Validation and Control Strategy to Reduce Fuel Consumption for RE-EV

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Keywords: Range Extended Electric Vehicle (RE-EV), Equivalent Fuel Consumption, Optimal Operation Line.

Abstract: In this study, a control strategy of the target RE-EV was analysed using BMW i3 test data from Downloadable Dynamometer Database (D^3) at Argonne National Laboratory. In addition, vehicle model was developed based on AVL Cruise and MATLAB/Simulink and validation of the developed model was carried out. Using the simulation and test data, a control strategy which operates the engine on the optimal operation line was proposed to reduce the fuel consumption. The performance of the engine control strategy was evaluated for the city and highway driving cycle.

1 INTRODUCTION

As the regulations against CO_2 emission has been strengthened, the demand of eco-vehicle has been increasing. Electric vehicle (EV) exhausts no emission, but its relatively short travel distance has been pointed out as a major drawback (Pavlat, 1993). Range extended-electric vehicle (RE-EV) is considered to be a solution to overcome the short travel distance of EV (Chih-Ming, 2013). RE-EV is a series type plug-in hybrid vehicle (PHEV) in which the internal combustion engine and generator are added in EV (Wu, 2015). In series type, the engine is used only to charge the battery through the generator and the motor propels the vehicle using the battery energy (Tate, 2008). Since the engine is the only means to charge the battery when RE-EV drives, the engine turned on/off timing (Pi, 2016), and how to control the engine are the essential elements to improve the fuel economy (Min, 2013).

In this study, the engine operation was investigated for BMW i3 RE-EV using the experimental data from Downloadable Dynamometer Database(D^3) at Argonne National Laboratory (Anl.gov, 2015). In addition, dynamic model of the RE-EV was obtained and a performance simulator was developed based on AVL Cruise and MATLAB/Simulink. The RE-EV model was validated by comparing the test results for various driving cycles. Using the simulation and experimental results, an engine control algorithm was proposed to improve the fuel economy.

2 MODELING AND VALIDATION OF TARGET RE-EV

In Figure 1, the target RE-EV, BMW i3 is shown. The target RE-EV consists of one engine, two motor/generator, battery and reduction gear.

The target RE-EV utilizes charge depleting (CD) mode and charge sustaining (CS) mode. In CD mode, the vehicle is propelled by MG2 using the electric power. In CS mode, the engine is turned on to operate MG1 and the electric power of MG1 is charged in the battery.

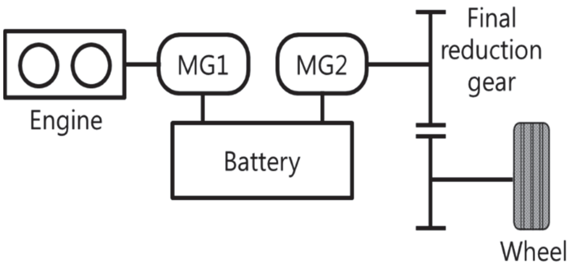

Figure 1: Vehicle configuration for RE-EV.

In Table 1, the vehicle specifications are shown.

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Table 1: Vehicle specifications for RE-EV (Insideevs.com, 2013).

Vehicle specifications		
Engine	Max power(kW)	25
	Max torque(Nm)	55
MG2	Max power(kW)	125
MG1	Max power(kW)	26.6
Battery	Battery energy (kWh)	22
	Capacity(Ah)	60
Vehicle	Mass(kg)	1315
	Tire radius(m)	0.33

2.1 Analysis of Test Data

In Figure 2, vehicle operating points and engine operating points are shown. As shown in Figure 2, When SOC is below 0.16, CD mode is changed to CS mode that operates engine.

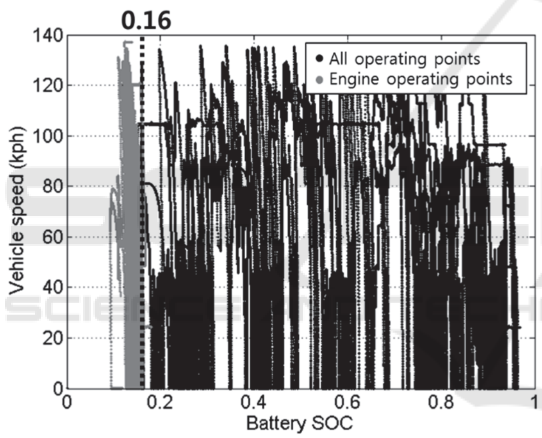

Figure 2: Vehicle and engine operating points.

In Figure 3, test data of the engine on/off for the vehicle speed vs. battery SOC are shown (data from ANL).

In CD mode, the engine is always off since only the electric energy is used to propel the vehicle. It is seen from Figure 3 that the engine on/off is determined by the vehicle speed and battery SOC. The engine is turned on when the battery SOC drops below SOC=0.16. In CS mode, the engine is turned on when the vehicle speed becomes higher than 20kph and turned off when vehicle speed is lower than 10kph.

Figure 4 shows the engine speed vs. vehicle speed for various battery SOC in CS mode. It is seen from Figure 4 that the engine speed increases with the vehicle speed. When the SOC is low, the engine is operated at higher speed meanwhile the engine is

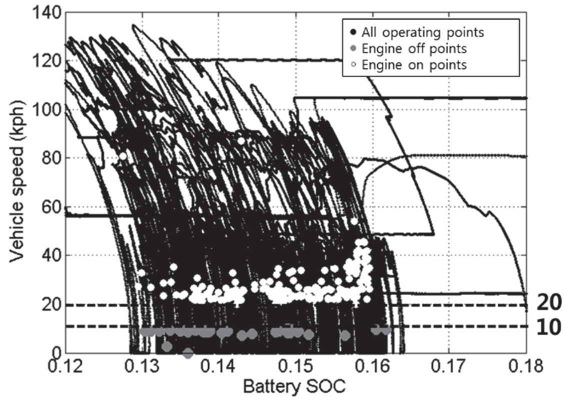

Figure 3: Points of engine turned on/off.

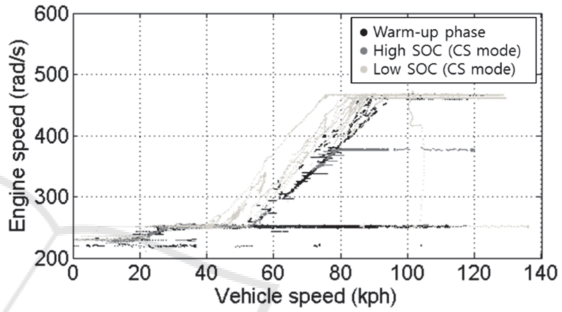

Figure 4: Engine speed vs. vehicle speed.

operated at lower speed for high SOC. It is noted that the engine speed is maintained low when the engine begins to operate at high SOC. This low engine speed is considered to warm up the engine and catalyst converter.

2.2 Modeling and Validation

The target RE-EV was modelled using Cruise. In Figure 5, Cruise model is shown. Each module in Figure 5 represents the dynamic model of the RE-EV component based on mathematical equations describing its characteristics. For the vehicle control, MATLAB/Simulink based controller was developed using test data. Co-simulation was performed using the Cruise vehicle model and MATLAB/Simulink controller.

In Figure 6 and Figure 7, simulation results are compared with the test results for UDDS cycle (city driving) and HWFET cycle (highway driving). As shown in Figure 6 and Figure 7, the simulation results of the vehicle speed, battery SOC, motor torque and speed, engine speed and the fuel consumption are in good accordance with the test results, which demonstrates the validity of the Cruise simulation model.

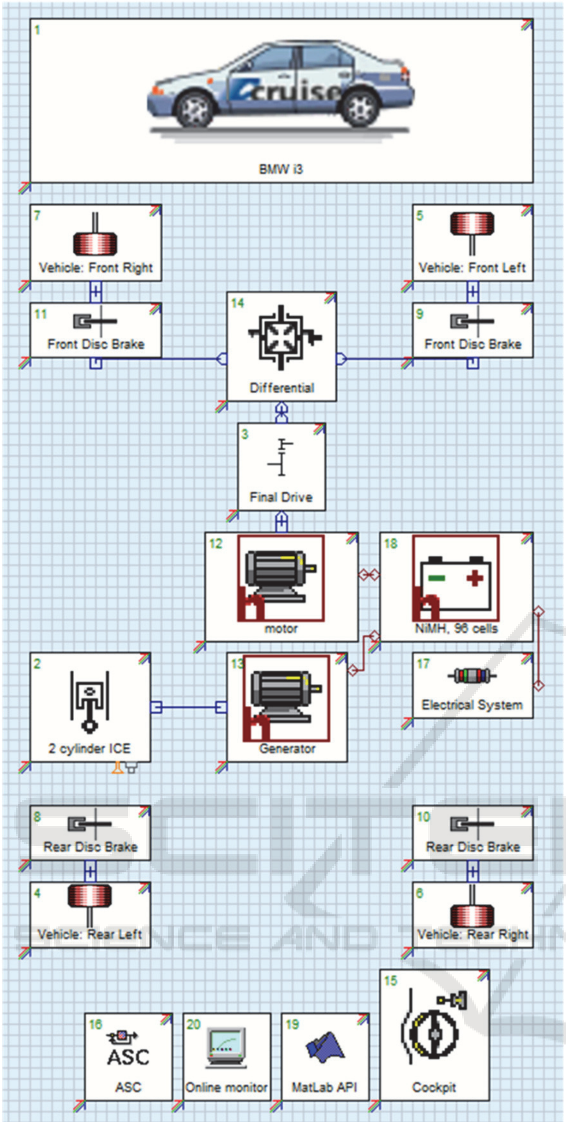

Figure 5: Cruise model of the target RE-EV.

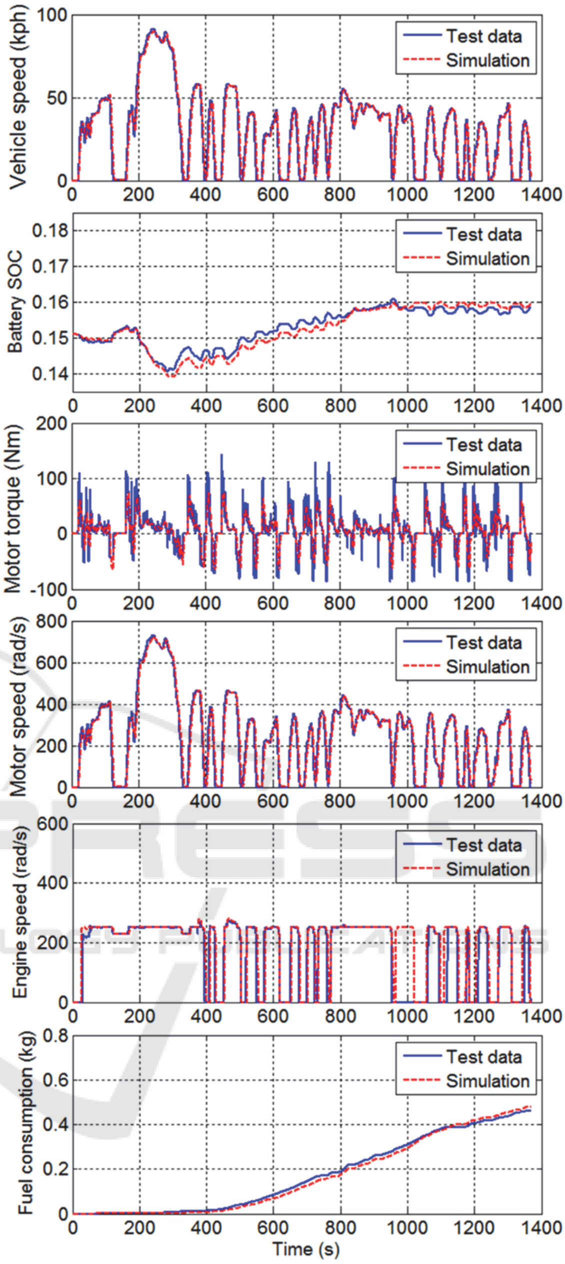

Figure 6: CS mode validation results for UDDS cycle.

3 CONTROL STRATEGY OF ENGINE OPTIMAL OPERATION

3.1 Optimal Operation Line (OOL) Control

As shown in the test results (Figure 2 ~ Figure 4), the engine operation of the target RE-EV was performed according to the vehicle speed and battery SOC without consideration of the engine thermal efficiency. Since the target RE-EV is the series type, it is possible to operate the engine independent of the vehicle speed.

In this study, a control algorithm was proposed to operate the engine on the optimal operating line (OOL) that provides the best thermal efficiency. As shown in Figure 8, the OOL was obtained by connecting the points which provide the minimum

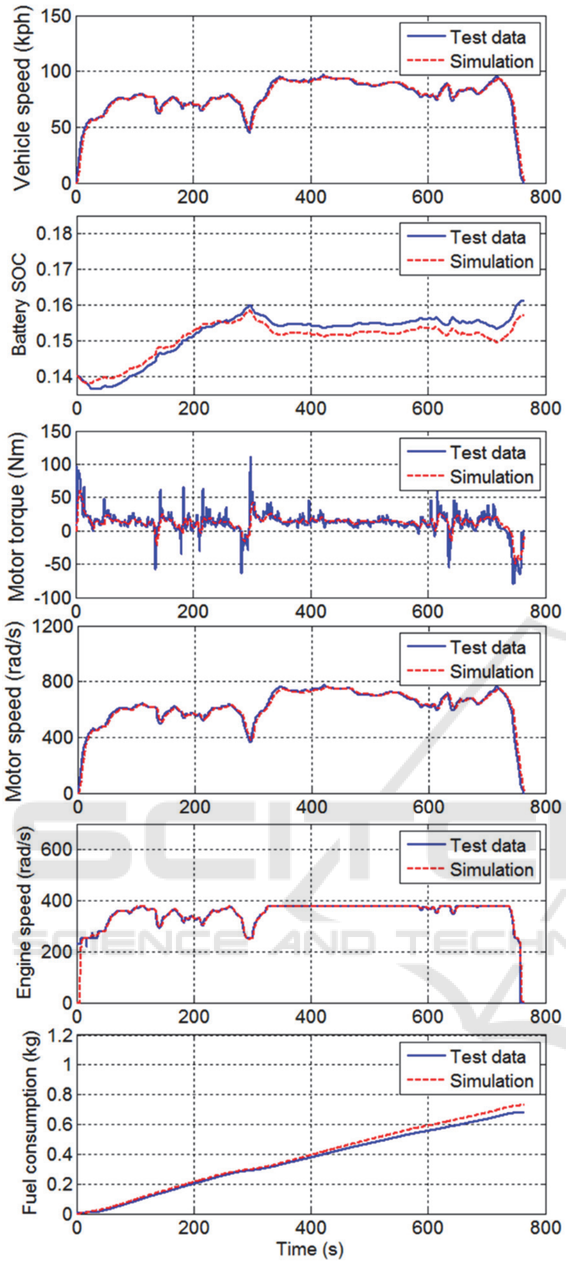

Figure 7: CS mode validation results for HWFET cycle.

fuel consumption for the demanded engine power (Ma, 2012).

The demanded engine power was obtained by the motor input power and weight factor considering the battery SOC balancing in CS mode. The battery balancing was performed using the weight factor. The weight factor was designed as a PI controller using the difference between the target SOC and present SOC as follows:

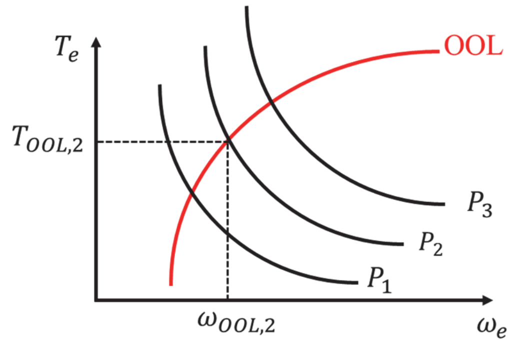

Figure 8: Determination of engine operating point in OOL control.

$$f(\mathrm{SOC}) = K_p(SOC_{target} - SOC) + K_i \int (SOC_{target} - SOC)dt \quad (1)$$

where $f(\mathrm{SOC})$ is the weight factor, K_p, K_i is the P, I gain of PI control, respectively.

The demanded engine power was obtained as

$$P_{eng\_dmd} = f(SOC) \cdot P_{MG} \quad (2)$$

where P_{eng_dmd} is the engine demand power, P_{MG} is the motor input power.

For the demanded engine power, the engine operating point (torque and speed) is determined from the OOL. MG1 controls the engine to operate on the OOL.

The mode change timing and engine on/off timing were used from the existing control based on the vehicle speed and battery SOC.

3.2 Results and Discussion

Simulations were carried out to evaluate the performance of the engine OOL control algorithm. In simulation, the initial battery SOC and target SOC were set as 0.18 and 0.16 respectively.

In Figure 9, simulation results are compared for the OOL control and existing control when the vehicle drives UDDS cycle. It is seen from Figure 9 that both control follow the driving cycle closely. The engine speed and torque by the OOL control show higher value than those of the existing control when the vehicle speed is high

In Figure 10, simulation results for HWFET cycle are compared. It is seen that the engine speed remained around the OOL (250rad/s), which is lower than that of the existing control, but the engine torque showed higher value.

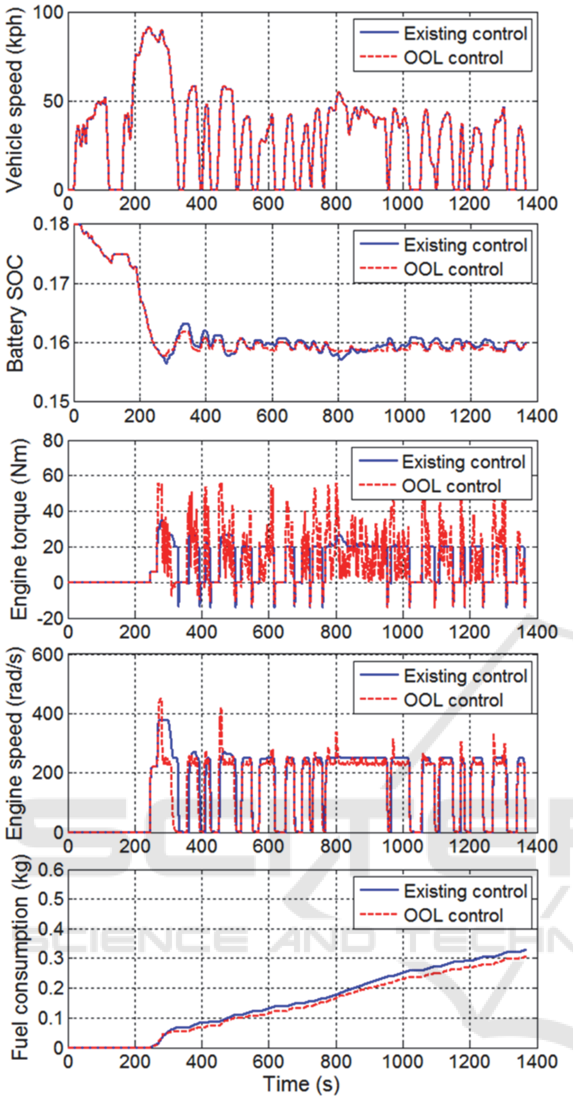

Figure 9: Simulation results for UDDS cycle.

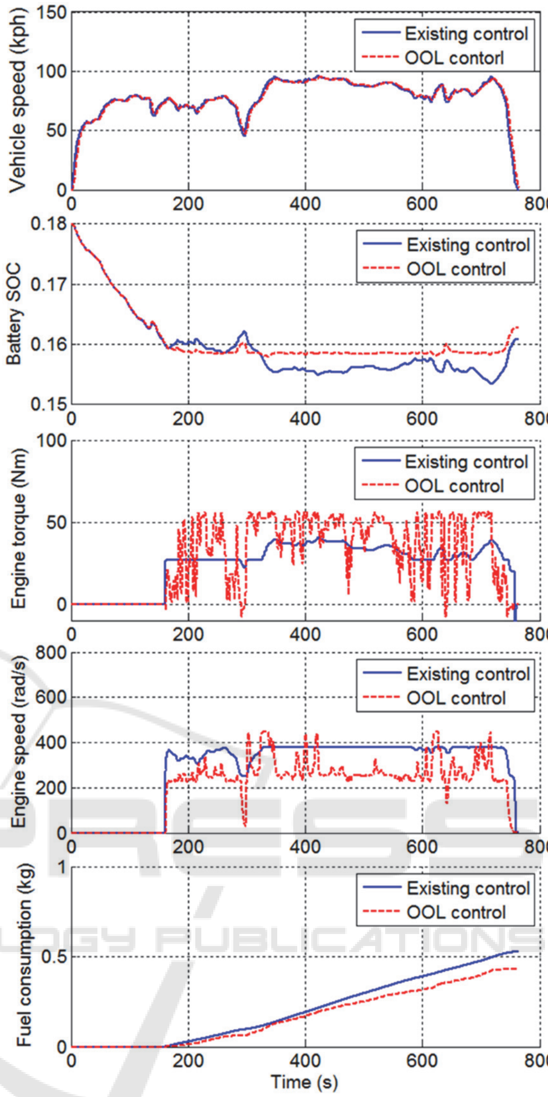

Figure 10: Simulation results for HWFET cycle.

The engine speed by the existing control varied according to the vehicle speed and battery SOC (Figure 4). The engine speed by the OOL control shows relatively lower values than the existing control. The engine speed and torque were determined from the OOL using the battery SOC, motor power and engine power.

To compare the fuel economy, the equivalent fuel consumption was calculated as follows:

$$C_{eq} = \frac{\frac{(SOC_{initial} - SOC_{final}) \times Q}{E_g} + \frac{\Delta m_{fuel}}{\rho_{fuel}}}{D} \quad (3)$$

where D is the distance of cycle, E_q is the equivalent gasoline energy of electric energy, Q is the battery capacity, Δm_{fuel} is the fuel consumption, ρ_{fuel} is the fuel density.

In Table 2, the equivalent fuel consumptions are compared for the OOL control and existing control.

It is seen from Table 2 that the equivalent fuel consumption by the OOL control is lower than that of the existing control for both UDDS and HWFET cycle. It is noted that the improvement rate of the highway cycle (HWFET) is much higher than that of the city cycle (UDDS). This because the engine operating points by the OOL control are almost close to the operation points of the existing control when the vehicle speed and demanded power are low in the city driving. However, when the vehicle speed and demanded power are high in highway driving, the engine operation by the existing control is performed

Table 2: Comparison of control strategy for UDDS and HWFET cycle.

		Final SOC	Fuel consumption (kg)	Equivalent fuel consumption (l/km)	Im-prove-ment
UDDS	Existing control	0.1599	0.3277	0.0474	-
	OOL control	0.1597	0.3037	0.0449	5.3%
HWFET	Existing control	0.1608	0.5258	0.0500	-
	OOL control	0.1628	0.4303	0.0415	17%

at low torque region when the thermal efficiency is relatively low meanwhile the engine operation by the OOL control is carried out at high torque region with high efficiency.

4 CONCLUSIONS

In this study, the target vehicle is modelled and validated with test data, and an engine optimal operation line (OOL) control strategy was proposed for a range extended electric vehicle (RE-EV) to reduce the fuel consumption.

The engine control strategy was derived by analysing the test data from Argonne National Laboratory. The mode and engine on/off timing are determined by battery SOC and vehicle speed. The engine speed is determined by vehicle speed. Using the engine control strategy, dynamic model of the target RE-EV which was developed based on Cruise was validated. It was found that the simulation results are in good accordance with the test results. Based on the simulation results, an engine control strategy was suggested, which operates the engine on the OOL for the demanded engine power. The demanded was determined by introducing the weight factor which balances the battery SOC. From the simulation results, it was found that the equivalent fuel consumption by the OOL control is reduced as much as 5.3% for UDDS and 17% for HWFET compared with that of the existing control.

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