

An Ecological Driving Control Strategy for Hybrid Electric Vehicles

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Summary

The objective of this paper is to research an ecological (eco) driving control strategy for hybrid electric vehicles (HEVs) and to establish the velocity profile for eco-driving. The performance simulator of hybrid electric vehicle and its control strategy are developed using MATLAB/Simulink. Limits for velocity and drivable velocity candidates are regulated. A forward velocity of minimum energy consumption is determined from efficiencies of engine and motor. With comparison the velocity profile to others, it shows that the suggested profile can help the vehicle to drive more eco-friendly for HEVs. This research helps to realize the energy management control strategies and extend to research on autonomous vehicle system for eco-driving.

Keywords: HEV (hybrid electric vehicle), eco-driving, power management, energy consumption, velocity profile

1 Introduction

Hybrid electric vehicle (HEV) has been advanced considerably and due to the development its fuel efficiency has been improved noticeably for several years. A HEV runs by fossil fuel and electrical energy. An internal combustion engine and an electric motor of HEV manage different driving conditions in different circumstances. It is controlled by an energy management strategy. Many researchers have studied the energy management strategy and it falls into two categories, rule-based approaches and optimal control methods. Rule-based approaches are easy to be realized in the real vehicle, but it is heuristic and not optimal [1, 2]. On the other hand, optimal control methods consider a whole driving cycle for the minimization of energy consumption. For example, there are one method using dynamic programming, equivalent consumption minimization strategy, and the others. However, those methods need *a priori*, a predicted velocity profile, because they are effective and sensitive to HEV when the profile is known in advance [2, 3].

There are methods to predict driving conditions. Above all, global positioning system (GPS) and intelligent transport system (ITS) can help vehicles to get the driving information [3, 4]. Here, it is assumed that vehicle velocity limitation is known from geographic information system (GIS). In addition, it suggests an ideal condition that driver does not interfere in the vehicle movement. This paper develops an ecological

(eco) driving control strategy for HEV. The control strategy proposes an optimal velocity profile for eco-driving. The profile can help to determine and predict future driving velocity if vehicle runs at that velocity, meaning that the energy management strategy is also improved by real-time implementation.

This paper is organized as follows. Section 2 formulates the HEV model and shows the engine and motor models to develop the HEV simulator for evaluation of its fuel economy. Section 3 deals with the evaluation of fuel economy. Section 4 develops and simulates the control strategy. The simulation results of fuel economy are compared on different conditions. Finally, Section 5 summarizes the paper with conclusion.

2 HEV simulator

HEV simulator can evaluate the fuel economy of HEV. The simulator consists of hybrid control unit (HCU), internal combustion engine, electric motor, battery, vehicle dynamic models, and so on. This paper doesn't mention the specification of modelling but it is presented on the previous researches [5].

2.1 Vehicle model

The vehicle model is formulated with longitudinal dynamic equation. It considers drag and rolling frictions.

$$V = \int 1/M (F_{traction} - F_{drag} - F_{roll}) dt \quad (1)$$

Where V and M are the velocity and mass of vehicle, respectively. $F_{traction}$, F_{drag} , and F_{roll} are the forces of traction, drag friction and rolling friction, respectively.

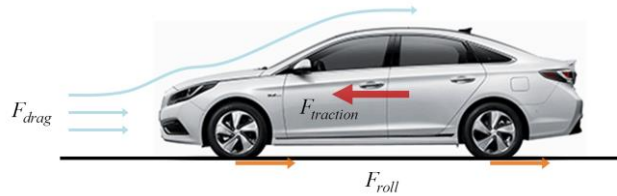


Figure 1: Longitudinal vehicle model

2.2 Engine model

Engine data consists of the maximum and minimum torque curves depending on radial speeds. It also includes a fuel hot map which represents a fuel mass rate depending on one operating point of torque and speed. Fuel consumption is determined by the fuel hot map. Figure 2 (a) is the specific engine map.

2.3 Motor model

Motor data consists of the propelling and regenerative maximum torque curves and a motor efficiency map. The efficiency map is applied to battery and considers both mechanical and electrical efficiencies. Figure 2 (b) is the specific motor map.

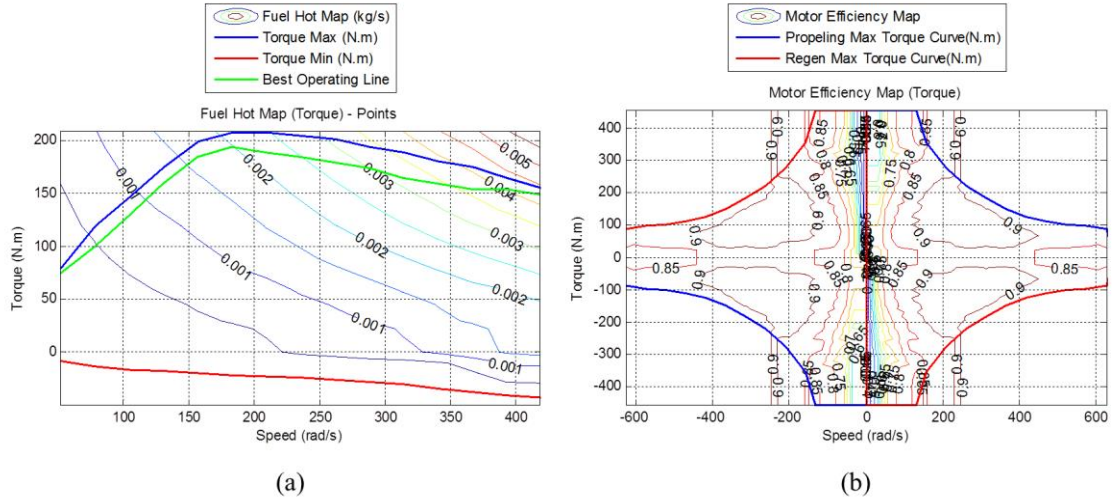


Figure2: Specific maps of engine (a) and motor (b)

3 Fuel economy

When HEV uses more than initial state of charge (SOC) of its battery by operating an electric motor, the evaluation of its fuel economy must be considered about electrical energy. A conversion factor is recommended by the U.S. Environmental Protection Agency (EPA) [6]. Fuel consumption (FC) and fuel economy (FE) are formulated as:

$$FC(l) = \text{fuel density}[l/g] \times \int \text{fuel rate}[g] dt \quad (2)$$

$$FE_{\text{equivalent}} = \frac{\text{Distance}[km]}{FC[l] + E_{\text{elec}}[kWh] / E_{\text{equivalent}}[l/kWh]} \quad (3)$$

Where $FE_{\text{equivalent}}$ is fuel economy with both fuel and electrical energy. E_{elec} represents consumption of battery, and $E_{\text{equivalent}}$ means the conversion factor to convert E_{elec} into equivalent volume of fossil fuel.

4 Control Strategy

4.1 Constraints of velocity and driving time

The control strategy determines an optimal velocity. Simulations were conducted on the assumption that different driving conditions given. The total driving course is 12 km and it is divided into two sections, 3 km and 9 km. The vehicle should run on Case 1 in the velocity limit range 30 km/h to 60 km/h, for 3 km. It should runs on Case 2 for 9 km in the velocity limit range of 60 km/h to 100 km/h. The whole driving time is limited less than 700 sec.

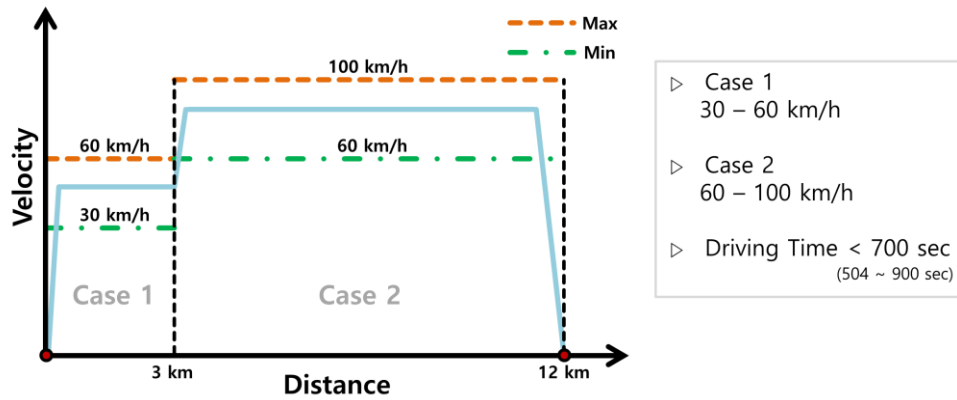


Figure 3: Constraints of two Cases

4.2 Simulation conditions and results

In the experiments, two driving modes, Electric Vehicle (EV) mode, and engine operating mode, were tested in both cases. It is suggested that the velocity profiles (km/h) of Case 1 and Case 2 are [30 40 50 60] and [60 70 80 90 100], respectively (Table 1). The number of velocity examples is twenty. Due to the constraint of driving time, the examples are reduced by 12 examples. Table 2 shows the simulation results of two different examples when those driving time are similar. There are four modes; first mode is only EV driving, second mode is EV and engine driving, third mode is engine and EV driving, and final mode is only engine driving.

Example #1 and #2 is only EV driving mode. Example #1 is more efficient driving than #2. Figure 4 shows the operating points of motor and its efficiency results. The efficient driving of electric motor increases in frequency in example #1. Next, example #3 and #4 are combined driving modes. The first mode is EV driving and the following mode is engine driving. In the two different examples, the differential SOC results are not different, so that the actual consumption of electricity in both examples is the same. However, the engine operating points of #4 are more fuel consuming than those of #3. It is shown in Figure5 (a). On the other hand, examples #5 and #6 have reverse modes, an engine driving mode and EV mode. The fuel economy of #5 is higher than that of #6. The reason is the same as the previous examples of #3 and #4. Finally, only engine driving is examples of #7 and #8. The engine operating points of #8 consumes more energy than those of #7 as shown in Figure5 (b). In this study, a control algorithm for selecting gear ratio of transmission uses a general method as input parameters are acceleration-pedal position and vehicle speed, which affects the engine operating points.

Table 1: Simulation conditions

# of case	Case 1	Case 2
Driving range	3 km	9 km
Velocity (km/h)	[30 40 50 60]	[60 70 80 90 100]
Mode	EV/engine driving	EV/engine driving

Table 2: Simulation results of different examples

Mode	# of Example	Velocity Case 1	Velocity Case 2	Driving time	Δ SOC	Gear	Fuel economy (equivalent)
Only EV driving	1	50 km/h	70 km/h	678 sec	-0.171	4→5	46.6 km/l
	2	40 km/h	80 km/h	675 sec	-0.185	3→5	43.0 km/l
EV→Engine driving	3	50 km/h	70 km/h	678 sec	-0.038	4→5	30.1 km/l
	4	40 km/h	80 km/h	675 sec	-0.032	3→5	28.2 km/l
Engine→EV driving	5	50 km/h	70 km/h	678 sec	-0.129	4→5	37.4 km/l
	6	40 km/h	80 km/h	675 sec	-0.148	3→5	31.6 km/l
Only engine driving	7	50 km/h	70 km/h	678 sec	+0.001	4→5	26.0 km/l
	8	40 km/h	80 km/h	675 sec	+0.002	3→5	22.7 km/l

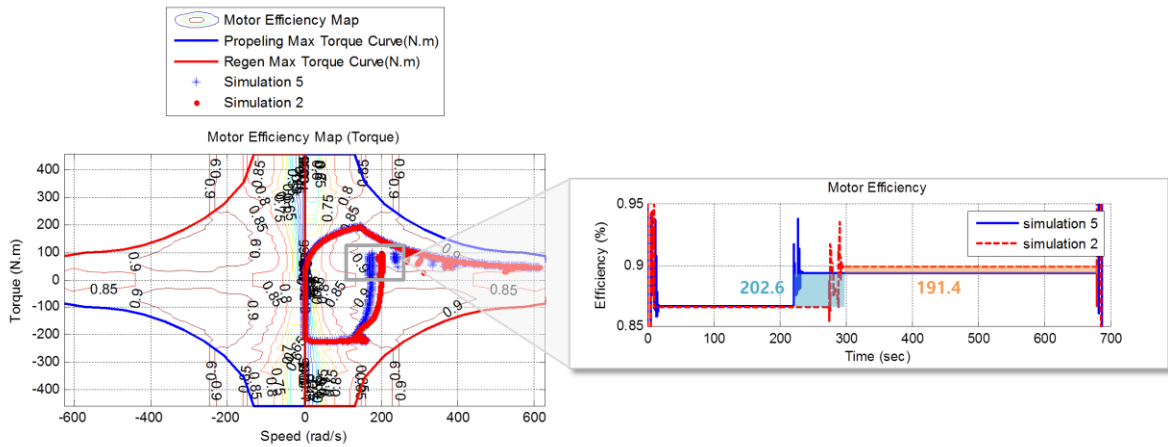


Figure 4: The operating points of motor for example #1

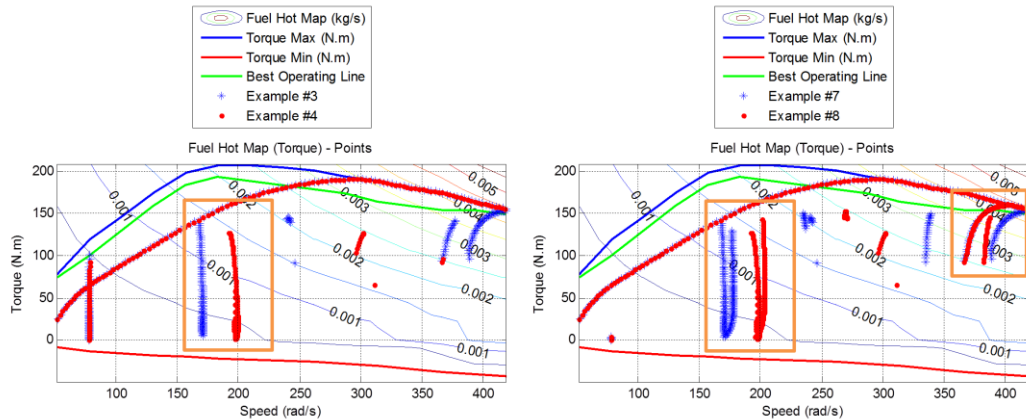


Figure 5: The operating points of engine for example #3 and #4 (a), and for #7 and #8 (b)

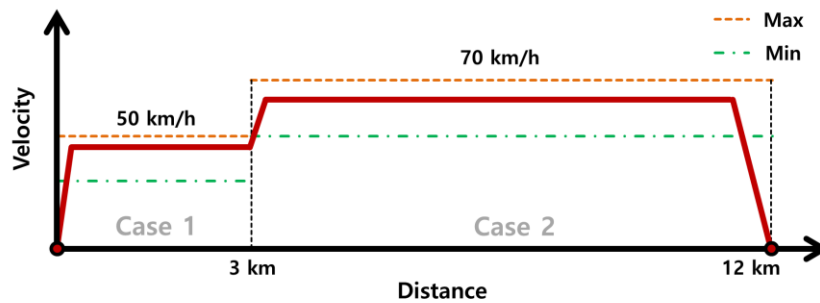


Figure 6: Optimal velocity profile

Based on the comparison analysis of simulation results from the velocity profiles, an optimal velocity profile of the vehicle can be chosen for the most efficient driving. Whatever the driving mode is, the optimal velocity profile is 50 km/h for Case 1 and 70 km/h for Case 2.

5 Conclusion

This paper proposes a control strategy to formulate optimal velocity profile, aimed at eco-driving. When velocity limits on each case are given, fuel economy of the combination of cases is evaluated. When driving one velocity profile on operating most efficiently torque and speed of engine or motor, HEV can improve its fuel economy because it depends on motor efficiency and fuel rate of engine. Therefore, the control strategy proposes optimal velocity profile for eco-driving.

This strategy will help to apply energy management strategy to real vehicles in that future velocity profile can be offered. In addition, the integrated strategy of both is expected to provide a synergy effect. However, it needs to be modified and improved in order that the proposed strategy is implemented on real-time process. The velocity profile can recommend that a driver of HEV be guided for eco-driving.

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