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Development of Optimal Control Strategy for Hybrid Electric Vehicle using Dynamic Programming and Fuel Equivalent Factor

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Abstract

In this study, a model-based optimal control algorithm has been developed, which mainly consists of power distribution(including EV decision) and shift strategy for full function parallel type hybrid electric vehicle. To make rules, first, a global optimization method using dynamic programming has been used. These results show the optimal operations for the best system efficiency, which means the minimization of fuel consumption. But these results can not be used directly for making vehicle control rules because it is impossible to make an analogical decision for various driving situations by just using those results. So here, secondly, we have used a local optimization method using the fuel equivalent factor for extracting rules. This method evaluates electric energy consumption by equivalent fuel consumption, which makes it possible to decide system operation for all driving situations. To investigate the validity, the results from the local optimization method have been compared with those of the global optimization method, and there were just small differences between two results. Developed supervisory control algorithm which is extracted from local optimization results was validated by forward-facing simulation. Finally, we are now testing prototype vehicles controlled by above supervisory control algorithm.

Keywords: HEV (hybrid electric vehicle), optimization, power management, control system, parallel HEV

1 Introduction

Rapid industrialization has caused rising consumption of fossil energy which exacerbates environmental problems. Vehicles are responsible for a significant portion of energy consumption and harmful air pollution in the world.

Compared to conventional vehicles, an emerging solution to reducing the fuel consumption and exhaust emissions is to use the hybrid electric system.

In general, a hybrid vehicle is a vehicle in which propulsion power is obtained from two or more kinds of power sources of mechanical, electrical, hydraulic, thermodynamic devices. In particular, hybrid electric vehicle (HEV) means a vehicle with coupling system of an engine, electric motor and battery.

The complicated interaction of an engine, electric motors, and electric energy storage makes the task of controlling a hybrid power train system difficult and causes the control strategy of how hybrid electric system operates to be an essential key in the HEV. Many control strategy approaches for

HEV have been studied to seek for the most efficient operation area of hybrid electric propulsion system.
The objective of this research is to develop the high-fidelity optimal control strategy capable of applying for the real-time controller of vehicle by using dynamic programming as one of global optimization technique and fuel equivalent factor as one of local optimization technique.
The HEV model and control strategy are validated by simulation and being tested on a prototype hybrid electric vehicle.

2 Optimal Control Strategy Approaches

The objective of optimal control is to find the best parameter combination to minimize the cost function. We choose two representative optimization techniques for extracting control rules.

2.1 Global Optimization

Global optimization technique looks for globally optimized solutions that can not be determined for an instant point in time by local optimization.
Dynamic programming is widely used as a representative method of the global optimization because of the advantages of easy and efficient applicable approach for solving multi-step process problem.
Dynamic programming is based on Bellman's optimization theory "If a-b-e is an optimal path to e from a, b-e will be the optimal path to e from b", in other words, a practical method reducing the optimizing process of original problem using optimal substructure. [1]
In this research, the goal of optimization is to minimize the cost function, J of fuel consumption for a given driving cycle. The cost function is shown at the following equation (1).

$$J = fuel\ consumption = \int \dot{m}\ ,\ (g) \qquad \dot{m} : fuel\ consumption\ rate(g/s) \tag{1}$$

During driving within a given driving cycle, the variation between initial SOC (State of Charge) and final SOC of battery explicitly needs to be in the cost function as a constraint. So, the cost function equation (1) can be modified as the following equation (2).

$$\begin{aligned} J = fuel = \int \dot{m} + K\ ,\ (g) \\ K = 0\ \ at\ SOC_{final} \geq SOC_{initial} \\ = \infty\ \ at\ SOC_{final} < SOC_{initial} \end{aligned} \tag{2}$$

The time dependent optimal solution of dynamic programming is globally determined for a given complete driving cycle but not be easily applicable to other type of driving conditions besides a given driving cycle.[2][3] For example, theoretically, under the same driving condition (same vehicle speed and same vehicle load), a different optimal solution may be computed according to time. It is nearly impossible to implement the dynamic programming on the vehicle controller because of requirements of driving condition look-ahead and heavy computational time. But the optimal results of dynamic programming can be useful as absolute criteria for the development of optimal control strategy to minimize fuel consumption.

2.2 Local Optimization

Local optimization determines the ideal output commands of hybrid electric system at discrete point in current time. Although this approach cannot obtain better results than the global optimization, it has advantages of simple and quick process.
Equation (3) shows the assumption of local optimization from the cost function of global optimization in given driving cycle

$$\begin{aligned} minnimization\ of\ \ J = \min(\int \dot{m}) \\ \approx \int(\min(\dot{m}))\ ,\ (g) \end{aligned} \tag{3}$$

The following equation (4) represents the cost function of fuel consumption rate for the local optimization.

$$j = fuel\ consumption\ rate = \dot{m}\ ,\ (g/s) \tag{4}$$

The above cost function is rewritten with fuel equivalent factor including the relationship of initial and final SOC of battery as shown in the following equation (5).

$$\begin{aligned} j = \dot{m} + FEF * P_{bat}\ ,\ (g/s) \\ FEF : Fuel\ Equivalent\ Factor(g/s/W) \\ with\ SOC_{final} \cong SOC_{initial}, \\ P_{bat} : Power\ of\ \ Battery(W) \end{aligned} \tag{5}$$

The optimization method using fuel equivalent factor is to equivalently convert the electric energy by battery to the amount of liquid fuel.
The local optimization technique can be more easily implemented to real-time control strategy thanks to its analogical approach for every driving conditions of vehicle. [4]

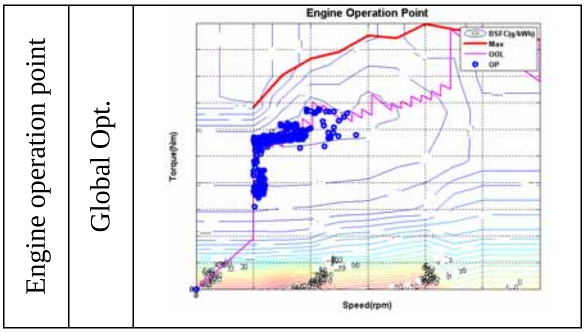
2.3 Comparison of Optimization Results

As mentioned previously, the dynamic programming provides the best optimal solutions for a given driving but has a drawback not to be applicable for various actual driving conditions. On the other hand, the local optimization using fuel equivalent factor is beneficial for various driving conditions because of computation at instant time and can be implemented effectively in actual vehicles but determines relatively less optimized solution.
If there is no significant difference between results of local optimization and global optimization, the local optimization approach will be an appropriate method to determine the control strategy of HEV.
For each optimization approach, the simulation results of fuel economy for UDDS driving cycle are shown at Table 1.

Table1: Fuel economy comparison

	Global Opt.	Local Opt.
Relative Fuel economy	100	99.2

Engine operation point, power of engine and motor, SOC of battery, and HEV mode distribution which are resulted from the local optimization and the global optimization are represented in Figure1.



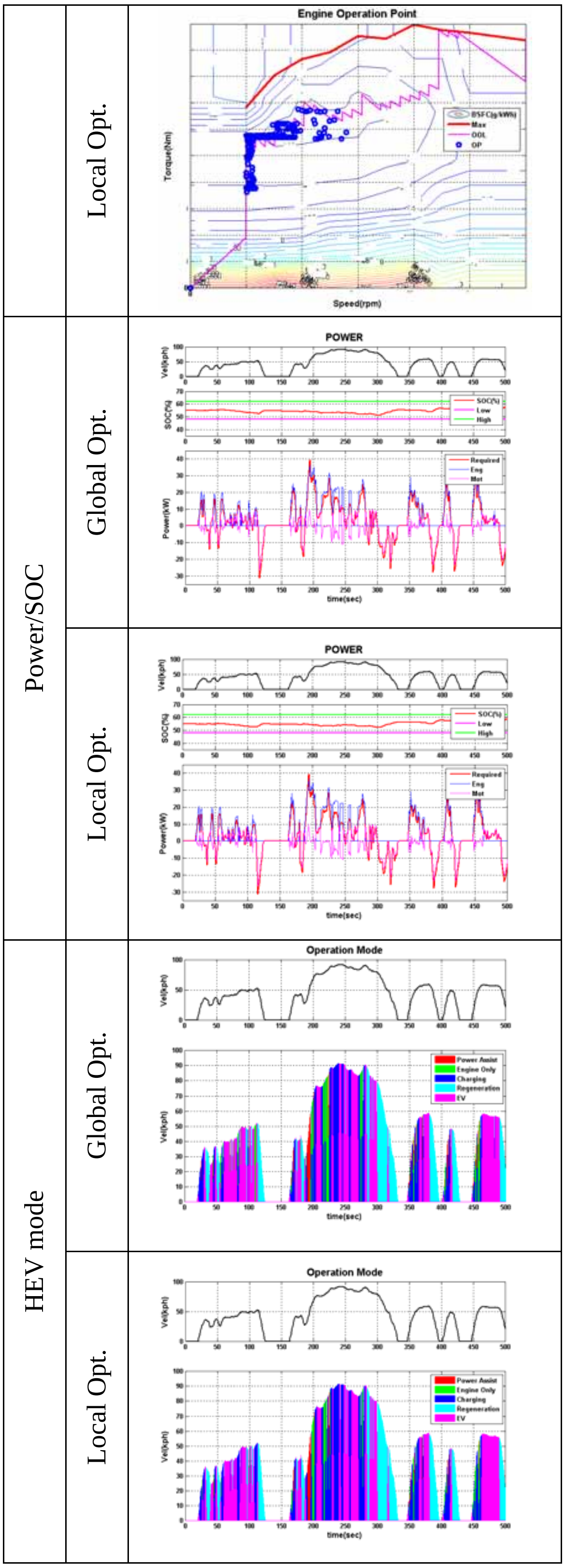


Figure1: HEV operational comparison

As shown at Table1and Figure1, the differences of fuel economy by two optimization approaches are

less than 1% and operational features is not significantly different as well.
We concluded that it is appropriate to choose the control strategy of HEV established by using local optimization.

3 Development of Control Strategy

The local optimization approach can decide power train operation for a given specific driving condition. We searched the optimal power train operations for whole driving conditions within system maximum output. From this result, we developed supervisory control rule by extracting simplified line, map, etc. for the real controller of HEV.

3.1 EV Decision

Figure2 shows how the operational zone of EV (Electric Vehicle) mode is decided from the results of optimization. Through the process, a simplified line is selected as a boundary of EV mode. A hysteresis is also drawn to avoid On/Off operation frequently switching.

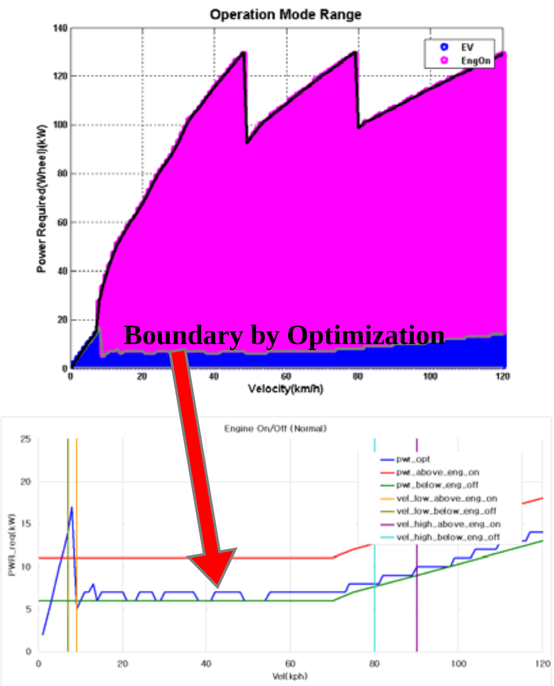


Figure2: Decision of EV zone

3.2 Shifting Map

Figure3 represents the process that transmission shifting maps are made in case of engine-on.

As deciding the area of EV, transmission shifting hysteresis lines are drawn also to avoid frequent gear shift.
We also checked the optimal shifting target for engine-off conditions (EV/regenerative braking)

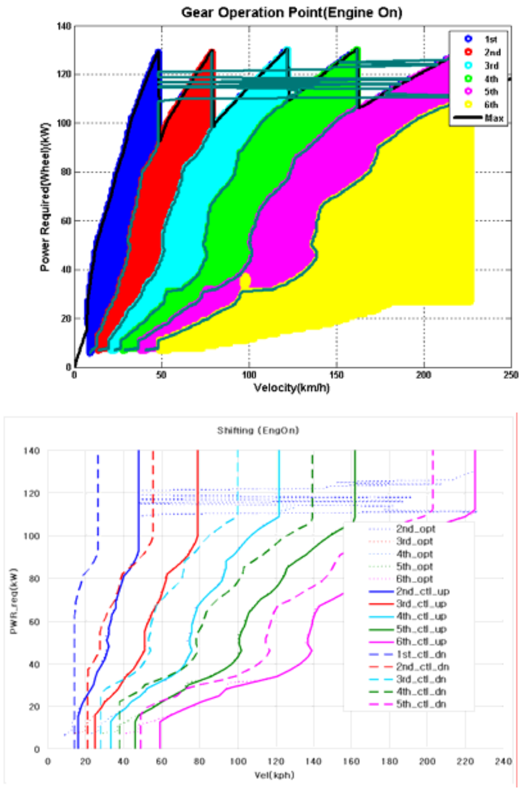


Figure3: Transmission shifting maps

3.3 Power Distribution

For each transmission gear ratio, power distribution maps between engine and electric motor are derived as shown at Figure4. The demanded power of electric motor is determined by the input values of required propulsion power and rotational TM input speed for each gear ratio. Figure 4 shows the raw results of motor operation power for 1st, 2nd, and 3rd gear.
The data of map was refined and resized in order to speed up the processing time of data and to cope with the limitation of data saving capacity. The same process is repeated to have the operation power map of motor for 4th ~6th gear.

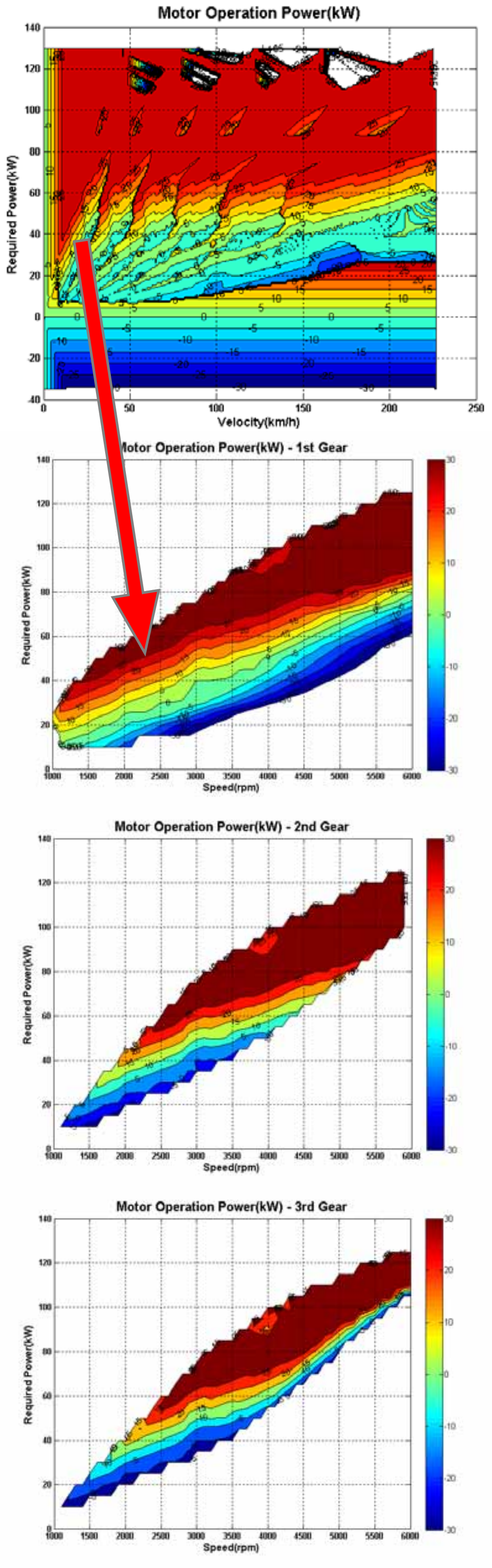


Figure4: Motor power maps

4 Validation of Control Strategy

We validated developed supervisory control using a forward-facing simulation. For this procedure, we made a vehicle model with a power train controller.

4.1 Controller Modelling

To facilitate control strategy development, Matlab®/Simulink® (Mathworks™)is used to build the schematic block of control strategy based on the optimal gear shifting line, engine on/off decision and motor operation map as shown at Figure 5.

Besides above mentioned core functions, the controller includes driver demand interpretation logic, regenerative braking logic, and limitation of power train, etc.

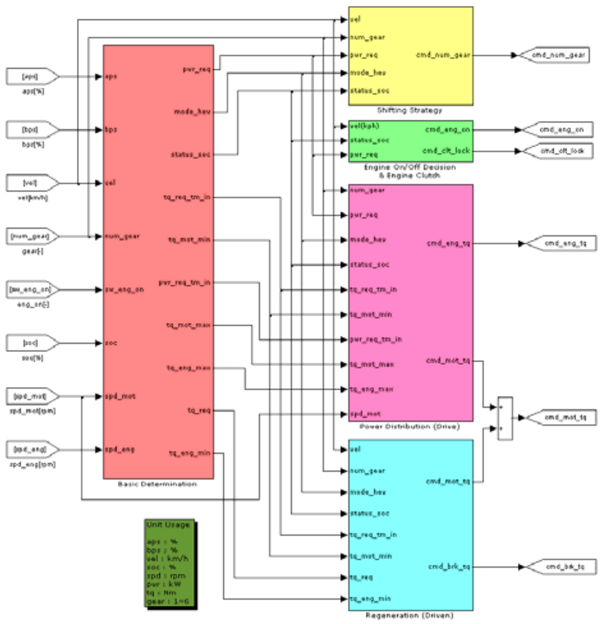


Figure5: Simulink block of control strategy

4.2 Vehicle Modelling

The model of vehicle for simulation was developed for this research. The model is drawn out by AMESim® (LMS®) which is used for dynamics modelling of vehicle. Developed Vehicle model is shown in Figure6.

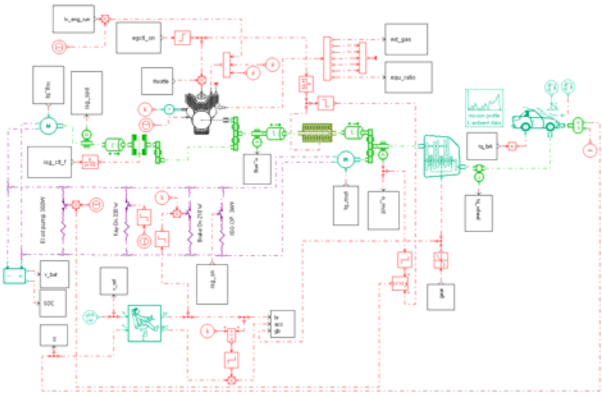


Figure6: Vehicle model

The configuration and specifications of vehicle and the power train components of HEV used in this simulation are shown in Figure7 and Table2.

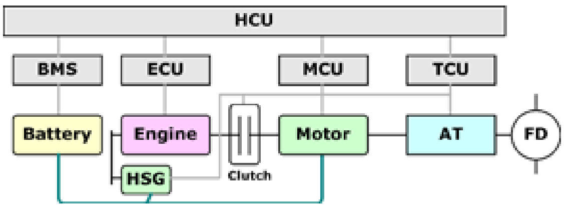


Figure7: HEV system configuration

Table2: Vehicle Characteristics

Vehicle	mid-size sedan
Engine	2.4L I4 gasoline
Motor	30kW
T/M	6speed AT
Battery	Li-PB
Brake	regenerative braking system

4.3 Forward-facing Simulation Results

The simulation of the forward-facing model can properly consider dynamic effects such as time delays and rotational moment of inertia, compared to the backward-facing simulation.

Table3: Fuel economy comparison

	Local Opt.	F-F Simul.
Relative Fuel economy	100	94.5

Table 3 shows the relative fuel economy of the forward-facing vehicle model at UDDS driving cycle. Compared to the results of the local optimization, the fuel economy of a forward-facing simulation is relatively decreased to about 6%. In spite of the effects of simplification and hysteresis for control operation, dynamics of vehicle, the results of simulation shows acceptable deviation of fuel economy.

Figure8 shows that the results of forward-facing simulation are compared to that of local optimization. The operation points of engine and electric motor were tracing closely along the results of local optimization.

As implemented to real vehicle, the proposed approach could improve the fuel economy of HEV by optimized operation.

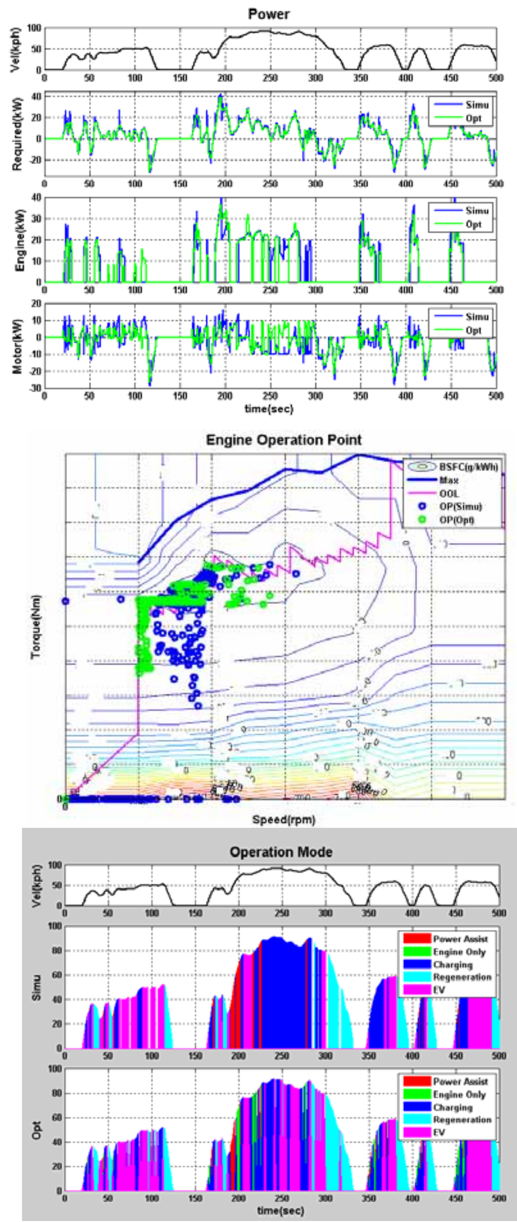


Figure8: Comparing results of forward facing simulation and local optimization

5 Conclusion

Referencing In this research, the control strategy of full function parallel type gasoline HEV was developed based on the optimization results minimizing the fuel consumption of vehicle.
The local optimization using fuel equivalent factor was adopted to derive the optimal control strategy for better fuel economy.
In order to validate the proposed optimal control strategy, the result of local optimization was compared to that of global optimization by dynamic programming approaches.
Also, forward-facing fuel economy simulation was used to validate its adaptability for real controller of vehicle and realistic fuel economy estimation.
The high-level supervisory control strategy of HEV developed in this research has been implemented in Hyundai's HEV and now being tested and tuned for better vehicle performance.

References

[1] Donald E. Kirk, *Optimal Control Theory - An Introduction*, Prentice-Hall Inc, 1970

[2] Chan-Chiao Lin, Huei Peng and Jessy W. Grizzle, *Control System Development for an Advanced-Technology Medium-Duty Hybrid Electric Truck*, SAE 2003-01-3369, 2003

[3] Chan-Chiao Lin, Jun-Mo Kang, J.W. Grizle, and Huei Peng, *Energy Management Strategy for a Parallel Hybrid Electric Truck*, Proceedings of the 2001 American Control Conference, Arlington, VA, June, 2001

[4] Sungtae Cho, *Fuel Economy Optimization of Hybrid Electric Vehicle with Single Performance Index*, Ph.D. thesis, Seoul National University, Korea, 2001

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