

Development of a Series Hybrid Electric Vehicle as Low-Floor City Transit Bus

Uk-Don Choi

*Hyundai Heavy Industries Co., Ltd. Electro-Mechanical Research Institute,
102-18 Mabuk-dong, Giheung-gu, Yongin-si, Gyeonggi-do 446-716, Korea, udchoi@hhi.co.kr*

Abstract

In this paper, simulation and test results of a low floor Series Hybrid Electric Vehicle running in BUSAN city driving mode are presented. Hyundai Heavy Industries Company and Daewoo Bus Corporation have jointly developed a prototype Series Hybrid Electric Bus (SHEB) to evaluate vehicle performance together with fuel economy as a part of feasibility study on hybrid bus operation. It is found that the fuel efficiency of a SHEB is 22% higher than that of a conventional internal combustion engine bus and our GENSET control method is quite effective in maintaining that battery's State of Charge (SOC) during bus driving.

Keywords: vehicle performance, SHEB, generator, fuel economy, series HEV

1 Introduction

Series Hybrid Electric Vehicle is intended for reducing exhaust emission and improving fuel economy during driving in a traffic-congested city. The method to improve the fuel efficiency is to use the larger energy storage system. A large capacity energy storage system (ESS) and an optimal electric power generator (GENSET) are used in the SHEV. These devices substantially have some weakness since it can take large portion of the vehicle price. In this study, the vehicle to minimize the capacity of the energy storage system together with the GENSET for the flat and even city road is developed with similar level of performance to conventional one. The performance test was conducted with the road running mode in downtown of BUSAN city, which has proven that the SHEV has the fuel saving effect of 22%

compared to the ordinary vehicles. This result is obtained considering the practical road running condition rather than the chassis dynamometer testing condition generally used in the test. Only the one-step planetary reduction gear with high efficiency which is directly connected to the electric motor without use of transmission is used in the test. The monitoring system is applied as a substitute for the existing meter cluster. The bus was exhibited in Seoul Motor Show held in 2007.

2 System configuration

The SHEV consists of a propulsion motor for driving the wheels, a battery as an energy storage system to undertake the power supply of vehicle, and the GENSET that plays roles in power supply of the motor and battery recharging, and auxiliary devices to drive the air compressor and others to control the power steering and brake. In addition, it

also has the monitoring system that may monitor the vehicle condition and replace various meters. Figure 1 shows system structure of the SHEB. As shown in Figure 1 and Figure 3, the propulsion motor does not use the transmission but the reduction gear of the planetary type. The output of the motor with reduction gear is connected to the differential gear of the vehicle through the drive shaft. The GENSET is directly connected to the engine as shown in Figure 1. Driving of a propulsion motor and an auxiliary motor is undertaken by an inverter, and the unit for the propulsion motor control is referred to as MCU (Motor Control Unit) and the GENSET control unit is referred to as GCU (Generator Control Unit). The dotted line as shown in Figure 1 is for the inverter for propulsion motor drive and the inverter for the generator and auxiliary motor.

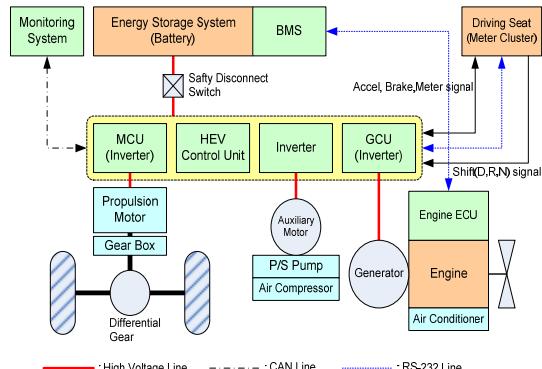


Figure 1: System Architecture of the SHEB

Target performance of the developed SHEB is shown in Table 1. The maximum speed of vehicle, acceleration and fuel efficiency is better than those of an Internal Combustion Engine Bus (ICEB) but the SHEB's gradeability is 75% of ICEB's since ICEB with a five-speed gear has more torque than SHEB.

Table 1: Target Performance

	ICEB	SHEB
0-60km/h Acceleration (sec)	16.4	13
Fuel consumption (km/liter)	2.1	2.58
Fuel improvement (%)	-	Over 20
Gradeability (%)	33	25
Maximum speed (km/h)	102	Above 100
Engine displacement (cc)	11,051	3,900
Battery (V/Ah)	-	336/53.8
Vehicle weight(kg)	1,570	1,550



Figure 2: Photograph of BC211M Hybrid Bus

2.1 System specifications

Specification of the developed vehicle is shown in Table 2. The details are the 322-HP of the propulsion motor and MCU, 60kW induction generator and GCU, 3.9-liter 4-cylinder with 110kW capacity of diesel engine for electric power generation, 6kW-capacity on-board recharger, auxiliary system of 10kW capacity and 2.8kW-level DC to DC Converter. The developed hybrid bus is the BC211M model of Daewoo Bus Corp. in low floor type with 50-passenger including the driver, and it has the 25-seat for the intra-city bus. Figure 2 shows the photo of the SHEB developed as BC211M.

Table 2: Specifications of the SHEB

Vehicle Model	BC211M (DWBC)	
Max Speed	102km/h	
Overall Length	11,000mm	
Overall Width	2,490mm	
Overall Height	3,235mm	
Wheel Base	5,400mm	
Gross Vehicle Weight	15,500kg	
Payload (Approximate)	3,500kg	
Seats(passengers)	1+25(50)	
Wheel	8.25 x 22.5	
Tires	11R22.5-16PR	
Gear Ratio w/o differential	2.93	
Air Conditioning	Yes	
Power Steering	Electrically -Driven Hydraulic power assist	
Brake System	Electric Vacuum Pump	
Low Voltage Power Supply	2.8 kW dc/dc	
On Board Charger	6kW Charger	
Electric Motor	322 hp	
Motor Control Unit	240kW	
Generator(GENSET)	60kW	
Auxiliary System(AC/PS)	10kW	
Engine for GENSET	Gross Power	110kW
	No. of cylinder	4 in-line
	Fuel	Diesel
	Displacement	3,900cc

2.2 Component layout

As described in the system configuration, main part of the hybrid is divided into five units. These units are propulsion motor with the MCU, generator with GCU, electric-driven auxiliary system, battery and Battery Management System (BMS) and monitoring system. In addition, the cooling system for the propulsion motor, GENSET, MCU, and GCU is designed separately from the existing engine cooling system. Separate cooling and heating equipment requires substantial amount of power so that the existing product is used without modification. Figure 3 shows component layout of the SHEB.



Figure 3: Component Layout of the SHEB

2.3 Electric drive system

The maximum output of the propulsion motor is 322 HP as in the output capacity of 11 liter engine for existing diesel bus (ICEB), and the continuous rated output power is 161 hp. The peak power of the propulsion motor for the hybrid vehicle is two times or more continuous output power, and the express drive is possible not by using the transmission but driving only with the one-step reduction gear for the entire driving territory, and the propulsion motor is controlled by the voltage source PWM vector control inverter. In addition, in reducing the speed of coming down on downhill, the mechanical energy is recovered to obtain the regenerative braking and the generated power is recharged into the battery.

2.4 Monitoring system

The monitoring system of the SHEB is integrated into one for the existing ICE vehicle meter cluster, and it monitors a variety of information on devices related to the hybrid power trains in real time. It also has the touch panel for the breakdown diagnosis. The indication mark is classified as the part for each

hybrid and information on existing vehicle system. The indicated screen is divided into five parts, and it has the initial screen marked when the vehicle is started and the main screen that displays various meters thereto. And on the lower part of each screen, there is an icon to move to the screen for each device below each screen. All screens of indicated device receive the information in CAN communication from each device to use the 32-bit DSP and mark it to the calculated value. [2]

2.4.1 Main screen

The main screen is indicated for the normal operation condition for air pressure of the vehicle, fuel meter, engine oil pressure, various telltale lamps, recharging condition of battery for SOC, and vehicle speed of the hybrid system.



Figure 4: Main Screen of the Touch Panel

2.4.2 CEU screen

On the main screen, when the CEU (Control Electronics Unit) icon is touched, the MCU displays operation condition for the charger system for battery voltage, current, output power, motor and drive device for temperature.



Figure 5: Screen for CEU Module

2.4.3 GENSET screen

On the GENSET screen, it shows the output of the GENSET, voltage, current, engine speed, cooling water temperature of GCU and generator for the GENSET.

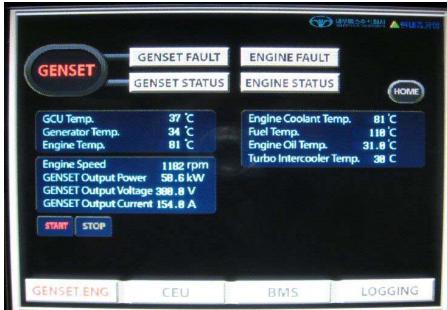


Figure 6: Screen for GENSET Module

2.4.4 BMS screen

Battery Management System (BMS) is the battery management device that displays each battery module with voltage, temperature, SOC, output, average, maximum and minimum voltage, and current. BMS controls the GENSET depending on SOC and the power demand for load condition of the SHEB.



Figure 7: Screen for BMS Module

2.5 GENSET

The GENSET in heavy duty hybrid electric vehicle like the SHEV has used about half of the motor capacity, but according to the thesis of Hori [4], under EVS19, he turns out there has been a case of developing the system that used less than half output capacity for Permanent Magnet Synchronous Generator (PMSG) and high power density lithium ion battery. However, in this study, the GENSET that combined the 3.9-liter small engine by designing induction generator of 93% for high efficiency and 60kW output capability is used in consideration of the system price. Figure 8 shows the system architecture of the GENSET. Figure 9 is photograph of the GENSET. The GENSET in general for the SHEV has been controlled by ON or OFF method with the maximum output in accordance with the battery SOC and the power required for the vehicle loading. [5]

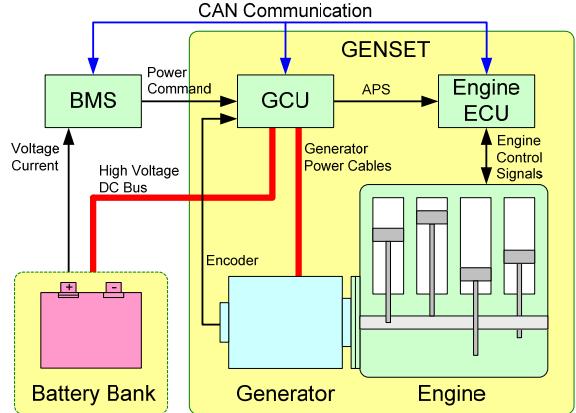


Figure 8: System Architecture of GENSET



Figure 9: Photograph of GENSET

2.5.1 Control Strategy

The target of this control strategy is to meet the power demand commanded by the driver and, at the same time, maintain the SOC of the battery within preset range in all test driving areas. The engine can be controlled at any operating point on its speed-torque plane. The engine should be controlled in its optimal operation region, where fuel consumption and emissions of the engine are minimized. Currently, two typical control strategies are introduced: (1) maximum SOC of peaking power source (Max. SOC-of-PPS) and (2) engine turn- and turn-off (Engine-On-Off) control strategy. [5] The proposed control strategy is combined and modified strategy (1) and (2) to maintain the SOC of the battery within preset range in BUSAN City driving test. Figure 10 displays the control logic of the GENSET to maintain the battery SOC within certain range. When the SOC of the battery reaches its preset top line, the GENSET is turned off and the SOC reaches bottom line, the GENSET is turned on. Figure 11 shows engine on-off strategy. In this paper, variable output control method was used to implement the road driving test. In Figure 11 and Figure 12, the horizontal axis is time and vertical axis indicates percentage of SOC and output power

of the GENSET respectively. Figure 10 shows the operation method of the GENSET depending on the battery SOC and the power required for the vehicle loading. The horizontal axis of Figure 10, X1, X2, X3 and X4 indicates percentage of the SOC respectively and vertical axis Y1, Y2 is the GENSET output power. In the case of Figure 11, when X1 and X3 are for the SOC 65 %, and X2 and X4 for SOC 70 %, the control status indicating GENSET ON for Y2 of 60 kW and OFF for the SOC 70 % is shown in Figure 11.

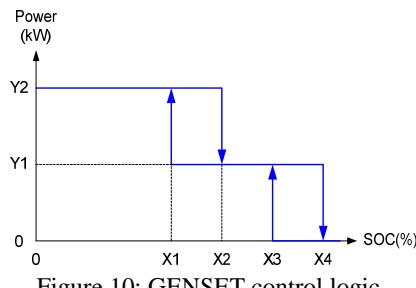


Figure 10: GENSET control logic

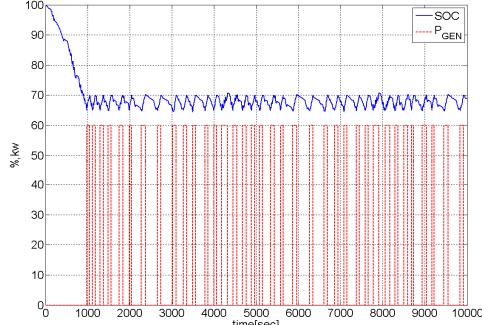


Figure 11: Engine On-Off control

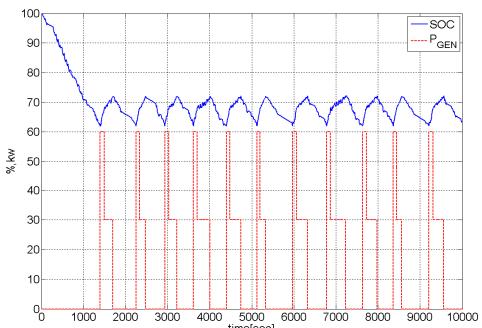


Figure 12 Variable Output Control

Figure 12 is illustrates the operation method of variable output control of the GENSET. When X1 and X3 are for the SOC 62 % and X4 for SOC 72 %, X2 is for SOC 67 % the control status indicating GENSET ON for Y2 of 60 kW and come down for Y1 of 30 kW is shown in Figure 12. The optimal operation point of X and Y was selected by the driving test. The GENSET should be operates in optimal operation region,

where fuel consumption and emission of the engine are minimized.

2.6 Auxiliary system

The auxiliary system is designed by connecting to the electric motor with the power steering and air pressure and is controlled by the inverter. In the event operated by the inverter, it may save the energy by preventing the inrush current of the power motor with the soft operation and suspension, and the sensor of the air pressure and the hydraulic pump are controlled to minimize the power consumption.

3 Simulation

Modeling for the hybrid cars and each component is realized with SIMULINK. The model is configured with the MCU, GENSET, BUSAN city driving mode, battery and others. In the event that the accurate tuning is made for the various parameters, the simulation result and the actual test result were consistent. The simulation was made for the acceleration capability, drive ability of gradient, and fuel consumption on city driving mode. As a result of the simulation, it has accomplished 22.8% of the fuel economy improvement and running for the slope of 25%. Table 3 displays the acceleration performance both ordinary bus (ICEB) and SHEB. As shown on Table 3, the acceleration of the SHEB would have 12.5 seconds to reach from 0 km/h to 60 km/h, and 23.5 seconds to reach from 0 km/h to 80 km/h respectively. Figure 13 is the simulation result of the acceleration time of the SHEB. Compared to the ordinary bus, the SHEB shows outstanding acceleration capability in the test result and simulation. Under the actual road condition, the acceleration test up to 80 km/h shows really excellent results. In addition, in the event that it is driven in BUSAN city driving mode, the GENSET control would maintain certain SOC on its entire area. During the simulation, it was implemented for 100% of SOC while the initial condition of the battery was fully charged. The driving mode used in simulation is provided by Daewoo Bus. Figure 15 shows the simulation result of BUSAN city driving mode. The horizontal axis of Figure 15 is time and vertical axis indicates percentage of SOC and vehicle speed. As shown in the simulation result, SOC control would maintain uniformly on its entire area. Figure 14 displays simulation result of gradability of the SHEB. Figure 16 is simulation result of high speed mode of the SHEB.

Table 3: Acceleration Performance

Speed (km/h)	ICEB (sec)	SHEB (sec)
0-60	16.4	12.5
0-80	27.1	23.5
0-100	45.6	42

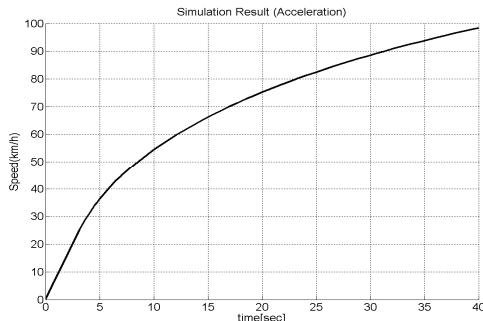


Figure 13: Acceleration of the SHEB

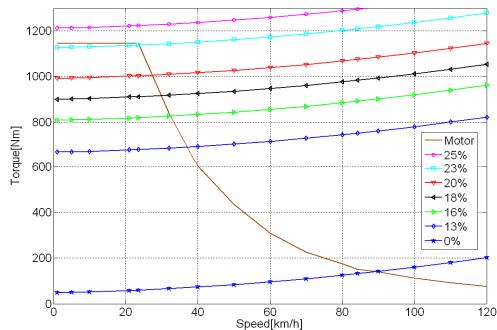


Figure 14: Gradeability vs. vehicle speed

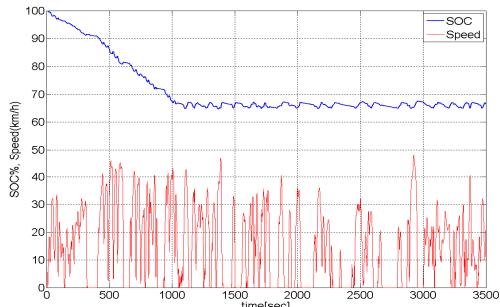


Figure 15: BUSAN City Mode

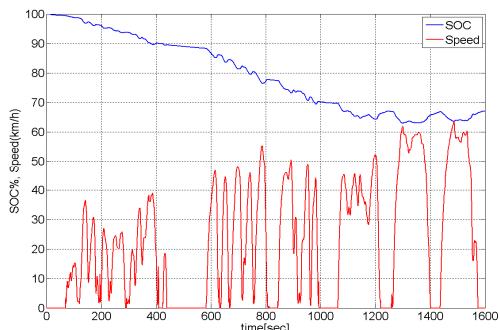


Figure 16: High speed mode

4 Test result and discussion

4.1 Test result

The driving test and acceleration test were implemented while 100% load (payload is 3,500kg) was fully made. Figure 17 shows the inside of the vehicle with the load of 3,500kg on the vehicle for the road running test. In the Figure 17, the black color is the sand bag of 10kg of weight that was used for the load. Figure 18 is the map of BUSAN city, and the driving road for testing is marked with bold and dark line. The driving mode used in the test is used for ordinary bus as the standard model used to evaluate the vehicle fuel economy test and it includes the running road exclusively for the bus. The result of acceleration performance in Figure 19 was measured in the road of an exclusive bus driving lane. Figure 20 displays the SOC of the battery measured during running and the inner-city driving mode. The horizontal axis of Figure 20 is time and vertical axis indicates percentage of SOC and vehicle speed. The red line is BUSAN city driving mode. As shown in the test result, the SOC was consistently maintained within 10% in all test driving areas. Table 4 is performance comparison of the simulation and test result of the SHEB. The result of simulation was almost consistent with test result. On the road, as a result of acceleration up to 60km/h, it was similar to the simulation result with 13 seconds, which is better than the case of ICE vehicle. Figure 21 is test result of high speed mode of the SHEB. The SOC was consistently maintained within 10% range. The drive ability of grade was carried out in hills, and the digital slope meter is used to have the consistent simulation result. The drive ability of grade was 23%.

4.2 Discussion

The SHEB that used the one-step reduction gear without the transmission had no problem in running on even road. With the minimized design of the battery and GENSET, it has certain limits in running uphill or running on drastic sloped road. The SHEB may guaranty the highest economic feasibility to have the design made in accordance with the service area and road condition. All tests had to be undertaken in actual road except measurement of exhaust gas per each running distance. Its measurement and review have to be made later. There is a need of changing the cooling and heating device into electric motor device, and

the design of the power system at this time has to be reviewed again. When the bus stops in the dense commercial area, and the maximum output of the GENSET is undertaken, the SHEB makes severe noises. However, in the event that the SHEB runs slowly about less than 10km/h or stops at the bus station, the noise can be reduced by the low output or stopping the GENSET.

As a result of the test, it was also found that there was no significant difference in maintaining SOC within the acceptable range during driving. It was also showing that fuel economy depending on the road condition, traffic and driving habit of a driver. In the event that the driving is made for high speed at the exclusive bus lane, the fuel economy was shown to be lower than the average value.



Figure 17: Inner View of vehicle with the Load

Table 4: Performance comparison

	Simulation	Test Result
Acceleration(sec) (0-60km/h)	12.5	13
Fuel consumption (km/liter)	2.58	2.56
Fuel efficiency (%)	22.8	22
Gradeability (%)	25	23



Figure 18: Road map of BUSAN City Test Route

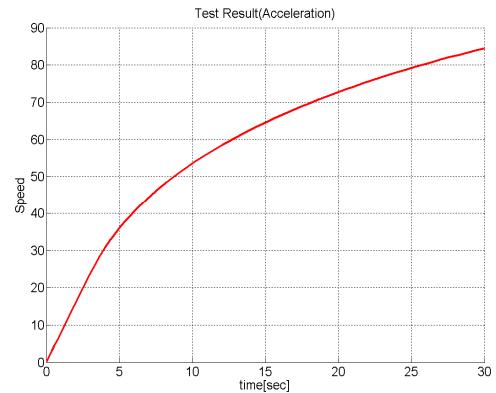


Figure 19: Test Result of Acceleration

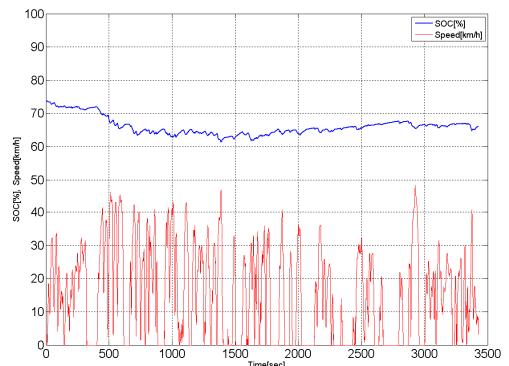


Figure 20: Test Result of BUSAN City Mode

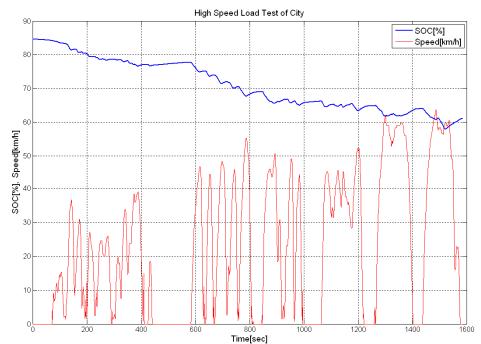


Figure 21: Test result of high speed mode

5 Conclusion

A prototype Series Hybrid Electric Bus has been developed to evaluate vehicle performance together with fuel economy as a part of feasibility study on hybrid bus operation. The test and simulation of the SHEB in an exclusive bus-driving lane has been performed including the measurement of fuel consumption. It was found that the developed SHEB was met the target fuel

economy with affordable system configuration, which was advantageous to commercialization of the system compared to other SHEB.

Acknowledgments

This work was performed by Hyundai Heavy Industries Company (HHI) and Daewoo Bus Corporation through the joint development. The GENSET used in this work was technically supported by Hyundai Enova Innovation Technology Centre (HEITC). The monitoring system was developed by university of Ulsan with financial support of HHI for the Industries-University R&D consortium program.

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Authors



Uk-Don Choi was born in Daegu, Korea, in 1955. He received his B.S., M.S. and Ph.D. degrees in Electrical Engineering from University of Yeung nam, Gyeongsan in Korea. He was involved in the joint development of the Series Hybrid Electric Bus with Daewoo Bus Corporation. His main research interests in power electronics, control of HEV/EV systems. He is principal researcher of Electro-Mechanical Research Institute of Hyundai Heavy Industries Co., Ltd.