*EVS30 Symposium*
*Stuttgart, Germany, October 9 - 11, 2017*

# Route based energy management for plug in hybrid electric vehicles

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**Summary**

Plug in hybrid electric vehicles (PHEV) can improve its fuel efficiency by shifting between charge depleting (CD) and charge sustaining (CS) mode based on the route conditions when it travels over its all electric range (AER). The route based strategy is feasible only if the distance until the next charging event (DUC) is greater than the AER and fuel consumption is inevitable. Finding out the optimal threshold to shift the mode utilizing a series of driving conditions along the route is also a challenging problem to be conducted on a real time controller. This study addresses possible approaches to estimate the DUC and suggests the practical maneuver to draw the adequate mode shifting decision against time variant characteristics of the route condition.

*Keywords: battery management, optimization, PHEV*

## 1 Introduction

PHEV has a high voltage battery that can be recharged by plugging it into an external electric power source. A typical PHEV has 2 distinct operating modes which are called charge-depleting (CD) and charge-sustaining (CS) mode. In CD mode, the vehicle is propelled by an electric motor predominately by consuming battery energy, whereas an internal combustion engine (ICE) covers the most of propulsion demand in CS mode.

### 1.1 Conventional mode shifting strategy

Most PHEVs operate in CD mode at start up, and switch to CS mode after the battery has depleted to its minimum state of charge (SOC) threshold, exhausting the vehicle's all-electric range (AER) as shown in Fig. 1. Operating as a pure electric-vehicle (EV) without consuming fuel and emitting any pollution within the AER and extending the vehicle's range over the AER by using an ICE is the effective mode shifting strategy that has been implemented to PHEVs up to date.

### 1.2 Limitation of the conventional strategy

J. Smart [3] studied the driving behaviour of PHEV users and represented the distribution of daily mileage as shown in Fig. 2. According to the study, the average daily mileage of passenger car drivers lies on around 40 miles statistically. Considering the average AER of the latest PHEV, it can be inferred that most of PHEV are driven in the manner of driving EVs. However, there are considerable drivers who travel over the AER as represented in Fig. 2. Travelling over the AER causes the transition from CD to CS and fuel consumption before the vehicle is plugged in. Under the conventional strategy which shifts the mode between CD and CS mostly based on SOC, EV and HEV modes may be activated on inappropriate condition in terms of energy efficiency. In example, if the highway driving phase is covered by CD in which EV mode is predominate, inefficiency can be induced due to the motor and battery characteristics having more conversion loss as increasing output power. Referring the efficiency characteristics shown in Fig. 3, the driving conditions such as power demand need to be considered in selecting the appropriate operating mode. The power threshold to turn on the engine in CD mode is set close to its maximum electric drive capability to extend the AER rather than to improve energy efficiency.

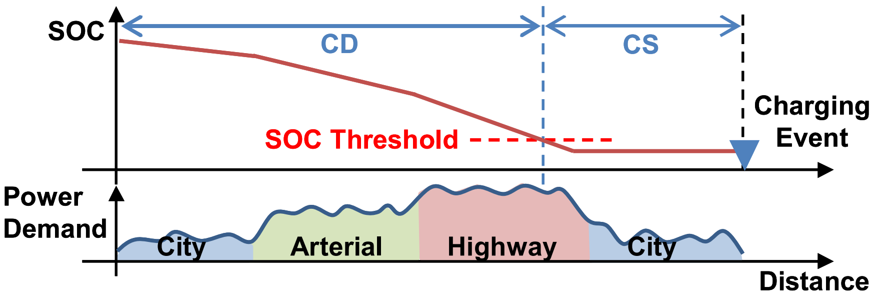


Figure1: Conventional CD/CS mode shifting strategy

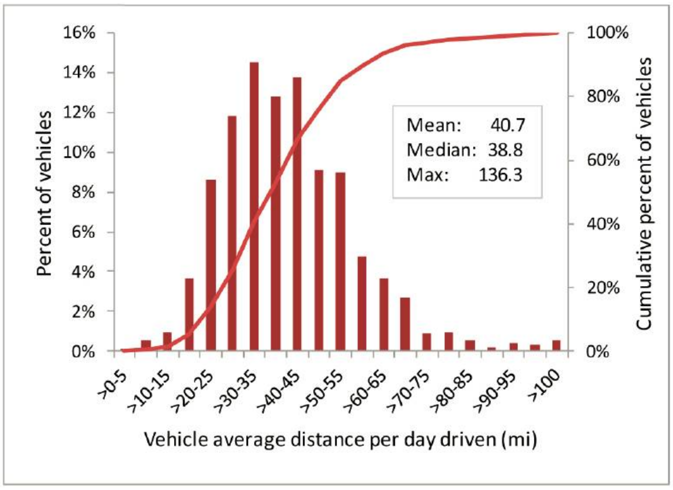


Figure2: Average daily driving mileage of PHEV users

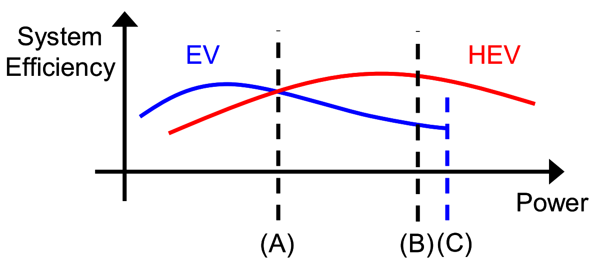


Figure3: Energy efficiency of EV and HEV modes; Engine on threshold for (A) CS, (B) CD and (C) maximum output power of motor

## 2 Route based mode shifting strategy

If the travel distance is expected to be longer than the AER in advance, the PHEV's energy efficiency can be improved by allocating HEV mode on high load driving conditions. This study introduces a new mode shifting strategy between CD and CS for PHEVs which takes the route information into account to activate HEV on appropriate driving condition as shown in Fig. 4.

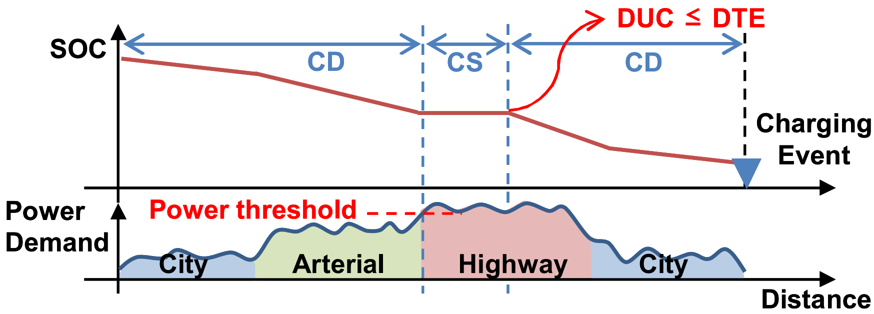


Figure4: Route based CD/CS shifting strategy

### 2.1 Estimation of DUC

Since the strategy is only effective when the vehicle is going to travel over its AER, it is important to estimate the distance travelled before next charging through electric grids which is called a distance-until-charge (DUC). However, estimating accurate the DUC is difficult since it lies upon the driver's intention. If the DUC is under estimated, the vehicle needs to be driven in CS for the DUC error regardless of driving condition and it might decrease FE improvement brought by the proposed method. On the other hand, if the DUC is over estimated, the strategy can try to preserve the battery energy for non-existent later use. It can increase cost by consuming fuel energy instead electrical energy which is available for that trip. The effect of the DUC estimation error is already addressed by P. Naghshtabrizi [2] as summarized in Fig. 5.

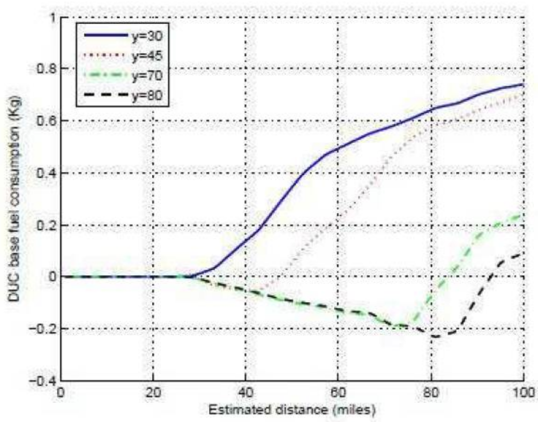


Figure5: Cost vs. the estimated DUC

The most reliable way to get an accurate DUC is getting it from the driver directly through a user interface. However, calculating the distance between current position and his or her terminal destination taking route variations into account would not be practical for the most users. It would be also an inconvenient process setting the DUC manually prior to driving the vehicle every time even if the DUC is already resolved. The inconvenience can be mitigated by developing the HMI incorporating with navigation systems and smart phone applications. Existing internet based services to find a charging station or plan the most efficient route for EV and PHEV drivers have great potential to offer the DUC since they already have relevant information.

The DUC also can be predicted utilizing previous driving data. Since many drivers have consistent driving pattern, practical results can be drawn if the prediction algorithm utilize adequate properties such as time of day (TOD) and day of week (DOW) [3].

Though much of effort has been made to estimate the DUC, the estimation error is inevitable. As described above, while negative estimation error reduces the effect of the suggested method, positive error can draw a side effect that increases overall cost, so, as represented in Fig. 6, the initial DUC should be the minimum value of the DUC range estimated with a certain meaningful probability.

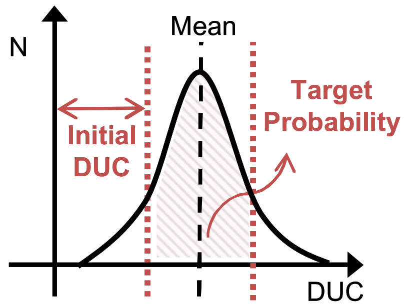


Figure6: Initial DUC from target probability

## 2.2 Mode shifting criteria

As described above, the mode shifting based on driving condition is only effective when the terminal destination can be reached by using the battery energy. So the comparison between the DUC and distance to empty (DTE) should be performed continuously during the trip. The DUC is decreasing from the initial estimated value as the vehicle travels while the DTE is decreasing from the AER which is smaller than the initial DUC in response to the consumption of the battery energy. From the moment when the DUC meets DTE, the vehicle operates in CD until it reaches the terminal destination since there is no need to use the engine. Only if the DUC is greater than DTE, the driving load is evaluated to activate CS as represented in Fig. 7

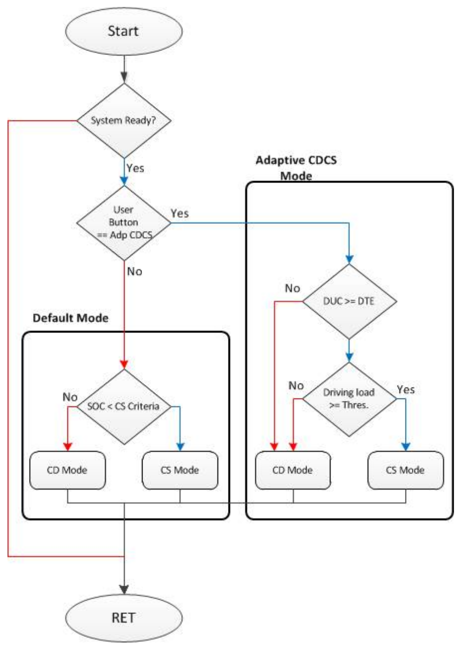


Figure7: Flowchart for CS activation

To distinguish high load condition which is more efficient with HEV mode, a criterion needs to be set up. A static threshold which is determined as a fixed value prior to driving considering the system characteristics can not assure the global minimum allocating CS to the most appropriate condition along the trip as represented in Fig. 8. To realize adequate mode shifting, it is crucial to get a series of road conditions along the route the vehicle is going to travel in advance. The route information can be acquired through telemetric systems. And the mode shifting threshold can be determined by examining all the driving condition along the route. However, it is not practical to plan the mode shifting by solving an optimization problem using the data on an embedded controller employed in the vehicle. Moreover, time variant characteristics of the data induced by the change of traffic might distort the effectiveness of the optimum solution and make the optimization process need to be performed repeatedly. So this study also addresses the practical maneuver to draw the optimum solution in real time with minimum resources of the controller. In the maneuver, all the different road conditions are characterized by type of road, average speed and slope grade, then, they are classified into several finite classes. Using test data for each road class, the electricity and fuel consumption rate are estimated in EV and HEV mode respectively. And all the classes are graded in appropriate order for EV mode by comparing the equivalent energy required for EV and HEV mode as shown in Fig. 9.

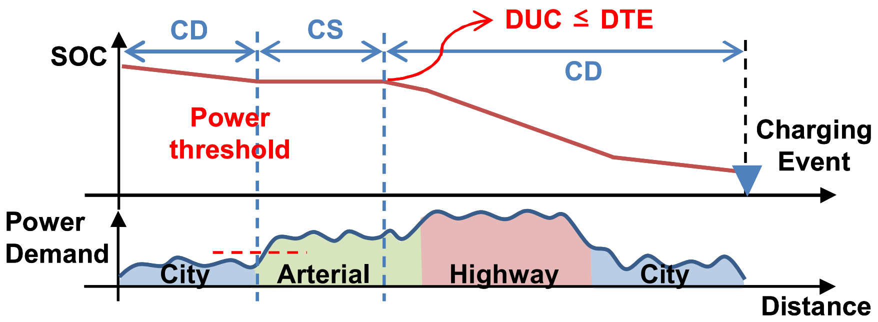


Figure8: Shifting CS based on a static threshold

The required electrical energy to travel each class in EV mode can be calculated by multiplying the electricity consumption rate by the traveling length of the class. Accumulating the required electrical energy in the appropriate order of the classes until it becomes the same value as the battery stored energy, the class lying on the boundary between CD and CS can be identified.

**Step 1**
Input driving condition data from telematics

| Segment | 1 | 2 | 3 | … | 8 |
|---|---|---|---|---|---|
| Avg. speed | 30 | 45 | 80 | … | 50 |
| Slope grade | 0 | 3 | 0 | … | -1 |
| Road type | City | City | Highway | … | Arterial |
| Length | 15 | 6 | 25 | … | 8 |

**Step 2**
Classify into predefined classes having EV/HEV equivalent factor (<1 means EV is efficient)

| Segment | 1 | 2 | 3 | … | 8 |
|---|---|---|---|---|---|
| Class | 2 | 6 | 9 | … | 5 |
| Equivalent factor | 0.85 | 0.97 | 1.1 | … | 0.9 |

**Step 3**
Sort in the appropriate order for EV and compare with AER

The class on the border becomes the threshold for the mode shifting

| Segment | 1 | 8 | 2 | … | 3 |
|---|---|---|---|---|---|
| Class | 2 | 5 | 6 | … | 9 |
| Battery Consumption | 23 | 13 | 11 | … | 50 |

**SUM > AER**

Figure9: Procedure to find the optimal threshold

While the road condition is approximated to one of pre-defined classes, error can be induced. However, it makes the problem simple and the solution can be drawn in response to the change of driving condition repeatedly on the embedded system.

## 3 Validation

The effectiveness of the proposed strategy was validated through a series of vehicle tests. In the tests, 2 vehicles travelled the same route which is longer than its AER simultaneously. One of them employed the conventional SOC based mode shifting strategy whereas the other was equipped with the suggested route based shifting strategy. Prior to start the journey, the terminal destination was set on the navigation system of the latter vehicle and a series of driving conditions along the planned route were transferred to the supervisory controller from the telemetric system. The controller conducted the process to identify the threshold class to activate CS with the driving conditions as described above. The latter vehicle shifted its operation mode from CD to CS whenever it met the threshold class as long as its DUC is greater than DTE. This validation test was carried out 9 times repeatedly for 2 different test routes. The proposed strategy brought 15% enhancement in fuel economy on average and the mode transitions between CD and CS along the route are appeared in Fig. 10 and 11.

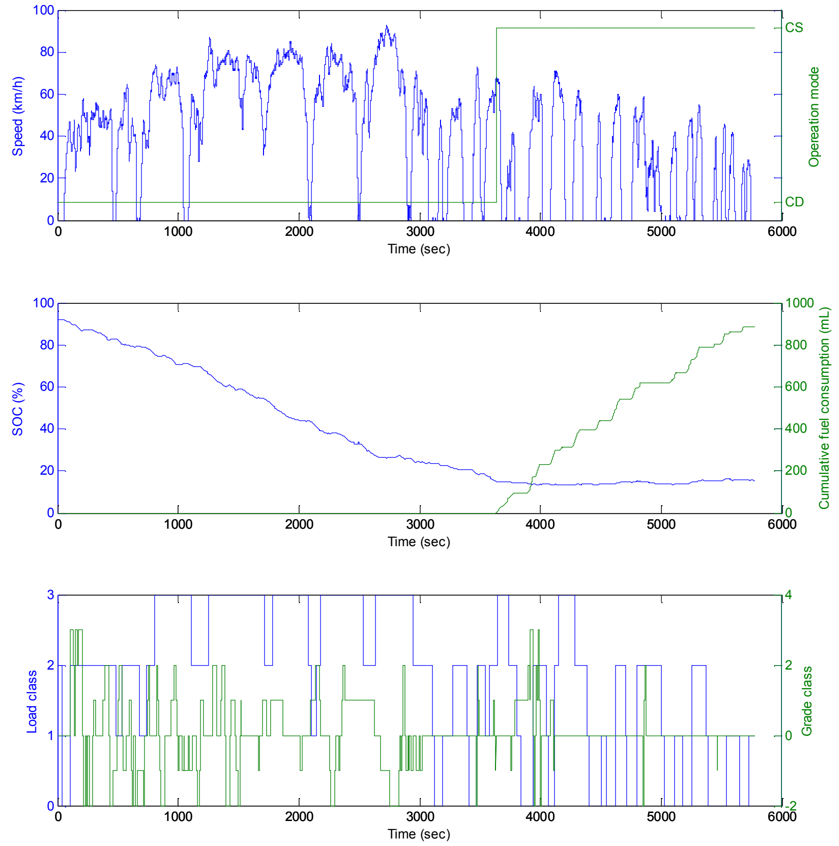


Figure10: Vehicle test results of the SOC based strategy

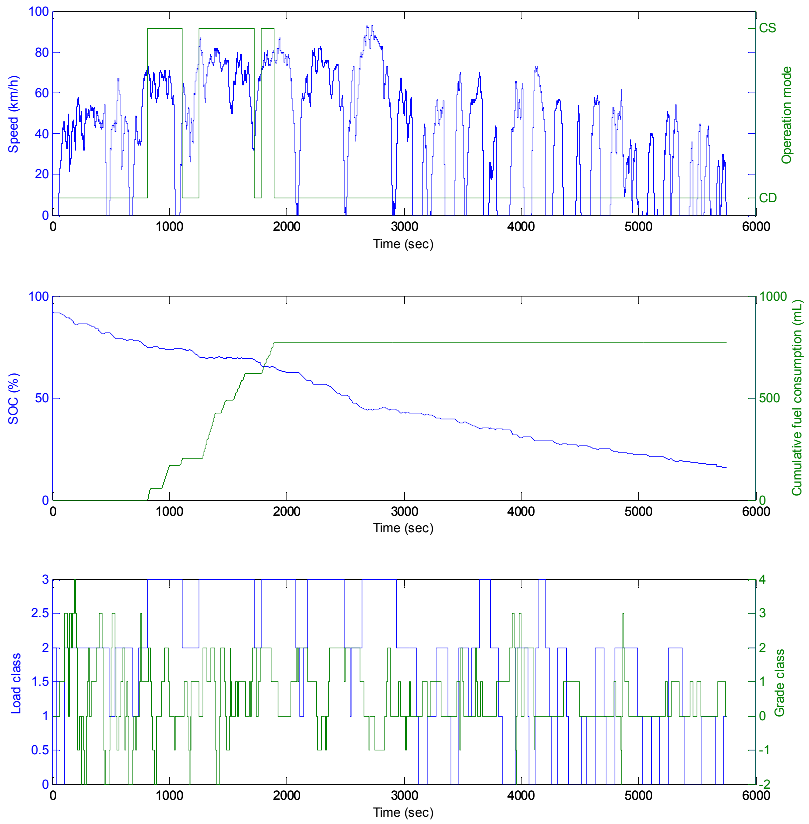


Figure11: Vehicle test results of the route based strategy

# 4 Conclusion

This study introduced the route based mode shifting strategy which activates CS mode when the driving load is high and appropriate for HEV mode. The suggested strategy is feasible only if the DUC is greater than the AER and fuel consumption is inevitable before the next plug-in charging event. So this study also addressed possible approaches to estimate the DUC and the concrete solution will be discussed in the future study. The maneuver to draw the optimal threshold for shifting between CD and CS was also represented to implement the strategy to the embedded controller. The feasibility of the strategy was validated through a series of vehicle tests carried out repeatedly.

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