is determined by the type of the vehicle. The HEVs or PHEVs with high all electric range (AER) require high battery energy and therefore the ratio P/E is low. Similarly hybrids with gasoline engine assisted by an electric motor (current hybrids like Prius) have high P/E since the battery has to handle high instantaneous powers for short time periods. This high PE ratio demonstrates how the battery energy can be less in the case of the HEV since the battery is not the primary energy source. Lower P/E ratios of 5 to 20 are considered ideal for "grid connected" HEVs or PHEVs [2].

$$\frac{P}{E}\left(\frac{1}{h}\right) = \frac{power(kW)}{energy(kW-hr)} = \frac{specific\ power\left(\frac{W}{kg}\right)}{specific\ energy\left(\frac{Wh}{kg}\right)} \quad (1)$$

The battery energy management is an important design consideration. The vehicle can be operated in charge sustaining or charge depleting modes as mentioned earlier. There are different types of charge depleting modes of operation for an HEV including 1) all electric, 2) engine dominant, and 3) electric dominant. In the all electric CD modes the engine is off while the battery operates thus only battery has to power the vehicle. Thus the size of electric motor to power the vehicle increases and the battery capacity is more which leads to additional costs in battery as well as in the electric motor. So, even though the all electric CD mode is emission free and energy efficient; the large battery capacity required for AER increases the cost of the vehicle considerably.

The engine dominant and electric dominant CD modes are known as blended modes of operation [3]. In blended mode of operation, the battery pack can be designed for a lower peak power as compared to the one in all electric-mode; since, some of the power can be supplied by the engine. This reduces the cost of the battery as well as the vehicle which could eventually lead to mass production of these vehicles. In the engine dominant CD mode the engine is supposed to deliver the average power of the vehicle and any extra power needed can be obtained from the battery. While in the electric dominant CD mode the battery supplies the average power requirement of the vehicle so for the same driving distance the electric dominant mode requires higher energy and power from the batteries and so may be costly. On the other hand the engine dominant blended mode may provide less fuel economy and more emissions compared to the electric dominant CD mode; since, gasoline is the primary energy source. Both of the above conclusions are based on the assumption that the driving distance is same for the electric and engine dominant CD modes. Therefore, the choice between engine dominant and electric dominant CD modes should be based on the driving distance and the type of drive cycle as proposed in [3]. The electric dominant CD mode is more efficient where the driving distance is less than the CD distance whereas the engine dominant CD mode is more efficient for driving distances greater than the CD distance of the vehicle.

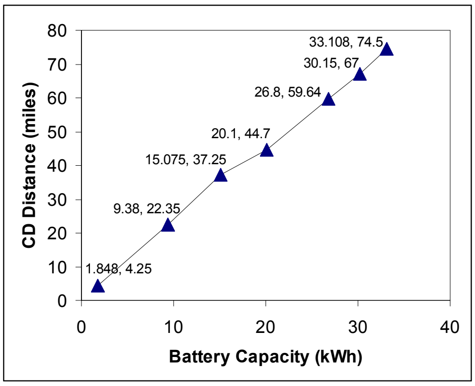

Figure 2. Battery capacity vs. CD Distance @ 0.7 SOC

CD distance is another important design parameter and it is defined as the maximum distance that the vehicle can travel in CD mode before the CS mode begins. It increases with the increase in battery energy capacity. The CD distance is extremely important as it gives a clear idea about the amount of distance a vehicle can travel in the most efficient, emission free manner for a given battery capacity. The CD distance can be determined for each battery capacity using the ADVISOR software. Based on the above considerations and considering that the average urban daily driving distance is around 40 miles, an electric dominant strategy would be good for a battery capacity which has a CD distance less than 40 miles and an engine dominant strategy will be good for battery capacity which has CD distance greater than 40 miles. In Fig. 2 the battery capacity plotted against CD distance with respective x, y values beside each point @ 0.7 SOC. It has been assumed that the battery is at an initial SOC of 0.7 which is a realistic value for the life of the battery considering that the maximum value of the SOC will degrade throughout the life of the battery. This value also allows for the study to remove differences imposed by different battery cell technologies; the 0.7 value also represents the lowest value of max SOC among Li-Ion, NiMH, and NiCd technologies [19]. For a 40 mile driving range if an electric dominant strategy is desired the battery energy capacity should be less than 20 kWh as can be seen from Fig. 2.

III. Simulation Results

Vehicle selection is also an important criterion. There are many hybrids in the markets which follow different topologies to improve the fuel economy. The Toyota Prius with its series/parallel drive train gives the HEV the advantages of both the architectures and it has a very good fuel economy and was therefore chosen. Of the 2 blended strategies the electric dominant CD mode was chosen since it is more emission free, improves the performance of the vehicle, and is ideal for urban driving distances of 40 miles.

In Fig. 3, a typical UDDS (Urban Dynamometer Drive Schedule) drive cycle for a 45 Ah battery is depicted. In an electric dominant strategy the battery operates for a major portion of the encircled region 1 when it is in CD mode where as in encircled region 2 when it is in CS mode the engine kicks in more often. In Fig. 4, the power supplied by the engine when the vehicle is operating in encircled region 1 is compared with that of encircled region 2. Thus Fig. 4 has the power supplied by the engine plotted against distance when the vehicle is operating in regions 1 and 2 respectively plotted one over the for comparison purposes. In Fig. 5, zoomed in area of Fig. 4 is depicted, which clearly shows that power supplied by the engine is not the same during CD mode and CS mode and that the engine operates more often during the CS mode which clearly indicates that the CD mode is more fuel efficient and emission free. However, the amount of distance that a vehicle needs to travel in CD mode depends on the application.

The ESS modules with following battery capacities 1.85, 9.38, 15.07, 20.1, 26.8, 30.15, and 33.10 in kWh were considered for simulation each for three different driving distances of 15, 30, and 75 miles, respectively. ADVISOR software was used to determine the fuel economy for a given battery capacity at given initial SOC values of 0.7 and 0.6, respectively (see Fig. 6). However, fuel economy alone does not give a clear idea when two battery packs with different battery capacities are compared; since, the final SOC will vary according to the size of the battery. Therefore, final SOC of the battery at the end of the drive cycle for different driving distances is plotted against the battery capacity (see Fig. 7). Final SOC values indicate the amount of distance (CD distance) the vehicle can further travel in CD mode which can be determined for each battery capacity using ADVISOR software. Fig. 2 has the CD distance plotted against the battery capacity. Once the CD distance for a given battery capacity is obtained then the fuel economy can be determined for that battery capacity and for a driving range equal to CD distance (see Fig. 8).

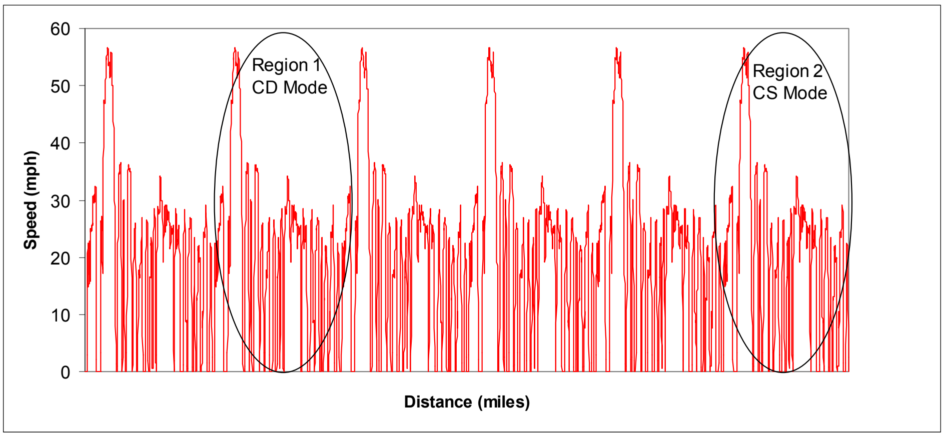

Figure 3. Comparison between 2 different regions of the same drive cycle

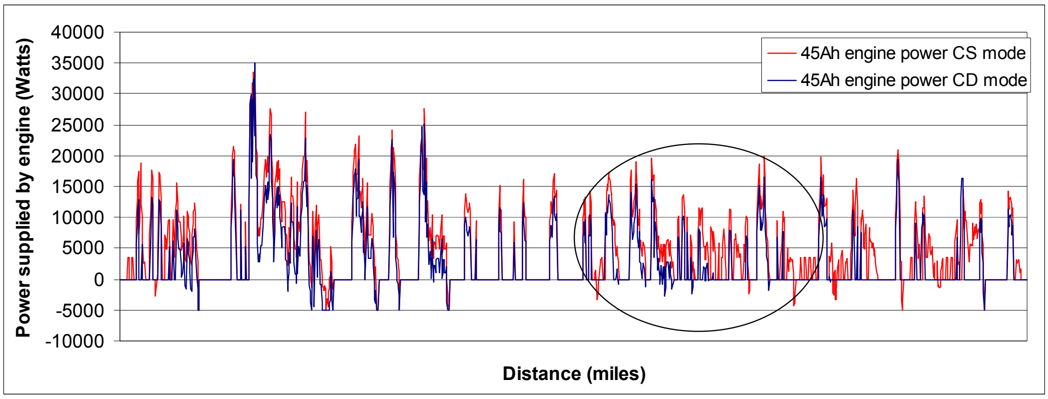

Figure 4. Power supplied by the engine during the beginning (CD mode) and at the end of drive cycle (CS mode)

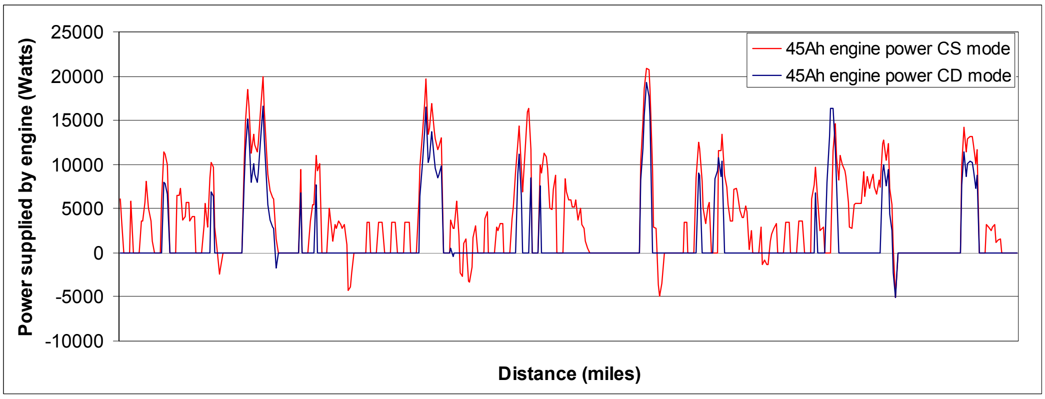

Figure 5. Zoomed in area of Fig. 4

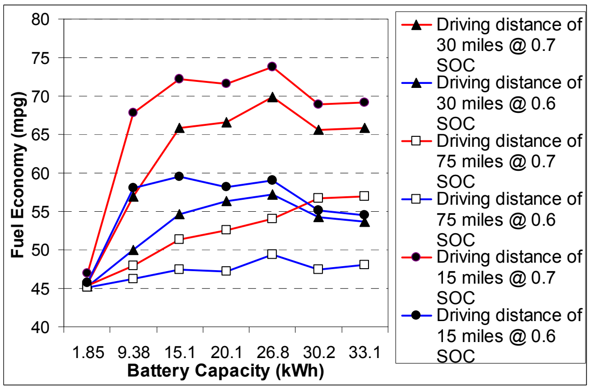

Figure 6. Battery capacity vs. fuel economy for initial SOC greater than 0.5

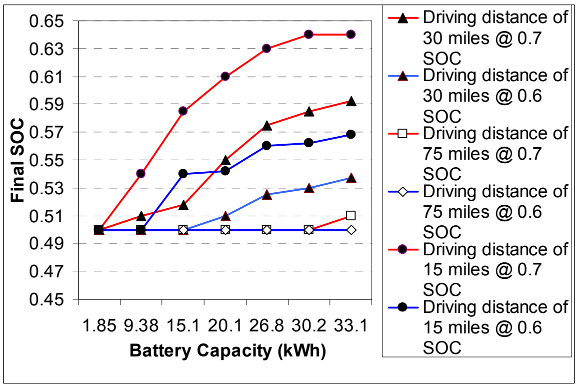

Figure 7. Battery capacity vs. final SOC

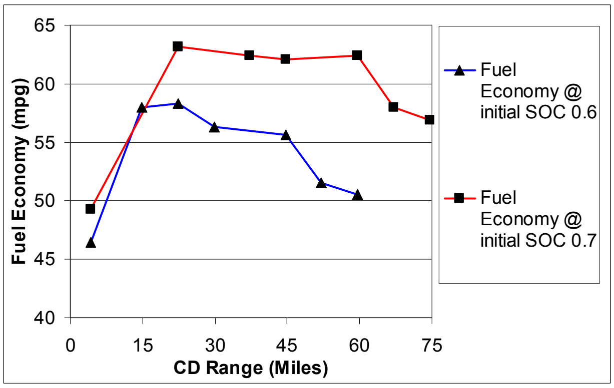

Figure 8. Charge depleting distance vs. fuel economy

The fuel economy plotted against CD distance is depicted in Fig. 8 which gives a clear idea about the effects the increase in battery capacity is going to have on the fuel economy of the vehicle. From Fig. 8, it can be concluded that the fuel economy of the vehicle does not increase with the increase in battery capacity. On the contrary it decreases slightly and stays close to 62 mpg for most of the battery capacities except for the battery capacities of 1.85, 30, and 33 kWh, respectively when the initial SOC of the pack is 0.7. The results for initial SOC of 0.6 follow a similar pattern. Thus, the increase in battery pack capacity alone does not increase the fuel economy of the vehicle. However, the amount of distance the vehicle can travel with fewer emissions will increase with an increase in battery capacity. The choice of the battery pack capacity should therefore be based on the average daily driving distance and the type of drive cycle. Considering that the average daily driving distance is 40 miles, drive cycle is UDDS, and the battery cost is linearly related to the battery capacity. A 15.07 kWh battery pack would meet these requirements while providing a fuel economy of 62.4 mpg for a UDDS drive cycle.

IV. CONCLUSION

Battery capacity is an important criterion in the design of an HEV. Proper battery design and a good choice of an energy management strategy could improve the fuel economy of the vehicle considerably. The selection of an energy management strategy would play a key role in the design and sizing of the batteries as well as the cost of the batteries. In this paper electric dominant CD blended mode of operation was considered as ideal for conversion of Prius HEVs to PHEVs. Choice of the battery pack capacity is another important design parameter which would influence the cost of the vehicle. The conversion of HEVs to PHEVs by increasing the battery pack capacity could improve the fuel economy of the vehicle and the use of the blended mode of operation would mean that the vehicle is not completely powered by battery alone thereby reducing the battery cost. This reduction in battery cost could define the future of PHEVs.

The simulation results provide an empirical study of the vehicle behavior when battery pack capacity is increased. Fuel economy of a PHEV depends on a combination of different factors and increasing the battery capacity alone would not increase the fuel economy of the vehicle. So, it is important to size the battery according to the application, average daily driving distance, and driver behavior. The general perception that the increase in battery capacity improves the fuel economy is not justified. Though increasing the battery capacity helps in traveling a longer distance with lower emissions. However, this increase in battery capacity would increase the battery cost and the overall cost of the vehicle which would in turn hinder the progress of PHEVs. The paper provides an insight into the choice of the battery capacity for PHEV conversion of HEVs like Toyota Prius.

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