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Optimization of Fuel Economy for a Multimode Plug-in Hybrid Electric Vehicle using Atkinson Thermodynamic Cycle Engine

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ABSTRACT

Recently, Plug-in Hybrid electric vehicles become a sustainable solution to strike a balance between performance and fuel economy. 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. Atkinson thermodynamic cycle has a higher expansion stroke compared to Otto cycle; which leads to more work, less emissions and higher thermal efficiency. In this work, the optimization of fuel economy for a multimode PHEV reference vehicle that resembles Honda Accord PHEV using Atkinson engine is conducted. The optimization is based on a combined driving cycle that includes both a city cycle and a highway cycle. Mapping technique is used to represent performance and fuel consumption of Atkinson engine. The mapping is calibrated to match Honda Accord PHEV performance data. Global generalized pattern search optimization method is utilized. The optimization is performed in two steps. In the first step, the driving mode-switching strategy is optimized to increase overall equivalent Miles-per-Gallon (MPG_e) for the combined driving cycle. In the second step, powertrain components are re-sized to further improve equivalent fuel economy. Optimization of driving mode-switching increased MPG_e from 48 to 64.5 (30% increase) and a further 10% increase to 70.5 is achieved by powertrain components sizing optimization. The developed optimization method proved to be a viable method to improve fuel economy of hybrid vehicles.

1. Introduction

Energy security and energy efficiency are main objectives for any energy policy framework [1,2]. A plug-in hybrid electric vehicle (PHEV) can improve both energy efficiency and vehicle emissions. The battery can be recharged by plugging it into an external source of electric power or by its on-board engine and generator. The drivetrain for PHEV can be series, parallel, or series/parallel [3-5]. In series hybrids, the internal combustion engine is connected to the generator to charge the battery. In parallel hybrids, the engine and electric motors cooperate to drive the car with a power split

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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.

Atkinson cycle engine was invented by James Atkinson in 1882 [6]. Atkinson cycle consists of an adiabatic compression, isochoric heat addition, an adiabatic expansion and isobaric heat removal. The idea is to increase the expansion stroke to get more work and higher efficiency. The disadvantages are lower power density and lower maximum torque. The engine is more suitable to hybrid engine configurations, where there is an electric motor to compensate for low power from Atkinson engine. Practically, Atkinson cycle can be achieved by adjusting exhaust valve opening and intake valve closing timings. Gases have more time to achieve full expansion and hence more work and less emissions relative to standard Otto cycle. This leads to an increase in efficiency at the expense of reduced power density and maximum torque. Some modern cars use a valve timing control mechanism to switch from conventional Otto cycle to Atkinson cycle depending on operating conditions.

Honda Accord Plug-in Hybrid uses a series-parallel drivetrain configuration as demonstrated in Figure 1 and Figure 2 [7,8]. Figure 1 shows the powertrain configuration, while Figure 2 shows the driving modes for the vehicle. The engine is an Atkinson SI engine. 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 the internal combustion engine (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 the drivetrain (in a parallel power-split mode).

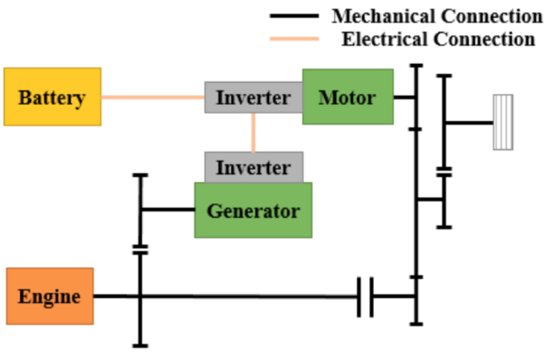

Fig. 1. Honda Accord Plug-in Hybrid powertrain configuration [7]

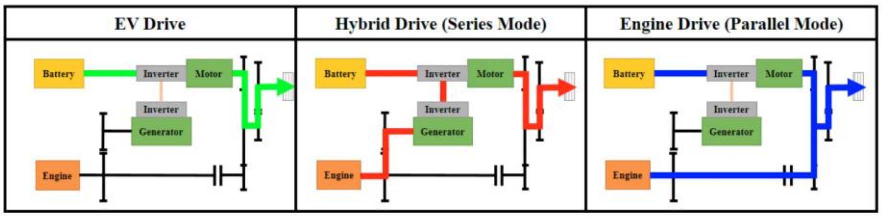

Fig. 2. Driving modes for Honda Accord Plug-in Hybrid [7]

Ibrahim *et al.,* [9] studied the effect of engine power, traction motor power and battery capacity on fuel consumption and carbon oxide emission for PHEV. They concluded that fuel consumption decreases as the motor power increases with the same battery capacity and engine power. In another study, Jabar and Abdul Rahman [10] compared powertrain components for a conventional boat and a Plug-in Hybrid Electric Recreational Boat (PHERB) for fuel consumption and emissions. They found that PHERB has lower fuel consumption and emission. In these studies, no attempts were made to optimize the sizes of the PHEV powertrain components for fuel efficiency.

Many methods are developed for energy management of a hybrid electric vehicle [11-15]. This includes heuristic, predictive controller and offline optimization. Heuristic methods include Boolean logic and fuzzy logic methods. They are simple, fast and allow designer intuitions to be implemented. Mangun *et al.,* [13,14] investigated fuzzy logic power management controller capability compared to optimal controller using dynamic programming. They concluded that fuzzy logic controller shows excellent performance. In the study by Montazeri-Gh and Mahmoodi-K [15], fuzzy logic controller was extended to include the effect of driving conditions. In this work, we focus on the driving mode decision and powertrain components sizing for a multimode PHEV. The energy management scheme is assumed to be already developed for the PHEV using heuristic method [7]. The driving mode selection strategy and powertrain components sizes are optimized for a reference vehicle based on 2014 Honda Accord PHEV. Matlab Powertrain Blockset and Simulink Design Optimization are used for the simulation [16,17]. A global optimization method based on generalized pattern search method is utilized to obtain a global optimization solution using stochastic method. It is a robust method that does not require gradient calculation.

2. Methodology

This section describes the methodology for multimode PHEV modelling, driving mode-switching optimization and sizing optimization of powertrain components.

2.1 Multimode PHEV Modelling

Figure 3 demonstrates the model for a full multimode hybrid electric vehicle (HEV). It consists of an internal combustion engine, transmission, battery, electric motor, generator, and associated powertrain control algorithms. 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 the 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, the engine capacity is changed from 1.5 L to 2 L and the engine performance maps are changed accordingly [7].

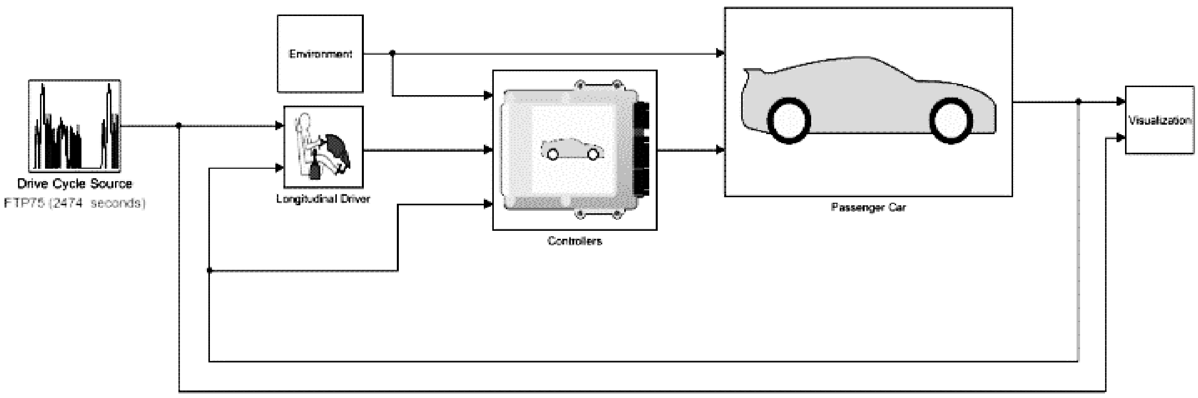

Fig. 3. Hybrid electric vehicle multimode reference application [16]

Performance maps and fuel consumption is represented by mapping equations as function of engine torque and engine rpm using Matlab Powertrain block Mapped Si Engine [16]. These maps are calibrated to match the performance of Honda Accord PHEV Atkinson Engine data.

2.2 Driving Mode Switching Strategy

The multimode reference application follows the energy management strategy developed for Honda Accord PHEV [7]. If the battery is charged (SOC is above 50%), charge depleting mode is selected and the vehicle utilizes stored electric energy. If the battery SOC drops to a predetermined level (50%), charge-sustaining mode is automatically selected (Low: 40%, High: 50%). 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 the 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).

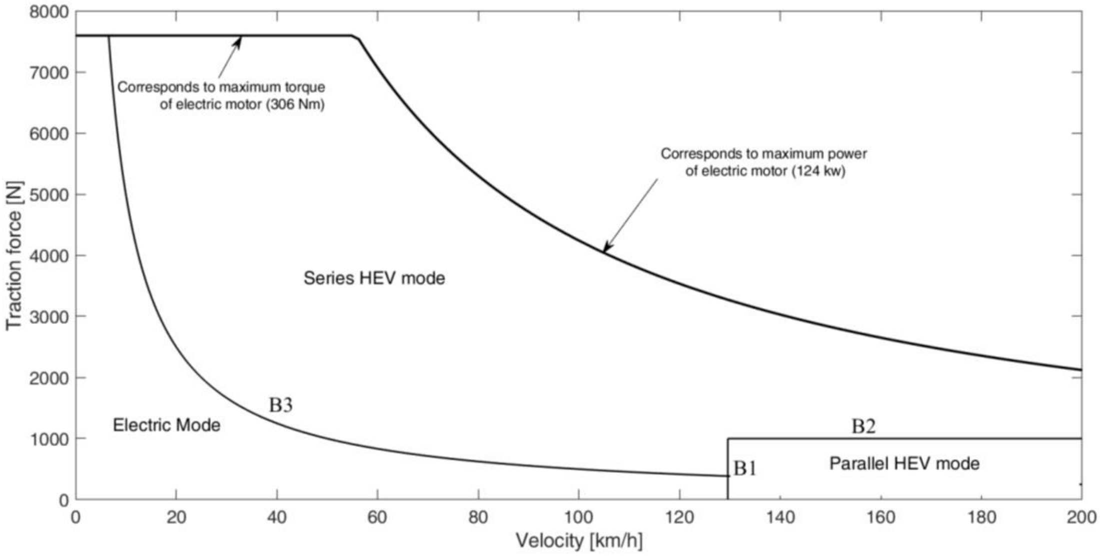

Fig. 4. Driving mode-switching strategy for Honda Accord PHEV [7]

2.3 Optimization

The optimization problem is defined such that the objective function is miles per gallon equivalent (MPG_e) for a combination of a city drive cycle (FTP75) and a highway drive cycle (HWFET) as shown in Eq. (1).

$$MPG_e = w_1 \, MPG_e|_{FTP75} + w_2 \, MPG_e|_{HWFET} \quad (1)$$

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

Simulink Design Optimization is used to implement the optimization process [17]. Global generalized pattern search technique is used as a global optimization method. It is a stochastic optimization method that 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. The maximal positive basis is twice the number of optimized variables. This means that the optimization requires a maximum of twice the number of optimized variables evaluations of the objective function for every iteration. Parallel computation is invoked to reduce computational time.

2.3.1 Mode-switching optimization

To optimize the driving mode-switching method as represented in Figure 4, the boundaries of the driving modes are represented by the following equations (Eq. (2)):

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

V is the vehicle velocity (km/h), F is the required traction force (kN) and $(C_1, C_2, C_3, C_4, C_5)$ are the optimized variables that dictates the boundaries. Thus, the optimization problem set up is:

$$
\begin{aligned}
&\text{Objective function:} \quad f(\boldsymbol{x}) = MPG_e \quad \text{obtained using PHEV Simulink model} \\
&\text{optimized variables:} \quad \boldsymbol{x} = [\, c_1\ c_2\ c_3\ c_4\ c_5]^{\boldsymbol{T}} \\
&\text{subject to:} \quad \boldsymbol{x_{min}} \leq \boldsymbol{x} \leq \boldsymbol{x_{max}}
\end{aligned}
\tag{3}
$$

Optimized variables limits $\boldsymbol{x_{min}}$ and $\boldsymbol{x_{max}}$ are selected by exploring possible boundaries movements within the traction force-velocity envelope. More details are explained in a study by Idres and Okasha [18].

2.3.2 Powertrain components sizing-optimization

The powertrain sizing variables are internal combustion engine displacement volume (V_d), electric motor maximum power (P_{EM}), generator maximum power (P_G) and battery capacity (B_C). Since these variables change during optimization, a scaling is required for components performance maps and car mass. Internal combustion engine torque and fuel consumption maps are proportionally scaled by the engine displacement volume. Electric motor and generator torque maps are proportionally scaled by maximum power. Battery charge/discharge maximum pulse power limit is limited to 40 kW following recommendations for PHEV [19]. Eq. (4) summarizes the car curb mass (M_c) scaling [13,20].

$$
\begin{aligned}
&M_c = M_n + M_{ICE} + M_{EM} + M_G + M_B \\
&M_n = 1345\ kg\ ,\ M_{ICE} = 82620\ V_d + 41.8\ ,\ M_{EM} = 0.532\ P_{EM} + 21.6 \\
&M_G = 0.532\ P_G + 21.6\ ,\ M_B = \frac{B_C}{0.0725}
\end{aligned}
\tag{4}
$$

M_n is the nominal car mass (curb mass without powertrain components), M_{ICE} is internal combustion engine mass, M_{EM} is electric motor mass, M_G is generator mass, M_B is battery mass, V_d is engine displacement volume in cubic meters, P_{EM} is electric motor power and P_G is generator power in kW and B_C is lithium-ion battery capacity in kW.h.

Powertrain sizing-optimization problem set up is:

$$
\begin{aligned}
&\text{Objective function:} \quad f(\boldsymbol{x}) = MPG_e \quad \text{obtained using PHEV Simulink model} \\
&\text{optimized variables:} \quad \boldsymbol{x} = [\, V_d\ \ P_{EM}\ \ P_G\ B_C]^{\boldsymbol{T}}
\end{aligned}
\tag{5}
$$

subject to: $\boldsymbol{x_{min}} \leq \boldsymbol{x} \leq \boldsymbol{x_{max}}$

Optimized variables limits $\boldsymbol{x_{min}}$ and $\boldsymbol{x_{max}}$ are selected by exploring typical values for PHEV vehicles.

3. Results

The reference vehicle data are shown in Table 1 (2014 Honda Accord PHEV [21]). Objective function weights are taken as w_1 = 0.55 and w_2= 0.45 (Eq. (1)). This gives more weight for the city drive cycle (FTP75). A conservative value of 50% for SOC is used as the initial battery charge for all simulations. Before conducting the optimizations, the model variables are tuned to resemble the MPG_e performance of the 2014 Honda Accord design point, which corresponds approximately to 48 MPG_e for the combined driving cycle. Optimization starts from the reference vehicle design point.

Table 1
Reference Vehicle Specifications

Parameter	Description
Curb mass	1723 kg
Acceleration time	10 s (0 to 100 km/h)
Drag coefficient	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, 100 Cells, 320 V
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)

3.1 Mode-switching Optimization

For driving mode-switching optimization, the optimized variables are $\boldsymbol{x} = [\ c_1\ c_2\ c_3\ c_4\ c_5]^{\boldsymbol{T}}$ (Eq. (3)). To explore traction force-velocity envelope, the minimum and maximum limits are selected as $\boldsymbol{x_{min}} = [30\ \ 0.5\ \ 0\ \ 0.5\ \ 0]^{\boldsymbol{T}}$ and $\boldsymbol{x_{max}} = [110\ \ 4\ \ \ 50\ \ \ 2\ \ \ 1]^{\boldsymbol{T}}$. The final optimized driving-mode strategy is demonstrated in Figure 5. Optimization increases the areas allocated for electric mode and series mode, while the parallel mode area shrinks. Figure 6 represents optimization history for the objective function and optimized variables. The optimized variables are scaled to fit in one graph, therefore the figure does not show the actual values but rather the relative changes during optimization. The objective function (MPG_e) increased from the reference vehicle value of 48 MPG_e to nearly 65 MPG_e. This represents an increase of 35%. The optimized mode-switching parameters are $\boldsymbol{x} = [\ 36\ \ 0.5\ \ 9\ \ 1.5\ \ 0.875\ ]^{\boldsymbol{T}}$.

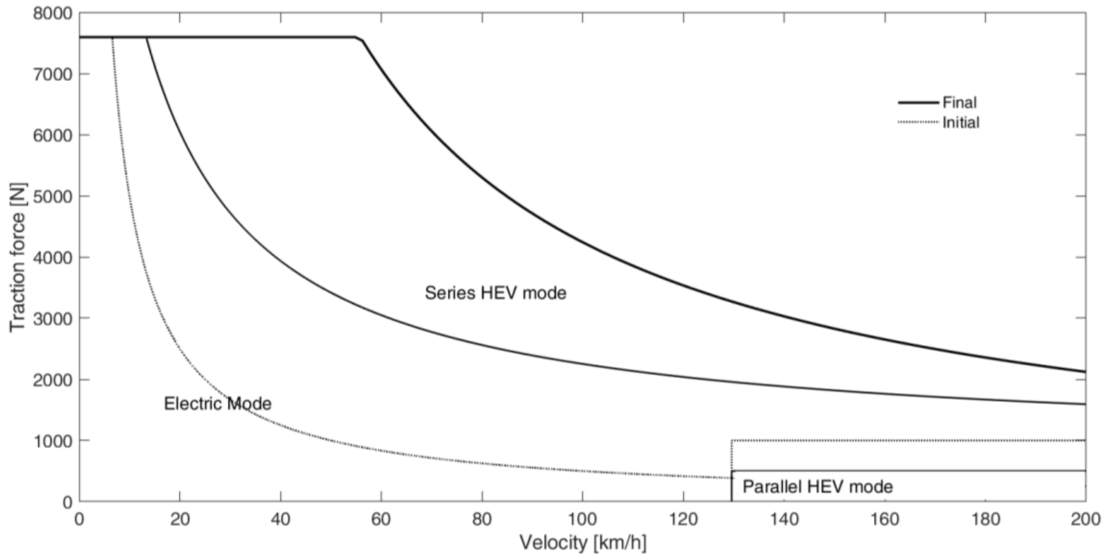

Fig. 5. Optimized driving mode-switching strategy

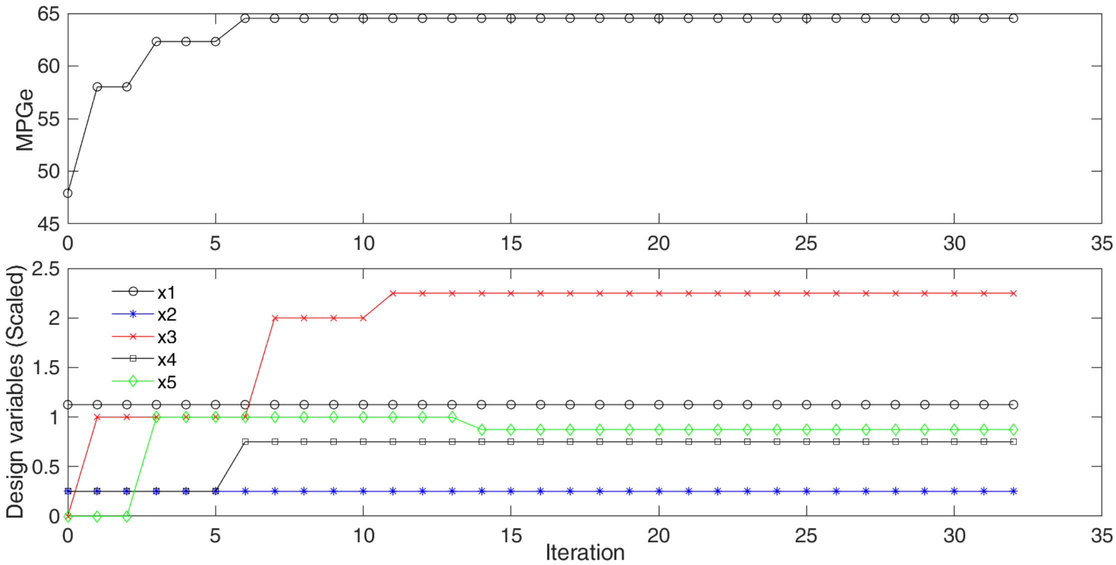

Fig. 6. Optimization history for mode-switching optimization

Figure 7 and Figure 8 depict optimized vehicle powertrain performance for city driving cycle (FTP75) and highway driving cycle (HWFET) respectively. Since the battery is initially assumed to be half-charged, both figures show charge-sustaining mode between the lower limit (SOC = 40%) and the higher limit (SOC = 50%). Battery charging (indicated by the increase in SOC) occurs every time the engine is activated. It is to be noted that MPG_e graph shows the instantaneous value during driving cycle simulation and the final value represents the value after completing the driving cycle.

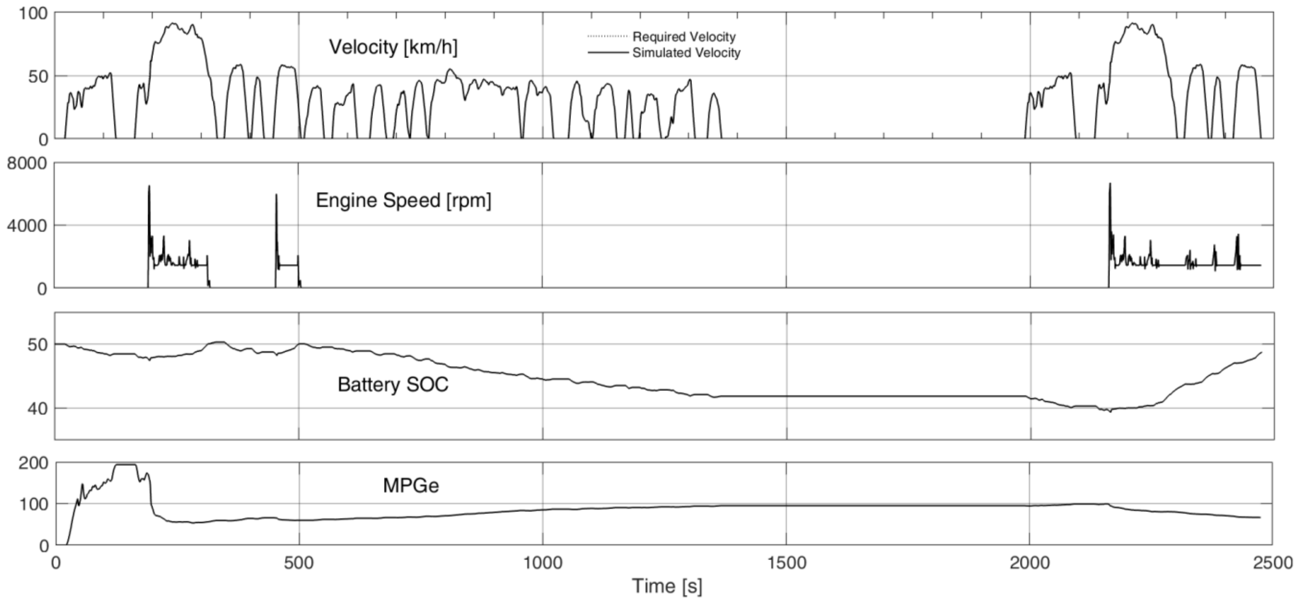

Fig. 7. Optimized vehicle powertrain performance for FTP75 cycle

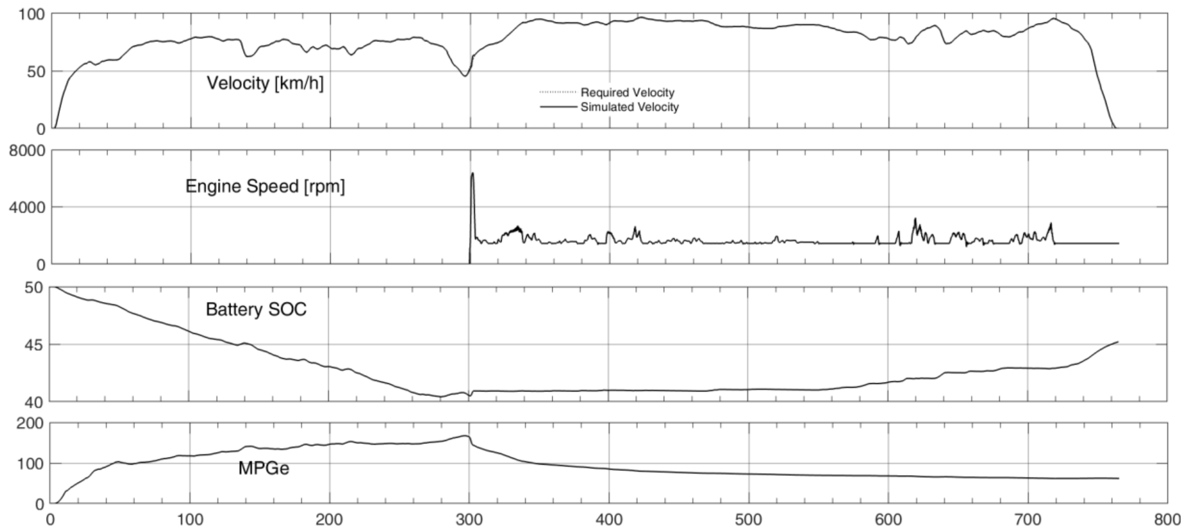

Fig. 8. Optimized vehicle powertrain performance for HWFET cycle

3.2 Powertrain Sizing-optimization

For powertrain sizing-optimization, the optimized variables are $\boldsymbol{x} = [\,V_d\;\; P_{EM}\;\; P_G\; B_C]^{\boldsymbol{T}}$ (Eq. (5)). Minimum and maximum limits are $\boldsymbol{x_{min}} = [1.3\;100\;90\;15]^{\boldsymbol{T}}$ and $\boldsymbol{x_{max}} = [3\;130\;120\;60]^{\boldsymbol{T}}$. During optimization, mode-switching variables are fixed at their optimized values, i.e., $[36\;\;0.5\;\;9\;\;1.5\;\;0.875]^{\boldsymbol{T}}$. Since electric motor characteristics dictate the traction force-velocity envelope (see Figure 5), the minimum value of P_{EM} is restricted to 100 kW. The optimization history is demonstrated in Figure 9. The optimization starts from the optimized solution for mode-switching problem. As shown in Figure 9, MPG_e has increased from 64.5 to 70.6 (10% increase). The final optimized powertrain sizes are $= [1.375\;\;100\;\;110\;\;15.4]^T$. It is to be noted that powertrain variables are treated as continuous variables. In reality, these variables are discrete variables, i.e. only available in specific values. Thus, the optimized variables should be approximated to the nearest available value. For example, the displacement volume is approximated to be 1.4 instead of 1.375. The final optimized powertrain performance is shown in Figure 10 and Figure 11 for city and highway cycles, respectively.

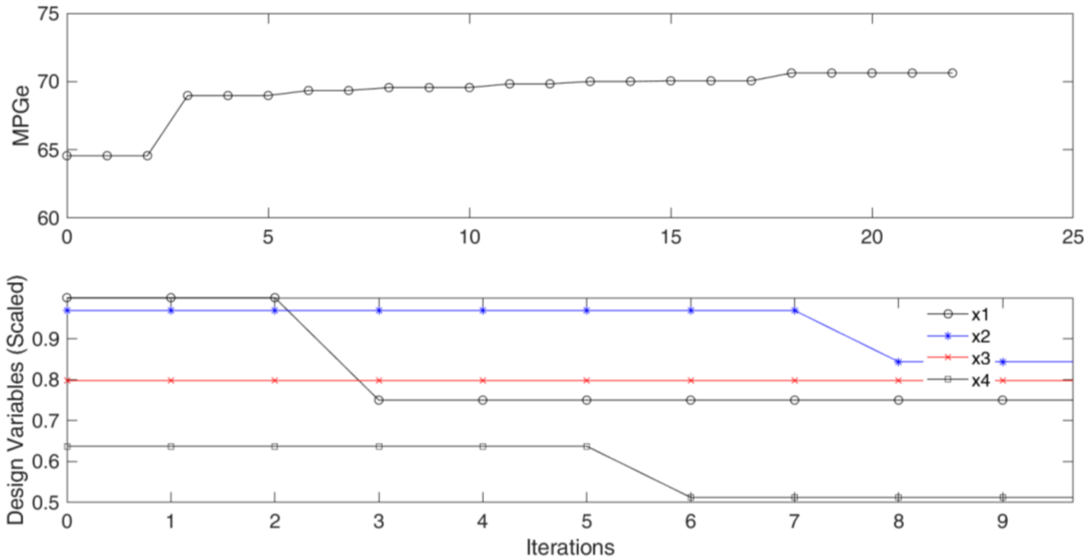

Fig. 9. Optimization history for powertrain-sizing optimization

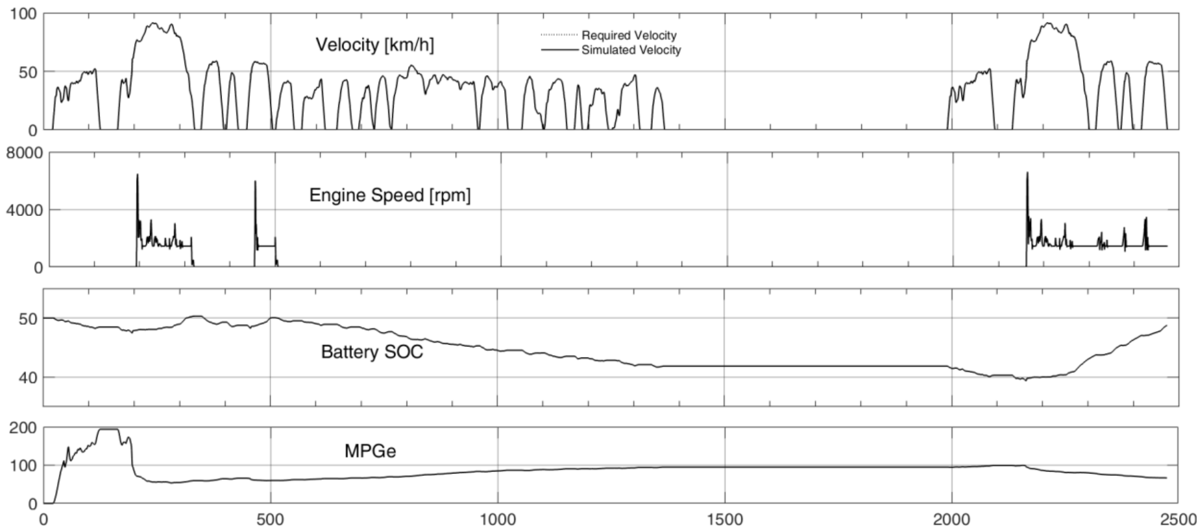

Fig. 10. Optimized vehicle powertrain performance for FTP75 cycle

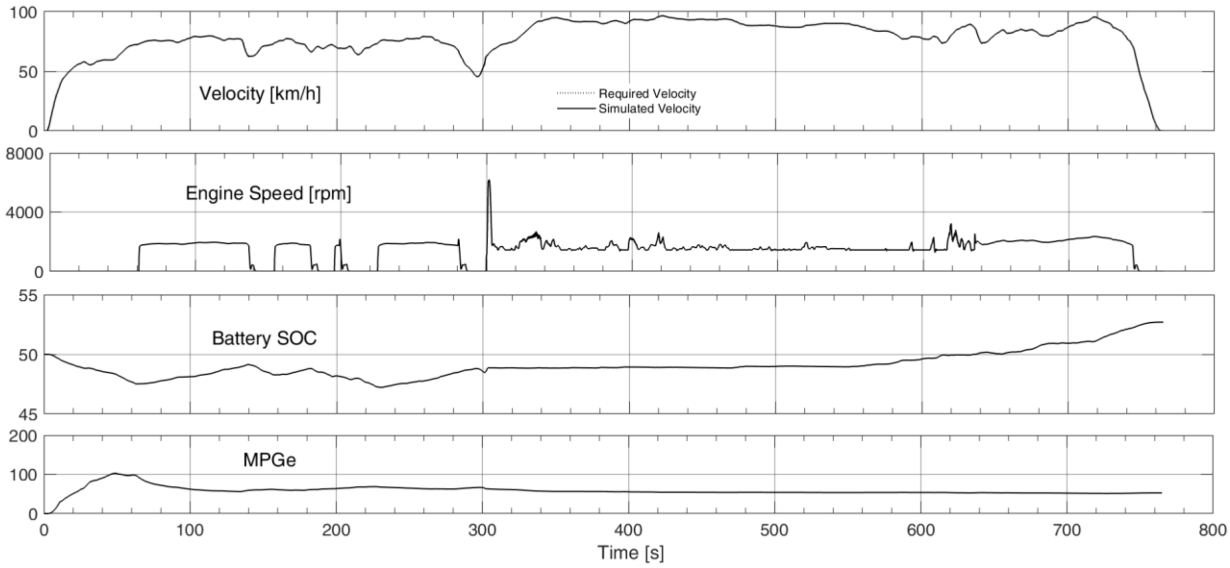

Fig. 11. Optimized vehicle powertrain performance for HWFET cycle

A final optimization run is conducted, where all variables for both mode-switching and powertrain sizing are allowed to vary during optimization, i.e., the optimized variables are $\boldsymbol{x} = [c_1\ c_2\ c_3\ c_4\ c_5\ V_d\ \ P_{EM}\ \ P_G\ B_C]^{\boldsymbol{T}}$. The minimum and maximum limits are kept the same as previous runs. The optimization history is shown in Figure 12. The optimization starts from the reference vehicle (48 MPG_e). The final optimized objective function is 69 MPG_e (close to the two steps optimization value of 70.6). The final optimized variables are $\boldsymbol{x} = [36\ \ 0.5\ \ 6\ \ 1.5\ \ 0.21\ \ 1.5\ 124\ \ 102.1\ \ \ 20.4]^{\boldsymbol{T}}$. Comparing these values with previous values, it is concluded that the optimization problem has multiple maxima. Thus, different optimization initial point or route will lead to a different maximum. This non-uniqueness of the optimum enriches designer choices.

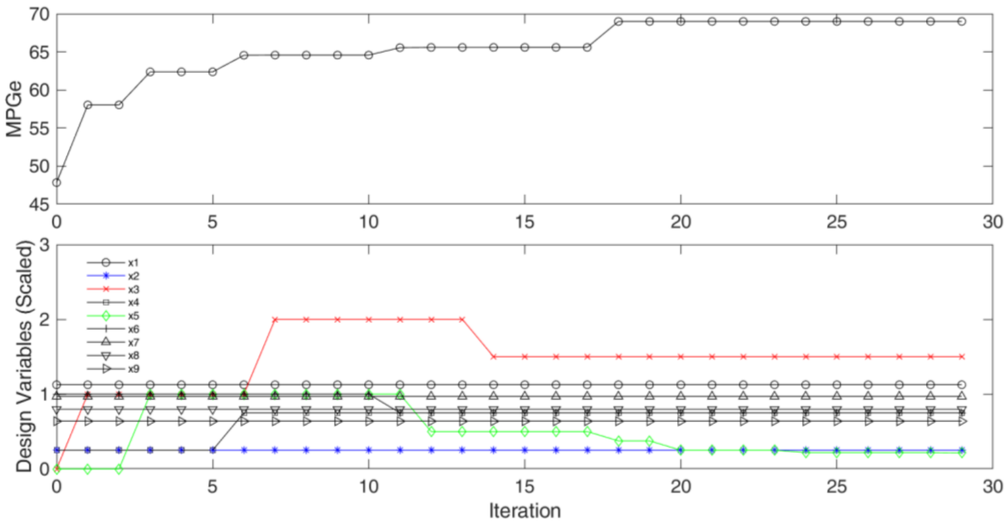

Fig. 12. Optimization history when optimization for both mode-switching and powertrain sizing are conducted concurrently

4. Conclusions

PHEV fuel economy is improved by optimizing driving mode-switching method and resizing of powertrain components for a PHEV. The study is based on a reference vehicle that closely resembles Honda Accord PHEV using Atkinson thermodynamic cycle SI engine. A global optimization method is utilized. This leads to overall MPG_e increase of 40% for a combined city and highway driving cycle. In a more realistic approach, the optimization must be constrained by the vehicle performance requirements or any other design requirements. Performance constraints include maximum cruise speed, minimum time to accelerate from 0 to 100 km/h and the steepness of grade that a vehicle is capable of climbing at an efficient speed (gradeability). This will be considered in a future extension of the current work.

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