Optimization of Driving Mode Switching Strategy for a Multimode Plug-In Hybrid Electric Vehicle

Moumen Idres, Mohamed Okasha

Abstract*: Hybrid electric vehicles have become increasingly popular recently. Switching from internal combustion engine to battery as a clean source of energy is considered as a solution to reduce city pollution due to vehicle emissions. PHEV is a viable balance between the two sources of energy to achieve higher fuel economy with lower emissions. For a multimode PHEV, the car switches among three operation modes; namely electric mode, series mode, and parallel mode to maximize fuel economy based on the driving conditions. In this work, minimization of fuel consumption is used to optimize the mode switching strategy for a PHEV. The study is conducted using a reference vehicle that resembles 2014 Honda Accord Plug-in Hybrid vehicle. Global optimization with constraints using pattern search method is utilized. Starting from a switching strategy with MPG_e = 30, optimization increased fuel economy to MPG_e = 51.4 for a combined cycle (FTW75 and HWFET). Optimization proved to be a feasible method to improve mode switching strategy.

***Keywords:* Hybrid Electric Vehicle, HEV; Plug-In; Powertrain; Multimode; Mode Switching; Optimization.**

1. INTRODUCTION

A plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle with battery that can be recharged by plugging it into an external source of electric power or by its on-board engine and generator [1-3]. Mass production of PHEV started in 2010. Since inception, PHEV production is growing steadily. Many commercial car companies produced PHEV; for example the Chevrolet Volt, the Mitsubishi Outlander PHEV, the Toyota Prius Plug-in Hybrid and Honda Accord Plug-in Hybrid.

The drivetrain for PHEV can be series, parallel, or series/parallel [4]. In series hybrids, the internal combustion engine is connected to the generator to charge the battery. The electric motor drives the car. In parallel hybrids, the engine and electric motors cooperate to drive the car with a power split mechanism. Usually, there is a clutch to allow the engine to charge battery and drive the vehicle concurrently. In series/parallel hybrids, planetary gear trains allow either series or parallel mode to be selected.

Honda Accord Plug-in Hybrid uses a series-parallel drivetrain configuration as shown in Figure 1 and Figure 2 [5, 6]. It uses four pairs of gears and one clutch to connect the two power sources to the output shaft. Figure 2 shows the power flow for the three drive modes; namely electric drive mode, series hybrid mode, and parallel hybrid mode. Depending on the initial state of charge (SOC) of the battery, the car control system can be charge depleting or charge-sustaining. With a full battery charge, the vehicle uses battery and electric motor until SOC is depleted to a specific value. At this SOC level, charge-sustaining mode is invoked, where ICE is activated either as a generator to charge the battery and supply power to the motor (in series mode) or to cooperate with the motor to supply power to drivetrain (in a parallel power-split mode).

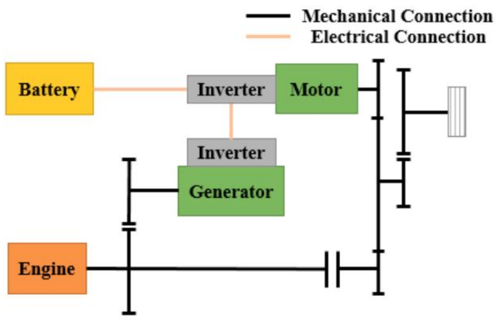

Fig. 1: Honda Accord Plug-in Hybrid powertrain configuration [5].

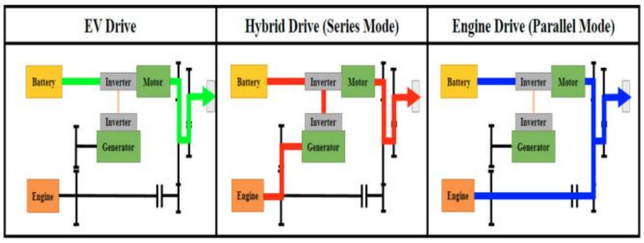

Fig. 2: Driving modes for Honda Accord Plug-in Hybrid [5].

Many methods are developed for energy management of a hybrid electric vehicle [7-10]. These studies assume complete control of the powertrain components. The current work focuses on the driving mode decision for a multimode PHEV. It serves as a higher level control, where the energy management scheme is already developed for the HEV [4]. We optimize the driving mode selection strategy for a reference vehicle that is built based on 2014 Honda accord Plug in HEV. MATLAB Powertrain Blockset [11] and Simulink Design Optimization [12] are used for the simulation. A global optimization method using pattern search method is utilized.

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2. METHODOLOGY

This section describes powertrain modelling, driving mode switching strategy and optimization problem setup.

2.1 Powertrain modeling

Matlab Powertrain Blockset [11] was introduced in Matlab R2016b for automotive powertrain modelling and simulation. It can be used for conventional, electric, or multi-mode hybrid vehicles. It uses dynamic approach (forward-facing). In this work, we use the hybrid electric vehicle reference application [11]. This is a full multimode HEV model with an internal combustion engine, transmission, battery, motor, generator, and associated powertrain control algorithms. It serves as a starting point for design trade-off analysis and component sizing, control parameter optimization, or hardware-in-the-loop (HIL) testing.

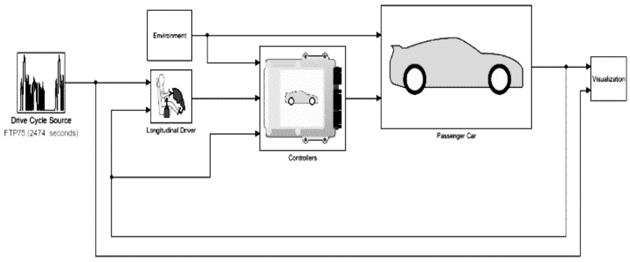

Fig. 3: Hybrid electric vehicle multimode reference application [11].

The driving cycle is defined as velocity versus time profile. This requirement is translated into driver acceleration and braking commands. Powertrain control module uses driver commands to control engine and electric motors. Both electric motor and generator are represented by performance maps (torque and efficiency as functions of rotation rate). Engine fuel consumption is represented by maps of fuel mass flow rate as function of torque and rotation rate. Vehicle is modelled by 3-DOF longitudinal dynamic model. To resemble 2014 Honda Accord Plug-in Hybrid [5], engine capacity is changed from 1.5 L to 2 L and engine performance maps are changed accordingly.

2.2 Driving mode switching strategy

The multimode reference application follows the energy management strategy developed by [5] for Honda accord PHEV. If the battery is fully charged, charge depleting mode is selected and the vehicle utilizes stored electric energy. If the battery state of charge (SOC) drops to a predetermined level (50%), charge-sustaining mode is automatically selected. Three driving modes can be selected depending on the driving load, as demonstrated in Figure 4. For low loads (city driving), electric mode is selected. When acceleration demand increases during normal load, series HEV mode is activated. For cruise, both electric motor and engine are cooperating in a power split mode to satisfy the power required. Charging of battery takes place when engine is activated (in series HEV or parallel HEV).

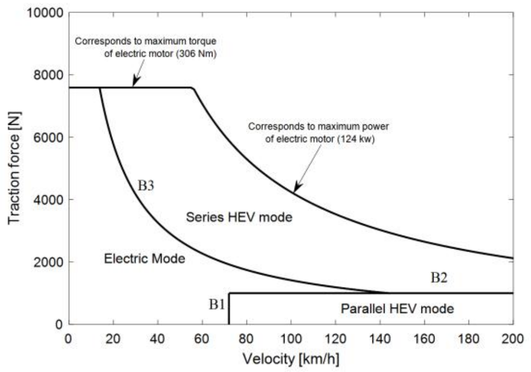

Fig. 4: Driving modes switching strategy for Honda Accord PHEV [5].

2.3 Optimization

The boundaries of the PHEV driving modes are represented by the equations (refer to Figure 4):

$$
\begin{aligned}
&V = C_1 && \text{Boundary 1 (B1)} \\
&F = C_2 && \text{Boundary 2 (B2)} \qquad (1)\\
&F = \frac{100\, C_4}{C_3 + V} + 0.001\, C_5 && \text{Boundary 3 (B3)}
\end{aligned}
$$

where F is the required traction force (kN), V is vehicle velocity (km/h) , $(C_1, C_2, C_3, C_4, C_5)$ are parameters. To optimize the operating modes boundaries, an optimization problem is defined such that the objective function is total fuel consumption for a combination of city drive cycle (FTP75) and highway drive cycle (HWFET). The optimized variables are the five parameters $(C_1, C_2, C_3, C_4, C_5)$ that dictates the boundaries. Thus, the optimization problem set up is:

Objective function: $f(\boldsymbol{x}) = MPG_e$

$$\text{subject to:} \quad \begin{pmatrix} 30 \\ 0.5 \\ 0 \\ 0.5 \\ 0 \end{pmatrix} \le \boldsymbol{x} \le \begin{pmatrix} 110 \\ 4 \\ 50 \\ 2 \\ 1 \end{pmatrix} \qquad (2)$$

optimized variables: : $\boldsymbol{x} = [\, c_1\ c_2\ c_3\ c_4\ c_5]^{\boldsymbol{T}}$

Optimized variables limits are obtained by exploring possible boundary movements within the traction force-velocity envelope.

MPG_e is calculated using a combination of FTP75 cycle and HWFET cycle as follows:

$$MPG_e = w_1\, MPG_e|_{FTP75} + w_2\, MPG_e|_{HWFET} \qquad (3)$$

where w_1 and w_2 are constants to indicate the relative importance of the driving cycles.

Simulink Design Optimization [12] is used to implement the optimization process. Pattern search technique is used as a global optimization method. This method does not require gradient calculation. A pattern is a set of vectors (optimized variables) that the algorithm uses to determine which points to search at each iteration.

3. RESULTS

The reference vehicle data are approximating 2014 Honda accord PHEV [13] as shown in Table 1. Optimization is

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Conducted using global pattern search method. The poll method is the generalized pattern search with a maximal positive basis of 2N (N is the number of optimized parameters).

Table 1: Reference Vehicle Specifications

Parameter	Description
Curb mass	1723 kg
Drag Coeff.	0.35
Engine	2.0-liter 4-cylinder Atkinson-cycle gasoline, 102 kW at 6200 rpm
Motor	124 kW
Generator	102 kW
Battery	20.8 Ah, 6.7 kwh
Power	102 (gasoline)/ 124 (elec)/ 146 (combined) kW
Torque	165.4 (gasoline)/ 306.4 (elec) Nm
Transmission	E-CVT: 2.450 (Gear ratio)/3.421 (differential gear ratio)

This requires a maximum of 10 objective function evaluations for every iteration. Parallel computation is activated to utilize multiple processors in an Intel core i5-5200U laptop. Optimization time is about 4 hrs.

Optimization results are depicted in Figure 5 and Figure 6. Objective function weights are taken as w_1 = 0.55 and w_2= 0.45. This gives more emphasis to the city drive cycle (FTP75). To test the strength of the optimization method, the initial values of the optimized parameters are selected such that the initial objective function is far from optimum (this means a low fuel economy). Thus, the initial parameters are $\boldsymbol{x}_{initial} = [36\ 0.5\ 0\ 0.5\ 0\ ]^T$, which correspond to $f_{initial} = 30\ MPG_e$. Figure 5 shows the evolution of the objective function and the optimized parameters. Parameters are scaled differently to appropriately appear in one graph. The scale is $\boldsymbol{x}_{scale} = [115\ \ 2\ \ 4\ \ 2\ 1]^T$. Two jumps in the objective function; one at iteration 1 (corresponds to a change in c_3) and the other at iteration 8 (corresponds to a change in c_1). The final optimized parameters are $\boldsymbol{x}_{final} = [93.6\ \ 2.5\ \ 10.5\ \ 1.5\ \ 0.96875]^T$ and the optimum mileage is $f_{final} = 51.4\ MPG_e$.

Figure 6 shows the movement of the boundaries from initial to final. When required traction power is high, parallel (power split) mode is favored. This explains the shift of B1 towards higher velocity and B2 towards higher traction force. Boundary B3 shifts right and upward adding more area to electric mode operation. B3 can be approximated by a curve of 30.56 kw traction power as shown in Figure 6.

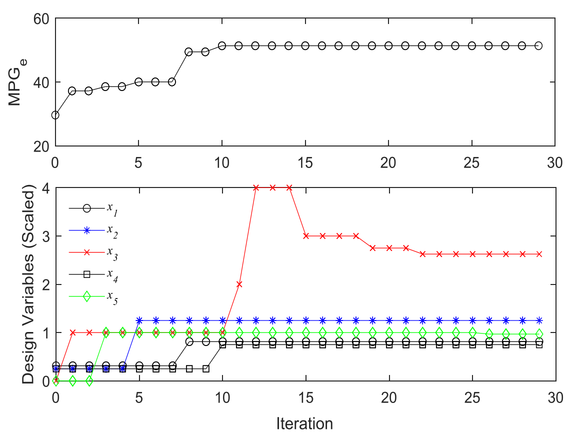

Fig. 5: Evolution of objective function and optimized variables.

More details about the optimized solution are explored in Figure 7 (FTP75) and Figure 8 (HWFET). Charge-sustaining mode is assumed for both cases. The initial battery state of charge is 50% and the minimum limit is 40%.

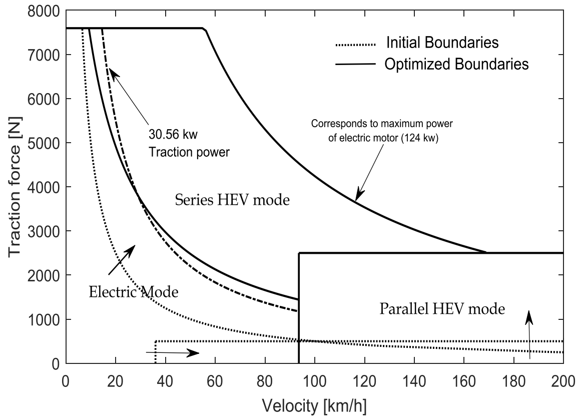

Fig. 6: Initial and optimized driving modes boundaries.

As shown in Figure 7 and Figure 8, the velocity tracking performance is excellent, where the simulated velocity in top of the required velocity. Engine speed shows that the engine is active when large acceleration/high power is required. Battery state of charge is always maintained above the lower limit (40%). For FTP75 cycle (Figure 7), fuel economy gradually increases to reach 190 MPG_e at 120 s, where until this time the car is on electric drive mode. This can be confirmed by observing the engine speed graph, where the engine speed is zero up to time = 200 s. The drive cycle fuel mileage is represented by the final value of MPG_e. For FTP75 cycle, the fuel economy is 52.8 MPG_e. For HWFET cycle (Figure 8), fuel economy gradually increases to reach 165 MPG_e at 300 s, where until this time the car is on electric drive mode. The fuel economy for this cycle is 49.7 MPG_e. Combined fuel economy based on equation (3) with w_1 = 0.55 and w_2= 0.45 is 51.4 MPG_e (2014 Honda Accord PHEV has 46 MPG_e).

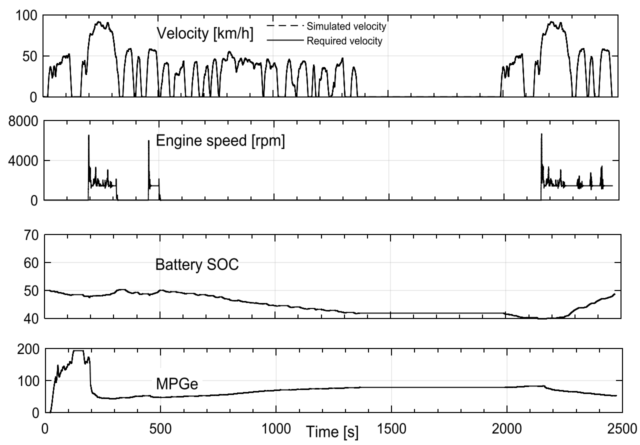

Fig. 7: Optimized solution results for FTP75 cycle.

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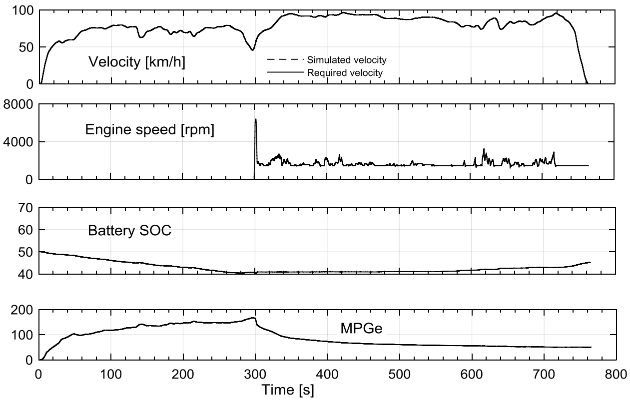

Fig. 8: Optimized solution results for HWFET cycle.

CONCLUSIONS

A global optimization method is developed for mode switching strategy of PHEV. The method is applied to a reference vehicle that is closely resembling 2014 Honda Accord PHEV. Optimization of fuel mileage for a combined drive cycle (FTP75 and HWFET) is sought. The pattern search global optimization method is used. The method successfully increased mileage to 51.4 MPG_e . Further improvement of the optimization procedure is under consideration. This includes different mode switching strategies and other optimization algorithms.

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