System Analysis of the Diesel Parallel Hybrid Vehicle Powertrain

Kitae Yeom and Choongsik Bae
Korea Advanced Institute of Science and Technology

ABSTRACT

The automotive industries are recently developing hybrid electric vehicle (HEV) to meet future fuel economy and emission regulation, combining two propulsion systems, mostly using an internal combustion engine and an electric motor. A HEV has the advantage of improving fuel economy and reducing exhaust gas using a high efficiency operation together with the assistance of an electric motor. Diesel engines used in the HEV are inherently more efficient compared to gasoline engines and, therefore, have a higher fuel economy. Besides it has the advantage of lower CO_2 emission. A lot of research is carried out most to incorporate diesel engine technology in a HEV. Furthermore, the recent development of high pressure injection systems and turbocharger systems for diesel engines enables more reduction of emissions and improvement of fuel consumption.

In this study, conventional diesel vehicle, parallel diesel HEV, and improved parallel diesel HEV are composed and optimized to compare fuel economy, performance, and emission. A one-dimensional engine analysis tool, WAVE, was used with a 2.7L diesel engine. ADVISOR, designed for rapid analysis of the performance and fuel economy of vehicle models, was used for a conventional and hybrid electric vehicle by applying output data from WAVE as the input engine data file for ADVISOR.

A parallel diesel HEV shows at least 34~71% better fuel economy and improved acceleration ability than a conventional diesel vehicle. The improved diesel HEV is about 0.5~3% better fuel economy than the parallel diesel HEV. The energy loss of the parallel diesel HEV is 23~28% less than the conventional vehicle by the regeneration.

INTRODUCTION

In recent years, as the needs of better fuel economy has become increasingly more stringent year by year, much attention has been moved to the development of the hybrid vehicle among car makers. Generally, the hybrid vehicle has the electric motor and reciprocating engine as a power sources [1]. Especially, diesel engine has better fuel economy than gasoline engine [2,3]. Due to this reason, the interest of the hybrid system with diesel is increased.

In this study, the diesel hybrid system was investigated using numerical methods. The vehicle performance and fuel economy were predicted. The optimization of battery and motor was performed. In addition, the effects of regeneration were also investigated [3-5].

HYBRID VEHICLE MODEL

In order to simulate the diesel hybrid vehicle, two different simulation tools were used. WAVE and ADVISOR were used for building the diesel engine and powertrain models. The diesel engine was 2.7 L equipped with the common rail high pressure injection system. The results from the engine model were used as an input data of the powertrain model. ADVISOR has the abilities of fuel economy and performance analysis of the conventional and hybrid powertrain.

DIESEL ENGINE

Table 1 shows the specifications of diesel engine. Maximum power and torque are 192 horse power (HP) at 4000 rpm and 410 Nm at 2000 ~ 3000 rpm respectively. Figure 1 shows the diesel engine model. WAVE is 1-dimensional engine simulation software. The intake system was made up the air filter, compressor, intercooler and intake manifold. The exhaust system was made up the exhaust manifold, variable geometry turbine (VGT), oxidize catalytic converter and resonator. 300 operating points were calculated to optimize the engine operation variables such as injection timing, quantity and boost pressure.

Table 1 Specifications of diesel engine

Engine	Diesel 2.7 L 5 cylinders
Displacement	2,696 cc
Bore	86.2 mm
Stroke	92.4 mm
Compression ratio	17.5

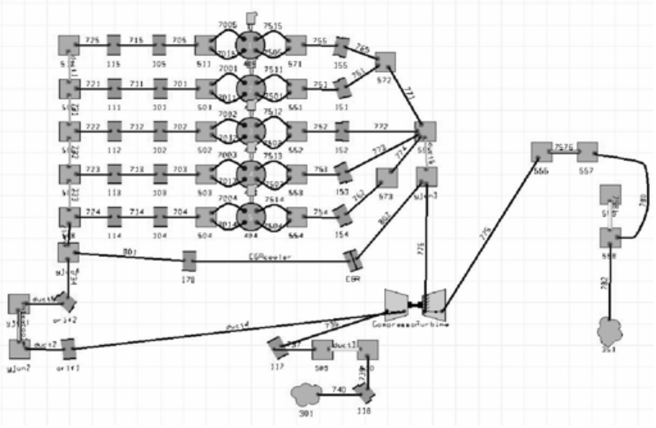


Figure 1 engine model

Table 2 Summary of components specifications

Model	Conventional diesel	Parallel diesel hybrid
Vehicle	SUV	
Fuel converter	2.7 L diesel engine	
Transmission	5 speed automatic	
Motor		PM motor 16 kW Lynx
Energy storage		NiMH 60 Ah 335 V
Exhaust aftertreatment	EX_CI	
Control strategy		Fuzzy control

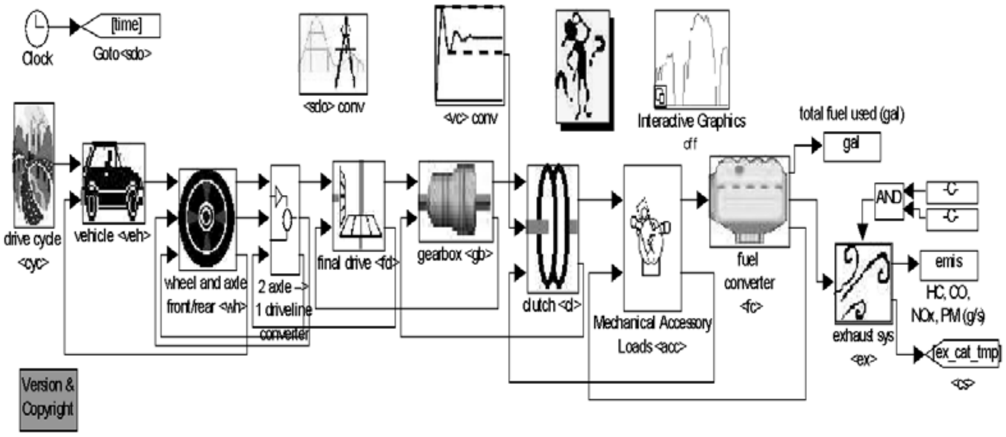


Figure 2 Conventional diesel vehicle block diagram

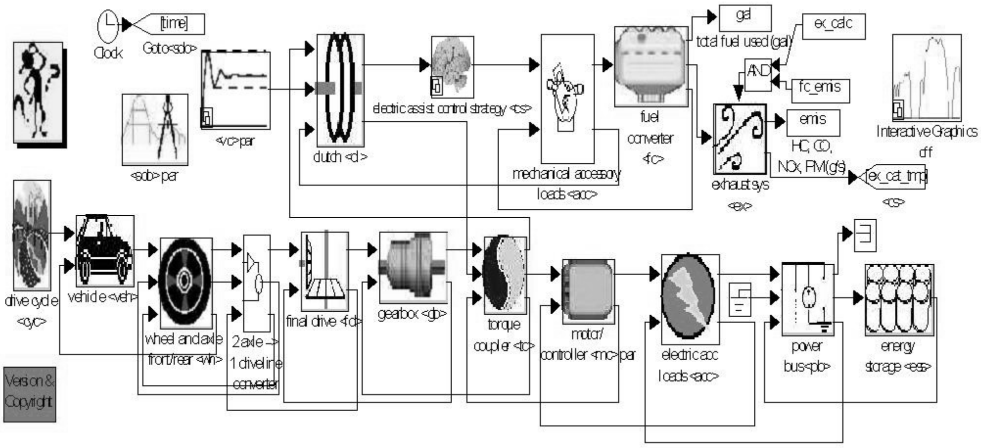


Figure 3 Diesel parallel hybrid vehicle block diagram

Table 3 Summary of driving cycles

CYC_UDDS	EPA urban dynamometer driving schedule
CYC_HWFET	US EPA highway fuel economy certification test
CYC_1015	Japanese 10-15 mode driving cycle
CYC_NEDC	New European driving cycle

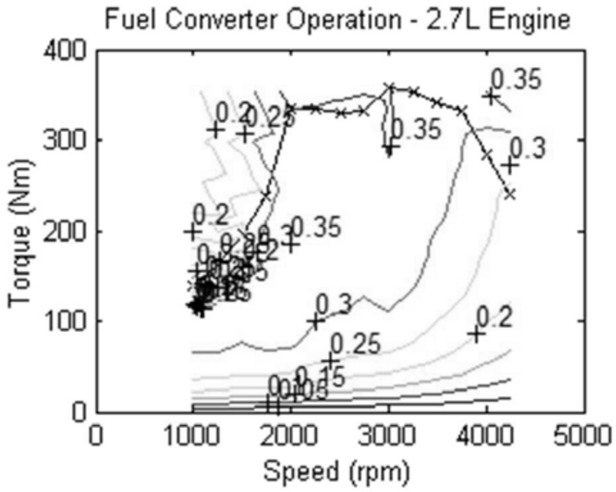


Figure 4 Fuel conversion efficiency of engine

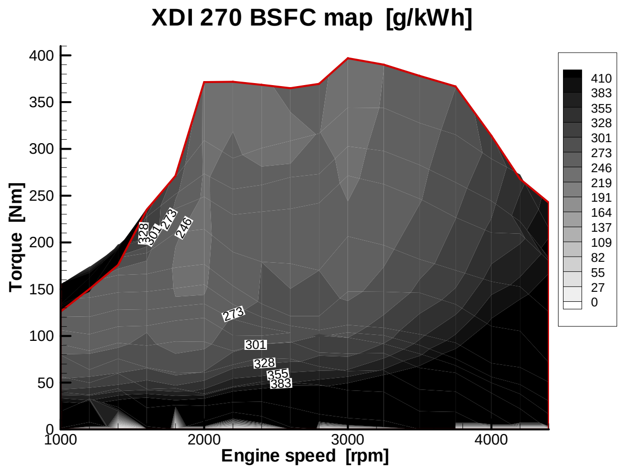


Figure 5 BSFC results from engine model

POWERTRAIN MODEL

The chassis type of simulated vehicle was sport utility vehicle (SUV) powered by diesel engine. The hybrid and conventional powertrain models were built based on the production model. Figure 2 and 3 show the powertrain model of conventional and hybrid powertrain. The components and features of two different powertrain were shown at Table 2. The results of engine model were used as the source of engine data at ADVISOR. A transmission was built on the basis of production type. The state of charge (SOC) is very important factor in terms of fuel economy. The SOC was maintained at 70% when the driving cycle was started and that was 65% at the end of driving cycle. Four different driving cycles were used to evaluate the fuel economy characteristics. Table 3 shows used driving cycles in this research. Urban dynamometer driving schedule (UDDS) was developed by environmental protection agency (EPA). This cycle is also called as LA-4 or federal test procedure – 75 (FTP-75). This driving cycle was developed in order to test the light truck and passenger cars in the United State. Highway fuel economy test (HWFET) was developed by EPA in order to test corporate average fuel economy (CAFE) and simulate the situation of highway. 10-15 is used to test the fuel economy of passenger car and light truck of Japanese market. New European driving cycle (NEDC) is used to test the fuel economy of light truck and passenger car of European market. The test duration and mileage of 10-15 is the longest among driving cycles. The effects of regeneration of hybrid powertrain can be observed clearly because the number of stops in this driving cycle is the most.

CONTROL STRATEGY

The driving strategy is one of very important factors in terms of fuel economy. The control strategy of this hybrid system was operated for maximum efficiency using fuzzy control strategy. This control strategy makes engine running at high load operating conditions which shows best brake specific fuel consumption (BSFC). Figure 3 and 4 shows the fuel conversion efficiency and BSFC of engine. High engine load conditions showed better BSFC performance than low load conditions. Fuzzy control strategy has also advantages in terms of battery SOC because of load leveling.

RESULTS

POWERTRAIN SIMULATIONS

<u>Powertrain optimization</u>

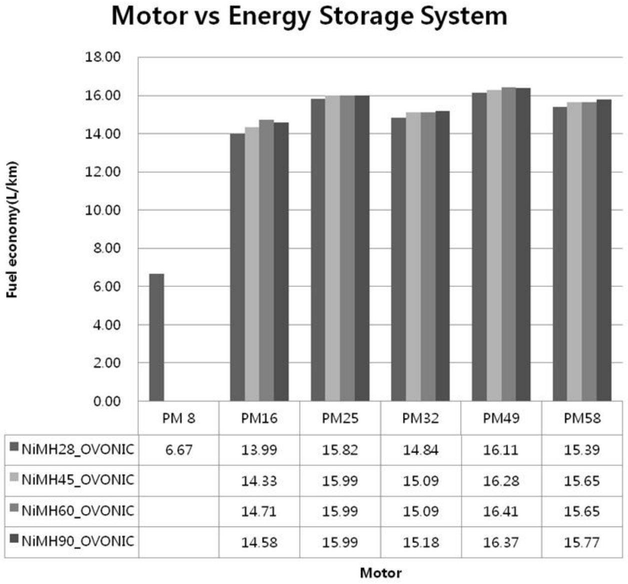
The motor and energy storage system (ESS) specifications are shown at Table 4 and 5. In order to optimize the motor and ESS, UDDS cycle was used. Figure 5 shows the results of optimization. The SOC was set to 70% at the start of driving cycle and that was 65% at the end of cycle. In the case of PM 8 motor, the SOC at the end of cycle was lower than 65% due to lower regeneration power. PM 49 motor showed best fuel economy. It attributed to the less weight than the others considering its power. The fuel consumption was increased as the motor power was increased due to heavy weight. However, the regeneration amount was also increased with higher motor power.

Table 4 Motor specifications

Motor	Motor power (kW)	Peak efficiency (%)	Mass (kg)	Max current (A)	Min Voltage (V)
PM 8	8	93	14	300	30
PM 16	16	92	21	300	30
PM 25	25	90	45	270	130
PM 32	32	90	38	300	60
PM 49	49	96	60	400	60
PM 58	58	92	70	480	120

Table 5 Energy storage system (ESS) specifications

ESS	Number of cells	Nominal voltage (V)	Ah	Mass (kg)	Nominal energy (Wh)
NiMH 28	50	335	28	180	175
NiMH 45	25	335	45	210	598
NiMH 60	25	335	60	290	750
NiMH 90	25	335	90	418	1100



	PM 8	PM16	PM25	PM32	PM49	PM58
■ NiMH28_OVONIC	6.67	13.99	15.82	14.84	16.11	15.39
■ NiMH45_OVONIC		14.33	15.99	15.09	16.28	15.65
■ NiMH60_OVONIC		14.71	15.99	15.09	16.41	15.65
■ NiMH90_OVONIC		14.58	15.99	15.18	16.37	15.77

Figure 6 Fuel consumption comparison of various motors and ESSs

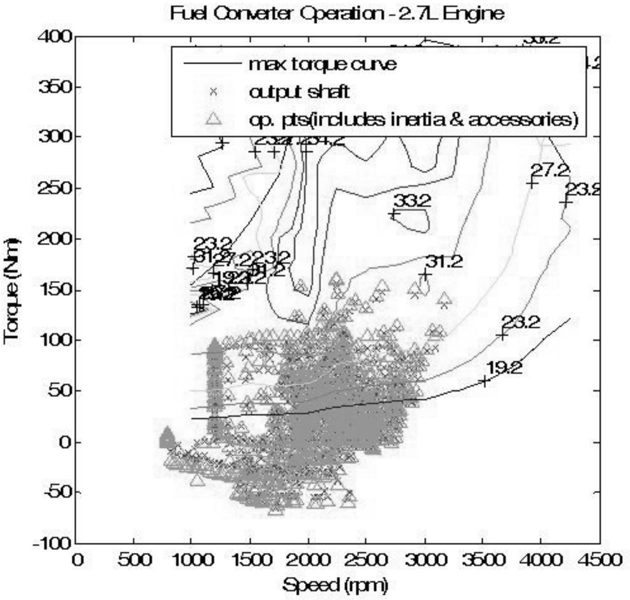


Figure 7 Operating conditions of diesel conventional powertrain

Due to these reasons, the fuel consumption was decreased optimized motor. PM 49 motor with NiMH 60 ESS showed best fuel economy results. It attributed to the adequate weight and power. The fuel economy was also affected by the ESS. In order to store the regeneration energy, the larger ESS is better than small one. However, the weight of ESS harms the fuel economy. In case of small ESS, it could not store all regeneration energy due to lack of capacity.

Engine operating point

Figure 7 and 8 show the engine operating points of conventional and hybrid powertrain during driving cycle using fuzzy control strategy. In the case of conventional powertrain, the engine operating points were spread over the range of 3000 rpm and 150 Nm. However, the operating conditions of hybrid powertrain were under 2000 rpm. The torque range was also higher than that of conventional powertrain. From the results of BSFC, the fuel consumption could be reduced when the engine was operated at high load condition. Negative torque operating conditions were observed at Figure 7 because of deceleration. However, these operating points were not observed at Figure 8. These points were eliminated due to regeneration. The motor produced the regeneration energy at negative torque points.

Engine operating conditions optimization

Figure 9 shows the improved engine result. From the results of previous chapter, the engine with hybrid system was operated at low speed and high load. In order to improve the fuel consumption of diesel hybrid powertrain, the engine operating conditions such as injection pressure, injection timing and intake boost were

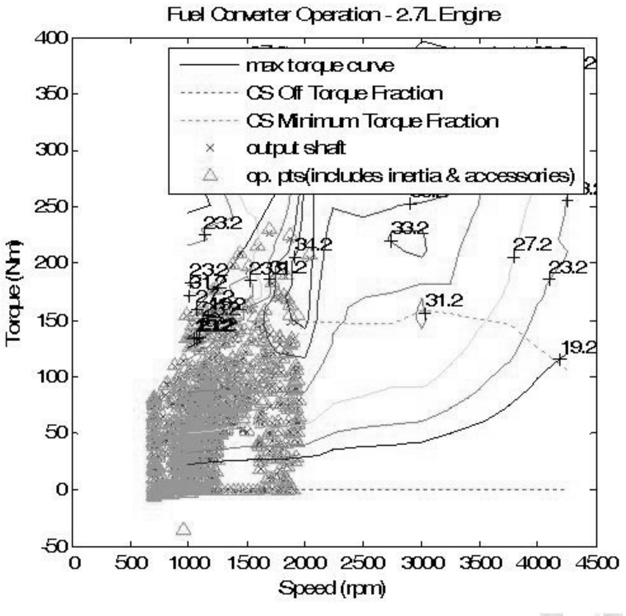


Figure 8 Operating conditions of diesel hybrid powertrain

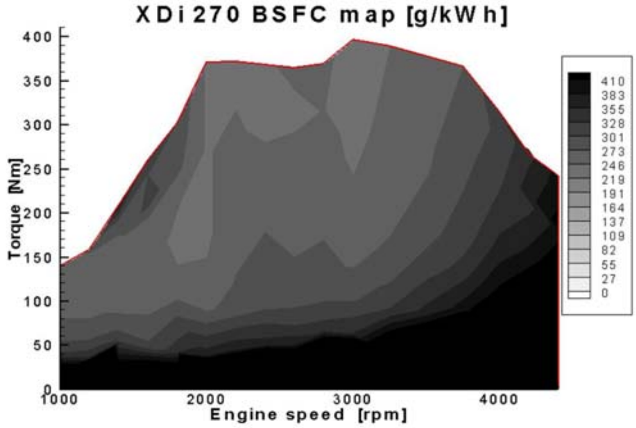
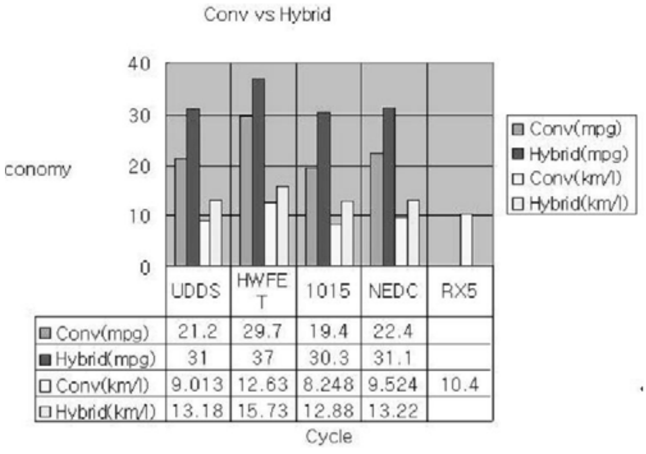


Figure 9 BSFC of improved diesel engine



	UDDS	HWFET	1015	NEDC	RX5
▨ Conv(mpg)	21.2	29.7	19.4	22.4	
■ Hybrid(mpg)	31	37	30.3	31.1	
☐ Conv(km/l)	9.013	12.63	8.248	9.524	10.4
☐ Hybrid(km/l)	13.18	15.73	12.88	13.22	

Figure 10 Fuel economy results of conventional and hybrid powertrain

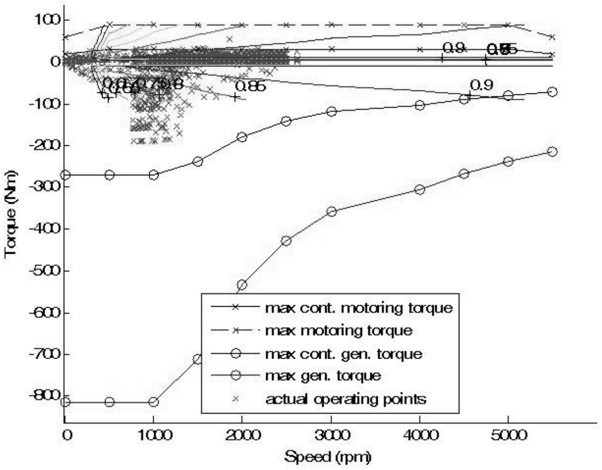


Figure 11 Regeneration torque of hybrid powertrain

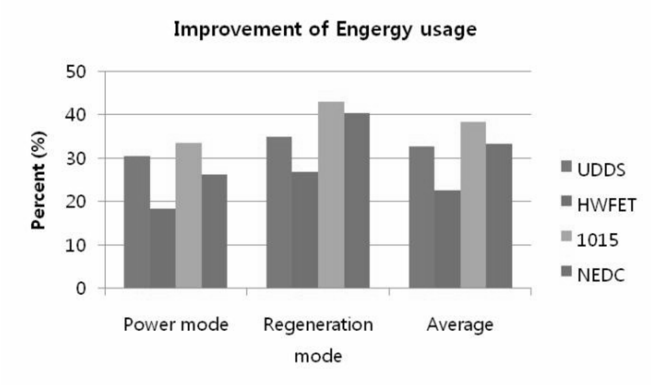


Figure 12 Improvement of fuel consumption due to regeneration

optimized focused on lower speed and higher load. From Figure 9, the improved BSFC was observed compare to previous model.

<u>Fuel consumption and performance</u>

Figure 10 shows the fuel consumption of conventional and hybrid powertrain. The fuel consumption of base vehicle is 10.4 km/l and simulation result of conventional powertrain was 9.85 km/l which is averaged value of four driving cycles. The result was well matched each other and the error was approximately 5%. According to Figure 10, the fuel consumption was improved around 36% by hybridization. It could be explained by the regeneration during deceleration conditions and the engine operating conditions which shows better BSFC.

In order to evaluate the acceleration performance, three different acceleration tests and top speed which are shown at Table 6 were simulated. The accelerations and top speed of hybrid powertrain were faster than those of conventional powertrain because of motor assist. At full load conditions, the motor assist the engine and total power output was increased compare to the conventional powertrain.

Regeneration

Hybrid system can save the braking energy as an electrical energy using the motor when the vehicle reduces the speed. Decelerating conditions which can produce the electrical energy are indicated at Figure 7. Figure 11 shows the regeneration torque of hybrid powertrain. Figure 12 shows the fuel improvement of hybrid powertrain by regeneration. Around 30% of total fuel consumption of hybrid powertrain was improved by regeneration.

CONCLUSIONS

In order to optimize and system analysis, the diesel hybrid and conventional powertrain were simulated using commercial software. The diesel engine was simulated and improved to reduce fuel consumption. The motor and ESS were optimized using fuel consumption analysis. Following conclusions regarding the hybrid powertrain simulation can be made.

1. Diesel engine and hybrid powertrain were simulated. PM 49 motor and NiMH 60 ESS were the best fit for the diesel hybrid powertrain.

2. The engine operating conditions with hybrid powertrain were higher engine load and lower speed than those of the conventional powertrain. It is very helpful for improve the fuel economy due to better BSFC.

3. 19~36% of fuel economy improvement were achieved by hybridization. This improvement was mainly due to regeneration and engine operating conditions change.

4. The acceleration and top speed of the hybrid powertrain were faster than those of the conventional one. It attributed to motor assist.

ACKNOWLEDGMENTS

The authors would like to show the appreciation to CERC (combustion engineering research center) at KAIST for financial support.

REFERENCES

1. Park J., Park S., and Kim H., "Development of Parallel type Diesel based Mild Hybrid Electric Vehicle", KSAE fall conference proceeding, Vol.2, pp.1408~1412, 2005.
2. Albert I., Kahrimanovic E. and Emadi A., "Diesel Sport Utility Vehicles With Hybrid Electric Drive Trains", IEEE transactions of vehicular technology, Vol.53, No.4, pp.1247~1256, July 2004.
3. Inman S., Haworth D. and El-Gindy M., "Integration of WAVE and ADVISOR Simulations for Optimization of a Hybrid Electric Sport Utility Vehicle", SAE Paper, No.2002-01-2856, 2002.
4. Klebak B., Inman S. and Noss R., "Design and Development of the 2002 Penn State University Parallel Hybrid Electric Explorer, the Wattmuncher", SAE Paper,No.2003-01-1258, 2003.
5. Rowe R., Topinka J., Brodsky E., Marshaus J. and Bower G., "Design and Optimization of the University of Wisconsin’s Parallel Hybrid-Electric Sport Utility Vehicle", SAE Paper, No.2002-01-1211, 2002.
6. Zeraoulia M., Benbouzid M. and Diallo D., "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study", IEEE transactions of vehicular technology, Vol.55, No.6, pp.1756~1764, Nov. 2006.
7. Montazeri-Gh M. and Naghizadeh M., “Development of Car Drive Cycle for Simulation of Emissions and Fuel Economy”, 15th European simulation symposium proceedings, 2003.

ABBREVIATIONS

BSFC : Brake Specific Fuel Consumption
EPA : Environmental Protection Agency
ESS : Energy Storage System
HEV : Hybrid Electric Vehicle
HSDI : High Speed Direct Injection
HWFET : Highway Fuel Economy Test
NEDC : New European Drive Cycle
SOC : State Of Charge
UDDS : Urban Dynamometer Driving Schedule