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Effects of Initial SOC of 270-Volt Battery on Operating Performance of Gasoline Engine and Electric motor in a Parallel Hybrid Vehicle under IM240 Driving Cycle Mode

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Abstract

Next-generation vehicles are under energy and environmental pressure to increase fuel economy and reduce emissions of green-house-gases (GHG) such as carbon dioxide, which is the main cause of global warming, while maintaining the performance and drivability characteristics of conventional internal combustion engine (ICE) automobiles. So, hybridization of both conventional ICE and electric motor powertrain systems hold great promise for environmentally friendly vehicles (EFV) to meet stringent CO_2 regulation and fuel economy requirements. This paper presents the effects of the initial state of charge (SOC) stored in the vehicle's battery on tractive propulsion characteristics as vehicle drivability performance that is obtained from both ICE and an electric motor simultaneously. Especially, the battery management system (BMS) plays a key role in a hybridized system based on an electric device. And a regenerative braking system recovers kinetic energy from braking and uses it to recharge the battery. In this study, in order to investigate the effects of various initial SOCs in a parallel hybrid gasoline-electric vehicle (HEV), an experiment was carried out on a vehicle chassis dynamometer with IM240 vehicle driving mode and a CAN protocol analyzer to collect data from a full HEV. A unique hybrid electric signal processor was designed to monitor the operational state of the ICE including fuel injection duration, hybrid starter-generator (HSG) and propulsion motor which depend on the initial SOC. The amount of energy recovered through the regenerative braking system was measured to investigate the collect rates of currents. The results show that the initial SOC stored in the battery causes big differences in the electric current balance in hybrid operating mode, and that careful coordination of ICE and motor is necessary to achieve vehicle propulsion capacity as well as to maintain the battery SOC at a reasonable level.

Keywords: Parallel hybrid gasoline-electric vehicle; State of charge; Regenerative braking system; Electric current balance; IM240 driving cycle

Introduction

Recently, the R&D trend of the automotive industry has been towards not only improving fuel economy but also using alternative power-drivetrain sources, due to the lack of traditional fossil fuels and stricter regulations on vehicle emission. Also, there are many investigations being undertaken into the use to take advantages of unconventional fuels in order to reduce carbon dioxide, which is the main cause of global warming. Among many technologies, the development of hybrid vehicles which run on two power sources, with an ICE and an electrical motor, has become a trend with the problem of energy shortage [1,2]. According to the Advanced Vehicle Testing Activity conducted by the US Department of Energy, the results with 16 HEVs of three model types show that a full HEV and a power-assisted HEV could offer much higher fuel economy than other conventional spark-ignited engine vehicles. For example, one HEV's mileage per gallon of fuel was increased by 94% compared to a power-equivalent conventional vehicle, and by 73% compared to a conventional vehicle of equivalent engine size [3,4].

There are two ways to categorize a HEV (usually with an ICE and an electric battery, and motor/generator) according to its degree of hybridization and its powertrain structure. First, HEVs can be divided into three types depending on the degree of hybridization: micro, mild and full hybrid. Micro HEVs have an ISG (idle stop and go) system and reduce about a 5% reduction in fuel consumption. A mild HEV system utilizes the hybrid system more, such as ISG system, power assist, and battery charging, and it offers about 15~30% improvement in fuel economy. As for a full HEV, it has an expensive system which is complex to control, but it provides about 30~50% improvement in fuel economy with a down-sized engine and a regenerative braking system which recovers the kinetic and potential wasted energies from braking in order to increase energy efficiency [5]. However, some expect the market penetration of the mild HEV system to be larger than that of the full HEV in the next 10~15 years due to its lower development costs, simpler architecture, and economic retrenchment in powertrain modifications [5-7].

Another way to classify an HEV is by its powertrain structure. Unlike a conventional gasoline or diesel fueled vehicle, a series HEV uses an electrical motor enabling "electric only" driving for vehicle propulsion. The engine, on the other hand, drives a generator to charge the battery, and the engine usually works within its optimal efficient range. A parallel HEV also makes use of an electrical motor like a series HEV, but the engine and motor are placed in parallel to produce propulsion or to generate electricity. The advantage of the parallel HEV

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is that the motor can drive the vehicle by itself, so there is no need to consume fuel. But, control of a parallel HEV is much more complex than for a series HEV because of the need to efficiently couple the motor/generator and the engine in a way that maintains drivability and performance [8].

One of the most important concerns with hybrid vehicles is market acceptance, which includes fuel consumption and drivability. And the main parameters of the ICE-electric hybrid system are the drivetrain performance of engine and permanent magnet motor, battery capacity, power electronics for hybrid control, transaxle with gear system and torque combination device. Therefore, these parameters have a decisive effect on vehicle tractive propulsion, operation efficiency, battery's SOC, and fuel efficiency.

As a result of using electrical power, managing electrical energy becomes important. For instance, the regenerative braking system in the HEV is one of the important techniques for improving energy efficiency. According to a study, about 30% of a typical vehicle's engine output is lost by braking [9]. However, another author says it is known that with a regenerative braking system and a down-sized engine in an HEV, consumption of fossil fuel can generally be reduced by up to 30% [10-12].

Even though HEVs have higher fuel economy and pollute the environment less with their emissions than conventional ICE vehicles, it is a complicated matter to control and optimize the combination of electric motor and ICE propulsion system because of electrical components such as the motor and the battery. Among the electrical parts, the battery management system especially has significant impact on the performance of an HEV because it manages the delivery and acceptance of electrical energy to and from the cells, as well as the operating cooling system, and so on [13]. Also, the battery's SOC plays a key role in the battery management system and affects many other electronic systems. Some research showed that the battery's SOC influences not only the life of the battery but also fuel consumption optimization in the HEV. That is, the control and management of the SOC affects propulsion characteristics and fuel economy. It can be noted from this research that engine operation is governed by the vehicle speed and the battery's SOC to optimize fuel economy [14]. Argonne National Laboratory Meyer et al. [15] investigated the effect of battery charge balance in an HEV on EPA (Environmental Protection Agency) fuel economy label values, using a Toyota Prius HEV.

The major target of this study is to determine the effects of varied initial battery SOCs on tractive propulsion characteristics such as vehicle drivability in a parallel hybrid gasoline-electric vehicle that can operate in six-step modes: electric only traction; battery charging from engine; ICE traction and charging; ICE only traction; hybrid traction; regenerative braking. Therefore, in this study, an experiment was carried out on a vehicle chassis dynamometer with IM240 vehicle driving mode and a CAN protocol analyzer to collect data from a full HEV. This paper reports on the achieved electric current balances for the six operating modes according to the varied initial SOCs of the full parallel hybrid application for a passenger vehicle based on a 2.0 L gasoline engine.

Experimental Apparatus and Procedure

Generally, there are two methods for investigation of a vehicle, and each method has pros and cons. First, a vehicle with test equipment mounted on vehicle can be driven on a real road. This method is very direct and effective in that the vehicle test is done under the actual environment where the vehicle is usually operated. However, this method has high initial costs, and it is hard to keep and inspect the testing condition and the effect of specific components of the vehicle. This method is behind generic terminologies such as "off-cycle test" or "in-use test". On the other hand, type approval testing of light-duty vehicles is currently done under controlled environmental conditions using a reference driving cycle on a chassis dynamometer to simulate actual road conditions like a road test, so it is convenient to conduct experiments. In this study, a commercial parallel HEV with six-speed AT for front wheel driving (2012 HEV, Hyundai Motor) was investigated on an EC-type chassis dynamometer with the IM240 transient cycle. All vehicle data were logged with a vehicle diagnosis tool (GDS) and a CAN analyzer from each control system in real time. Also, electrical current in and out of the battery was measured with a clamp current sensor (Hioki Co.). For investigation of the effects of initial SOCs, the SOCs were chosen from the study of Kim et al. According to Kim's study, SOC is largely divided by the absolute value of SOC and into five bands: critical low, low, normal, high, and critical high. Each of the five bands has a different battery charge and discharge strategy to manage the SOC effectively.

So, in this study, low, normal, and high levels were chosen as 35%, 50%, and 65% respectively of the initial state of charge stored in the battery. For each set of SOCs, the gasoline engine and the motor were operated during vehicle pre-running in accordance with vehicle test condition to set the SOC. The schematic of the experimental setup is shown in Figure 1, and the data in Table 1 show the experimental conditions used in this study for each of the three sets of SOC.

Vehicle and parallel hybrid system description

A 2WD chassis dynamometer certified for BAR97 US standard and control system was used to measure vehicle speed, torque, and power from the wheels. The vehicle used as reference, as shown in Figure 2a, has a full-hybrid parallel powertrain that is basically composed of a 2.0 liter gasoline MPI engine, a 30 kW electrical motor and a specific high-voltage lithium-polymer battery system with 5.3 Ah of capacity at 270 volts (LG Chem.) as summarized in Table 2. The 4-stroke 4-cylinder ICE runs on the Atkinson cycle that has a lower compression ratio than

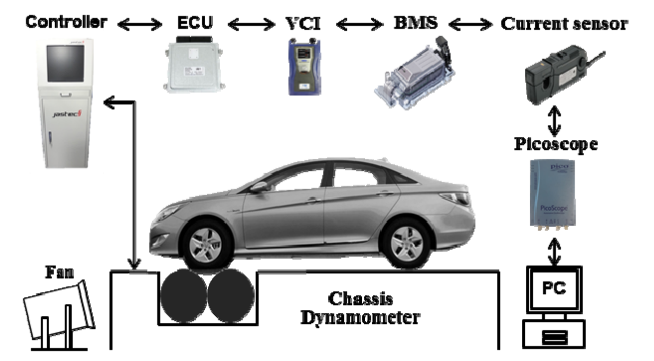

Figure 1: Schematic diagram for HEV experiment.

Parameter	Specification
Driving cycle	IM240 mode
Initial SOC	35%, 50%, 65%
Ambient temp.	24 ± °C
Fan speed	Constant
Eco mode	On

Table 1: Experimental condition.

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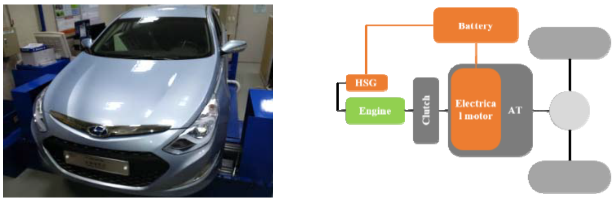

(a)Parallel HEV mounted on chassis dynamometer (b) Layout of parallel HEV system

Figure 2: Configuration of full parallel HEV used in this study.

Engine	2.0 L Atkinson cycle DOHC Max. Power : 150 PS Max. Torque : 18.3 kg m
Motor	30 kW (41 PS)/20.9 kg m 8.5 kW for HSG
Battery	270 V Lithium polymer 5.3Ah 1.5 kWh

Table 2: Specification of the HEV main component.

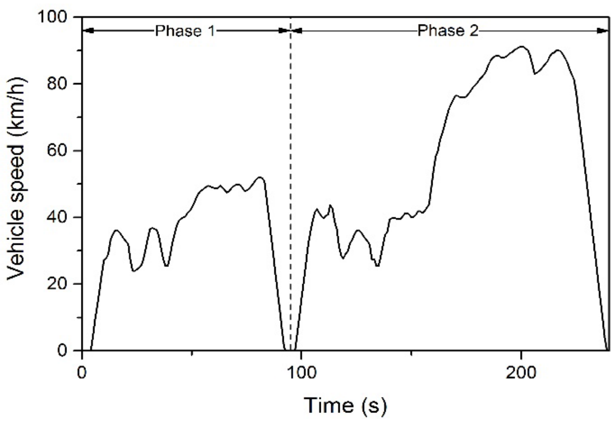

Figure 3: IM240 driving cycle.

its expansion ratio. The electric motor (20.9 kg m maximum torque) makes possible exclusive hybrid functions: electric vehicle operation and regenerative braking. The electrical motor mounted on a six-speed automatic transmission, called by a TMED (transmission mounted electric device), is in parallel with ICE. Further, it has a hybrid starter generator (HSG) of 8.5 kW to provide more charging capacity. Figure 2b shows the basic layout of the parallel hybrid configuration. In a parallel HEV, a transmission is needed to adjust the ICE speed range to the vehicle speed. The electric motor is used to level the load on the engine by adding or reducing torque to or from the system.

The Inspection and Maintenance 240 (IM240) driving cycle used in this study is shown on Figure 3. This cycle was formulated based on selected segments of the FTP-75(Federal Test Procedure) cycle which is created by US EPA to represent a commuting cycle with a part of urban driving including frequent stops and a part of highway driving. In Korea, the IM240 is recommended as an inspection and maintenance driving cycle for in-use vehicles. The IM240 driving cycle is a transient mode that is conducted on a chassis dynamometer, and consists of an urban cycle and an extra-urban cycle of total test duration of 240 seconds, representing a 3.1 km route with an average speed of 47.3 km/h. The first phase, the urban cycle, is of 94 seconds with an average speed of 34 km/h, whereas the average speed in the second phase, the extra-urban cycle, is 56 km/h over 146 seconds and with a maximum speed of 91.2 km/h.

Powertrain data acquisition system

The hybrid control system has overall control of energy, electric supply power by ECU (engine control unit), MCU (motor control unit), and BMS (battery management system). Also, overall control of the hybrid system for vehicle drive power is conducted by hybrid-ECU. In this study, these control systems were continuously monitored by the vehicle global diagnosis tool (GDS) that is connected with the VCI (Vehicle Communication Interface) and VMI (Vehicle Measurement Interface). The VCI is connected to an OBD-II terminal in vehicle and the signal data were sent to a PC by wireless transmission while conducting the test. With the GDS, it is possible to monitor only one control system at a time. For this reason, a CAN analyzer was adapted to the GDS to log the data and to give access to another system at the same time while testing. The key signals for ICE, MCU, and BMS are listed in Table 3. In particular, an integrated signal panel system, as shown in Figure 4, was designed and built inside the test vehicle for intensive monitoring of the signals in real-time simultaneously from MCU and BMS by the picoscope system, a computer-based oscilloscope for automotive use. And it was thus convenient to measure the voltage, current, and frequency of the sensor signals to evaluate the influence of differing levels of battery's SOC. Additionally, the current in and out of the battery was directly measured with the clamp current meter installed at the battery, as listed in Table 4.

System	Sensors
ECU	Engine speed Vehicle speed Injection duration Engine torque Throttle position sensor
MCU	Drive motor speed Drive motor torque Drive motor phase current (RMS) HSG speed HSG torque HSG phase current (RMS)
BMS	State of charge (SOC) Battery DC voltage Battery DC current HCU engine start signal

Table 3: List of electric signals measured in this study.

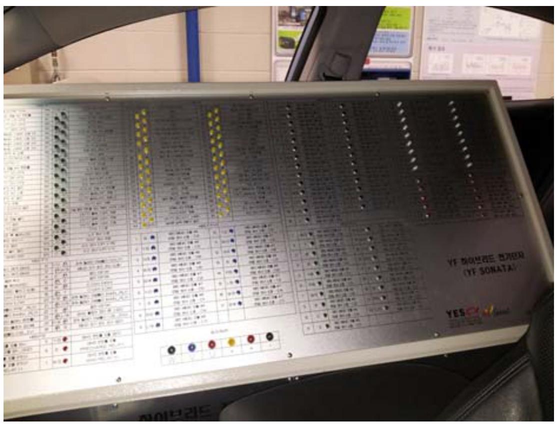

Figure 4: Sensor panel connected to ECU and BMS made in this study.

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Rate current	200A AC/DC (continuous 350A)
Freq. bandwidth	DC to 100kHz (±5%, f.s)
Accuracy (DC and 45 to 66Hz)	± 0.5% rdg. ± 0.05% f.s, phase ± 0.2°
Max. Circuit voltage	600V peak (insulated wire)
Core jaw diameter	ϕ20 mm (0.79 in)

Table 4: Specification of clamp current sensor.

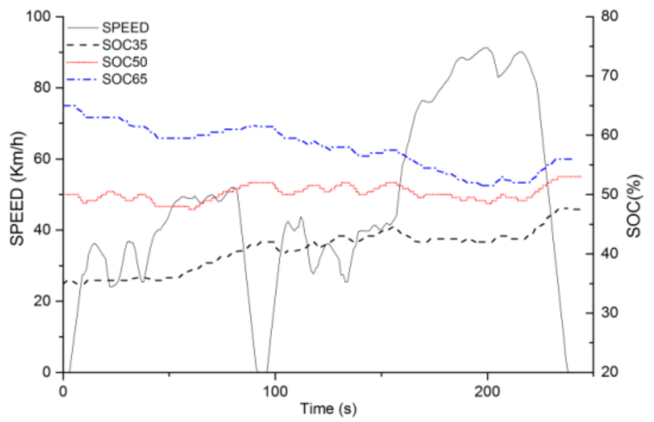

Figure 5: Time histories of initial SOCs according to vehicle speed.

Results and Discussions

Powertrain electrical characteristics

The comparable results of the effects of different SOCs are shown in Figure 5. When the initial SOC was 65%, it was observed that there was a tendency for the SOC to decrease during the driving cycle, due to the discharging strategy. In the case of SOC of 50%, the SOC was stable and well balanced as the test proceeded. For an initial SOC of 35%, it was noted that the SOC increased gradually due to the charging strategy. In all SOC cases, SOCs fell slightly at high vehicle speed due to high propulsion demand, but the SOC had also slightly increased about 3% to 5% by the end of the test due to the regenerative braking system. As shown, the SOCs were finally leveled at around an SOC of 50% at the end of the cycle. As a result, it can be considered that the ideal SOC for performance and battery condition is around 50%.

Figure 6 shows the variation of instantaneous SOC and in/out current at the 270 V lithium-polymer battery depending on the initial SOC. When the vehicle speed was increasing from low speed, the current from the battery was observed to be relatively high with the positive sign, regardless of SOC. It can be considered that the hybrid-electric vehicle consumed electric power and the electrical motor produced the propulsion at the beginning of the urban cycle. As a result, the SOC decreased slightly when the vehicle started to move, even when it was initially as low as 35%, and it has good agreement with the results shown in Figure 7. High torque was seen at the beginning of the urban cycle as well as at low speed, since the electrical motor produces high torque, as shown in Figure 7. On the other hand, as vehicle speed is increasing, higher power is required more than high torque, as also shown in Figure 8. In order to meet the cycle speed, the engine was more likely to generate not only propulsion power but also electricity to produce enough power. As a result, battery current and SOC fluctuated at high speed where both the engine and the electrical motor generated driving power. At the end of the driving cycle, when vehicle speed steeply dropped, the SOC was dramatically increased regardless of initial SOCs because the regenerative braking system recovered electricity from wasted braking energy.

Figure 8 shows battery current balance according to the different initial SOCs during the IM240 driving cycle. Changes to the SOC can indicate the difference between initial and final state of charge storage in a secondary battery, while current balance represents the currents in and out of the battery. If the current balance is a positive number, it means that discharge occurs on average. But, the current balance with a negative sign represents battery charging overall. As shown in Figure 8, the current balance varied in accordance with different initial SOCs and it is thus an important factor in energy management.

Powertrain mechanical characteristics

Figure 8 shows the time-histories of vehicle speed, power, and torque measured from the chassis dynamometer over the IM240 driving cycle from initial SOCs of 35%, 50% and 65%. Regardless of the initial SOC, the power and torque obtained from the test showed similar features to each other. At the beginning of the cycle, when the hybrid-electric vehicle started to move, the torque from the vehicle was

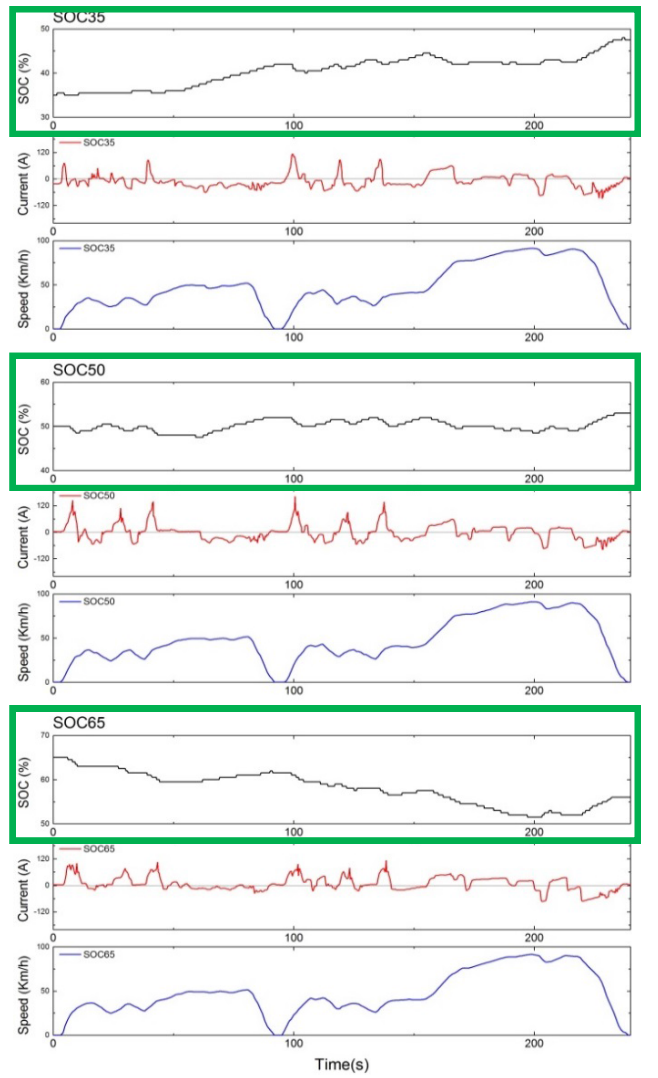

Figure 6: Variation of instantaneous SOC and battery current according to different initial SOCs in IM240 cycle.

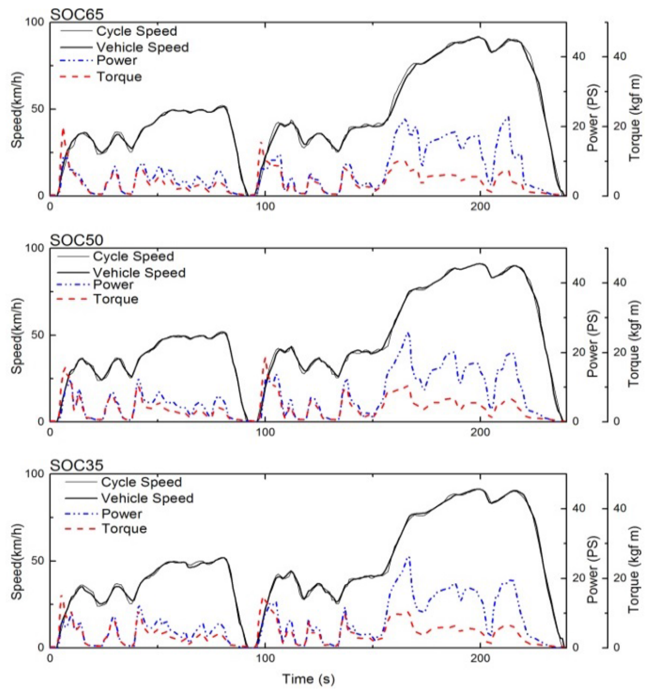

Figure 7: Time histories of vehicle speed, power, and torque over IM240 cycle for different initial SOCs.

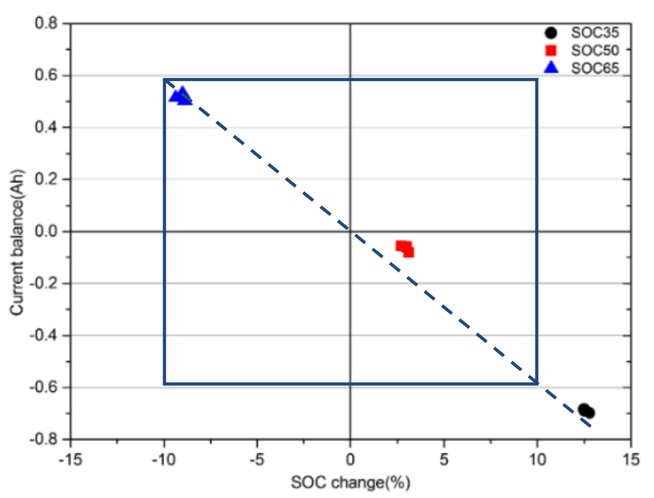

Figure 8: Battery current balance according to different initial SOCs.

measurably higher and this indicates the necessity for an HEV to be able to use both power sources in order to improve fuel economy.

On the other hand, as the vehicle speed increased, higher power was monitored where the engine produced propulsion power. Although the initial SOC is variable, the state of charge of the battery is controlled in a stable way.

Figure 9 shows engine operation times according to different initial SOCs. Before conducting the driving cycle test, it was found that the engine re-started at SOC of 42.5% to charge and maintain the battery power, and it kept running until it reached around SOC of 50% on idle. From this result, it can be determined that it is in a well-balanced state between SOC 42.5% and SOC 50%.

During the driving cycle for this study, it was observed that the engine was more likely to be operated when initial SOC was lower, as shown in Figure 9. When initial SOC was 35%, the engine kept running to charge the battery during the overall cycle. In the case of 50% SOC, the engine running time was about 181seconds, while the engine running time for SOC of 65% was 167 seconds, a reduction of 7% from that of 50% SOC. By comparing engine running times, the results indicate that the vehicle makes use of EV mode when battery power is available thus helping to keep fuel consumption low.

Figure 10 shows the variation of instantaneous behavior of engine torque and motor torque during the IM240 driving cycle. Overall, motor torque well followed on the driving cycle, and engine torque keep within about 40% of motor torque during engine running. Also, there was a tendency of the engine and motor torques to show opposite behaviors. Further, as shown in Figure 10, varying initial SOCs affected engine torque and motor torque. When the initial SOC was 35%, the engine was running during the entire cycle in order to either generate the propulsion power or produce electricity through HSG to recover battery power. In addition, it was noticed that when the battery is charging with HSG, engine torque was leveled around 20%, but when the engine generated propulsion power, the torque was doubled up to 40%.

In this study, fuel injection duration was used as a parameter to estimate fuel consumption. As shown in Figure 11, both instantaneous and accumulated injection durations varied according to the initial SOC. Instantaneous fuel injection durations showed good agreement with engine torque, as shown in Figure 10, and the maximum durations were similar. In the case of SOC of 35%, the injection duration in engine generating mode was about 3.3 ms which was half of the maximum duration. When initial SOC was 65%, accumulated injection duration was reduced by about 22% from that of SOC of 50%. Also, in the case of SOC 50%, it was observed that the accumulated injection duration was decreased by about 14% from that of SOC of 35%. These results indicate that the SOC has an important influence on fuel economy performance because it is significantly affected by engine running time and the torque. Therefore, initial SOC should be considered not only for regulating on fuel economy, but also for battery management, which can play an important role in fuel consumption in an HEV system.

As regards the regenerative braking system, when the vehicle is slowing down under braking, the regenerative system is operated to

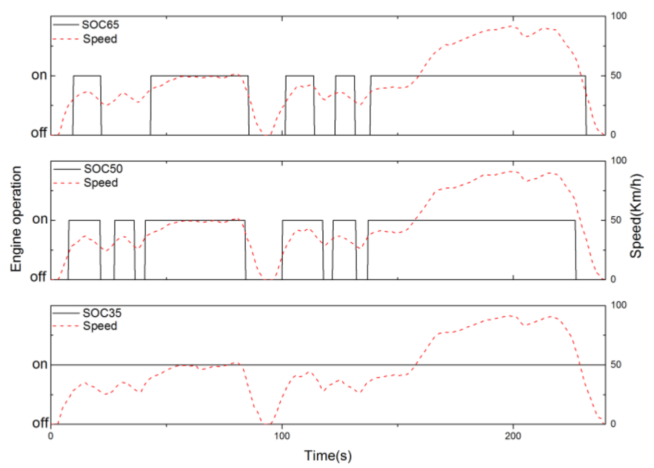

Figure 9: Engine operation to parallel hybrid-drive time according to different initial SOCs.

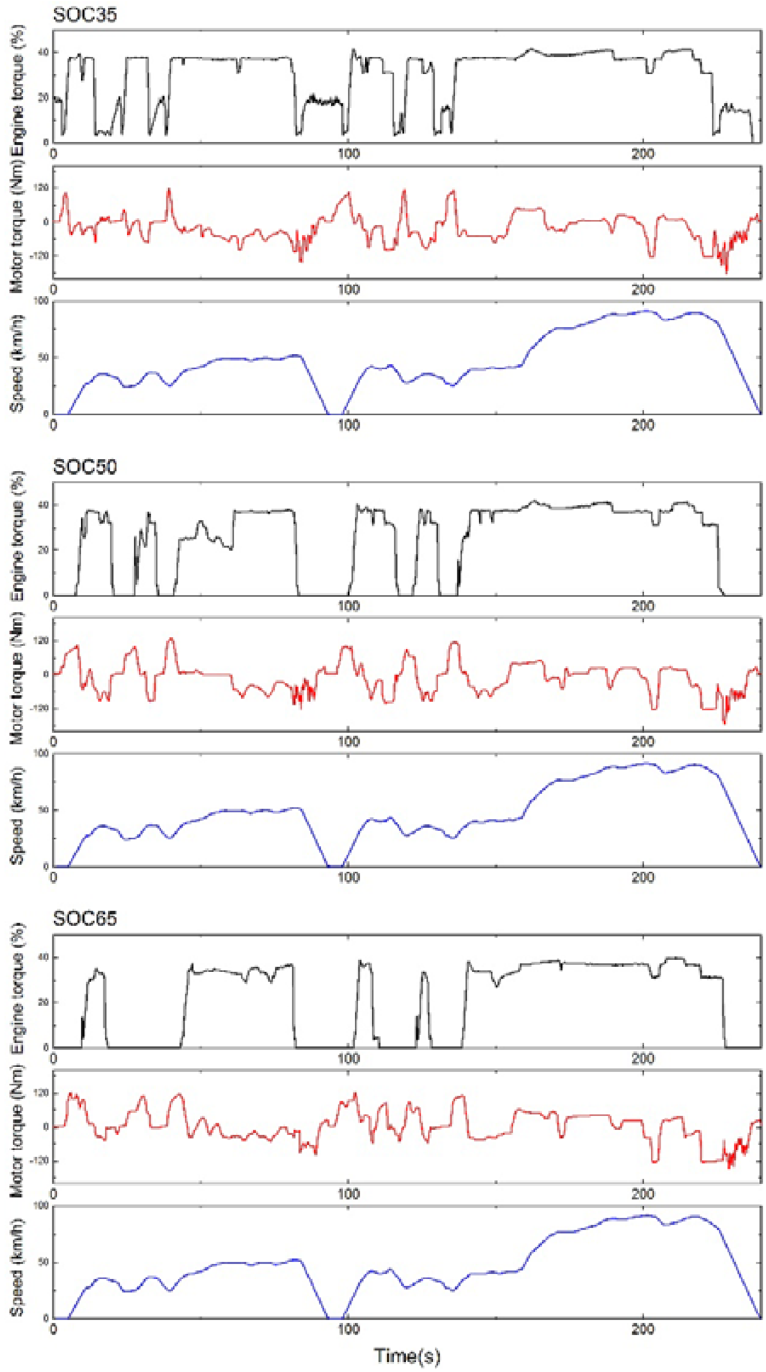

Figure 10: Variation of engine torque and motor torque over IM240 driving cycle for different initial SOCs.

recover wasted energy from braking. In the IM240 driving cycle, there are two main spots where the regenerative system is activated. The first is at around 90 seconds, and the second spot is at the end of the driving cycle. In this study, it was observed that when the regenerative braking system was operated, the engine torque and the current oscillated as shown in Figures 6 and 10 respectively. When the initial SOC is 65%, the collect rate of the regenerative current is about 1.9% of the total capacity of the battery. For an SOC of 50%, the collect rate of the regenerative current went up to about 2.5%. In the case of SOC 35%, its rate increased about 3.6%. Therefore, it was found that as initial SOC decreased, the regenerative energy increased, as shown in Figure 12. It is considered these results can have significant impacts on fuel economy which is governed by engine operation time in hybrid-electric vehicles.

Figures 13-15 present the characteristics of six-driving modes with different initial SOCs. In this study, the driving modes of the parallel HEV were estimated based on engine and motor speed, engine and motor torques, currents, and SOC. As shown in the above Figures, the driving modes were EV mode (electric only traction), engine charge mode (battery charging from the engine), engine charge and power mode, engine power mode (engine only traction), HEV mode (hybrid traction), regeneration mode (regenerative braking). Firstly, EV mode

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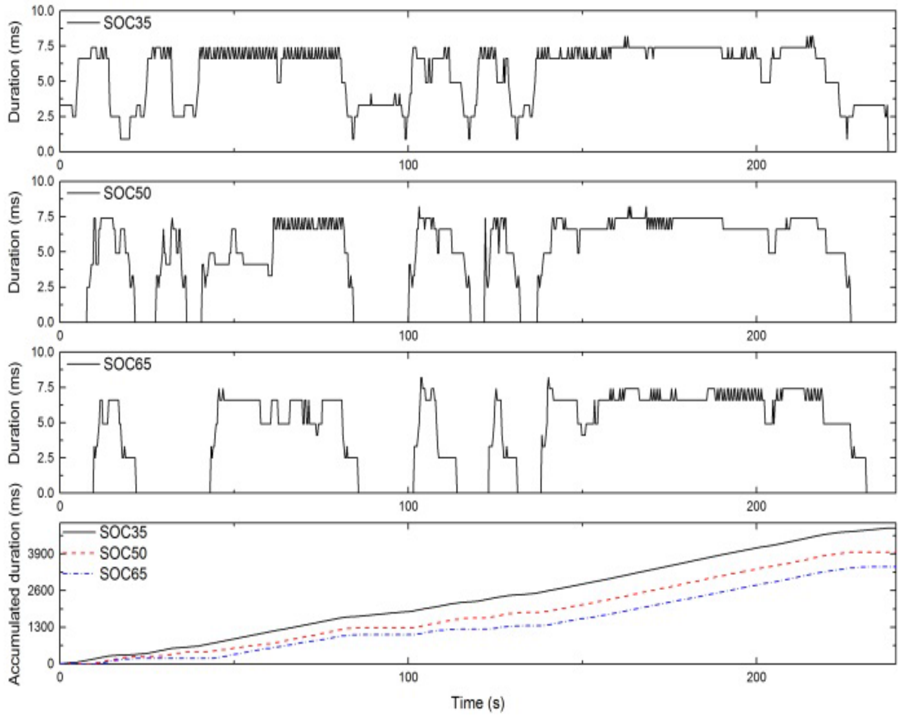

Figure 11: Instantaneous and accumulated fuel injection duration according to different initial SOCs.

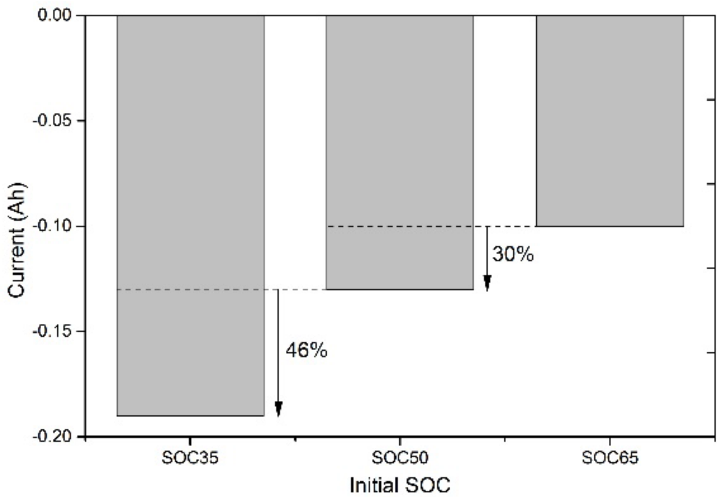

Figure 12: Regenerative current in accordance with different initial SOCs.

was defined as being where motor speed and motor torque increased without engine operation. Engine charge mode was where the engine ran to generate electricity but without producing propulsion power. This mode was seen in some areas where the vehicle speed was either decreasing or was zero, as shown in above Figures. Also, engine charge and power mode was defined as being when the engine produced both propulsion power and electricity. As a result, it found that the engine torque got up to 40%, and the battery was charged. In engine power mode, the engine produced propulsion power with neither assistance from the electrical motor nor generation. For HEV mode, the engine and electrical motor generated propulsion power at the same time, so the torques of both engine and motor were positive. As a result, it was found that battery current was consumed, and the SOC dropped slightly. For the regeneration mode, the mode was defined when the regenerative braking system operated during slowing down.

From the results mentioned above, it was seen that because of its TMED powertrain structure, engine and motor speed were the same, as denoted by the shaded area in Figures 13-15, when the engine runs with the motor to generate either propulsion or electricity. Also, it was found that the proportion of the regeneration mode was from 8.4% to 9.3% with respect to the initial SOCs, as presented in Table 5, even

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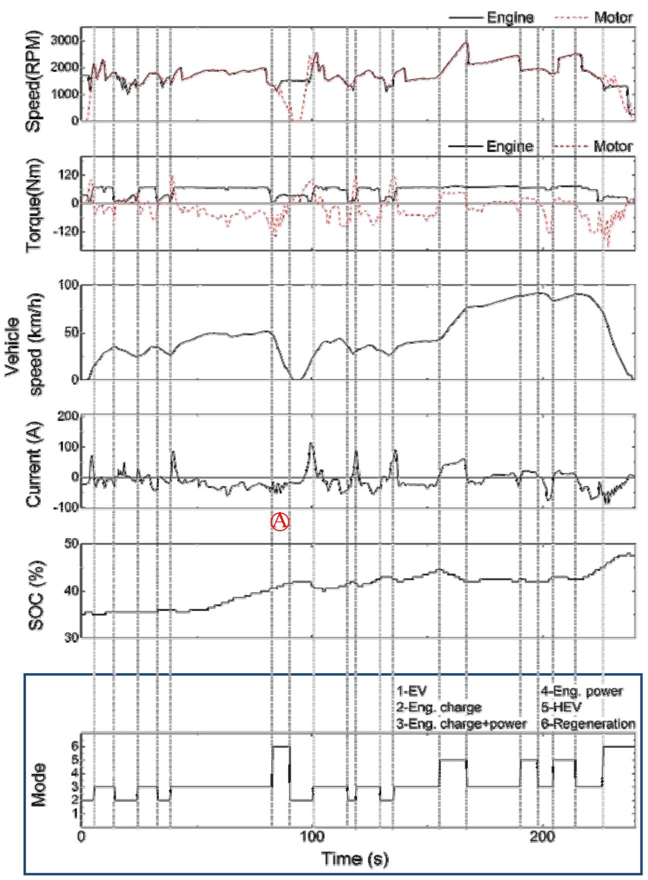

Figure 13: Six-driving modes characteristics at initial SOC of 35%.

though the amount of regenerative current is different in Figure 12. Therefore, it can be thought that the key factor for regenerative current, as shown in Figure 12, is the peak current during regeneration rather than the length of time, as denoted by A in Figures 13-15.

Conclusion

In this study, the propulsion characteristics of drivability performance in a parallel hybrid gasoline-electric vehicle were investigated over the IM240 transient driving cycle, to research the effects of different battery's initial SOCs. All the data of an in-use parallel HEV were logged with an OBD signal port, CAN analyzer at every 300 ms, and vehicle diagnosis tool (GDS). Also, engine operation time was measured by instantaneous and accumulated fuel injection durations with respect to varying initial SOCs to estimate fuel consumption characteristics. Moreover, in order to figure out the effects on regenerative braking feature, the amount of regenerated current stored in a secondary battery was analyzed. The main results drawn from this study are summarized as follows.

1. By comparing characteristics of electrical components, the in/out current of battery and SOCs were affected by initial SOC. It was found that in the case of 35% SOC, there was a charging strategy, and it showed an ascending trend of the SOC and negative currents during the IM240 cycle, whereas SOC of 50% was stable overall. For SOC of 65%, the state of charge tended to decrease during the driving cycle, for consuming electrical power and less fuel consumption.

2. As an effect of changing initial SOCs, engine operation time was influenced. For SOC of 35%, the engine operated throughout the test. When the initial SOC was 50%, the engine operated for 73% of the test. In the SOC of 65% case, engine operation time was reduced by 10% from that of SOC of 50%.

3. Instantaneous and accumulated fuel injection durations, as an alternative method, were measured to inspect the fuel consumption. The instant fuel injection duration data showed a good agreement with engine operation time in the hybrid mechanism considered by this experimental approach, and accumulated fuel injection duration was affected by initial SOCs.

4. Finally, six driving modes were classified with the behavior of engine and motor speed, torque, current, and SOC in this study. The vehicle often took advantage of EV mode with SOC of 65% to improve fuel economy, while in the case with SOC of 35%, the vehicle couldn't utilize the EV mode due to having to prevent the battery from sustaining electrical damage. As for regeneration, when the initial SOC was 35%, the recovered current was the greatest among the cases because the peak current was the highest. It can be concluded that initial SOC has an important influence not only on the powertrain and electrical performance, but also on fuel economy.

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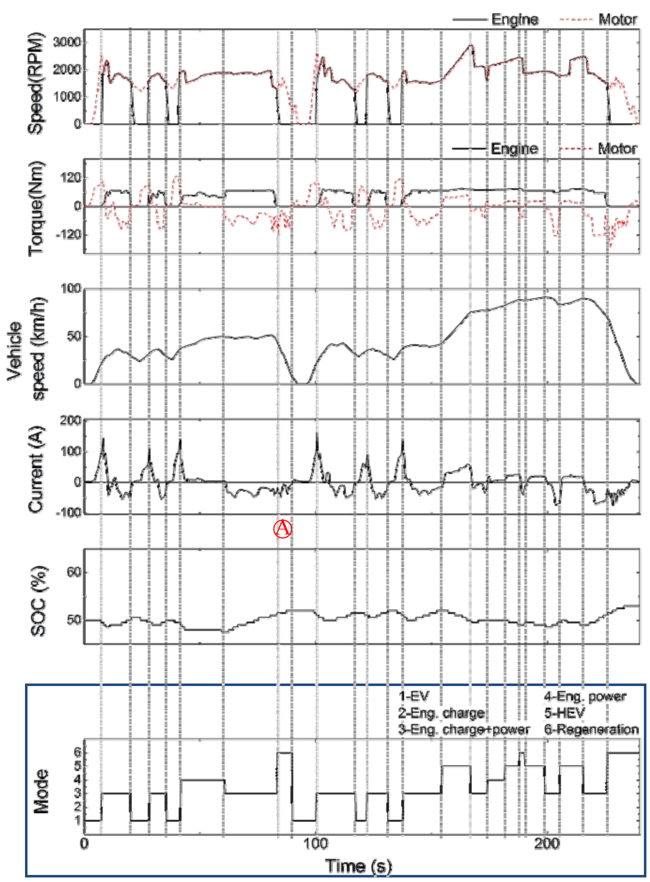

Figure 14: Six-driving modes characteristics at initial SOC of 50%.

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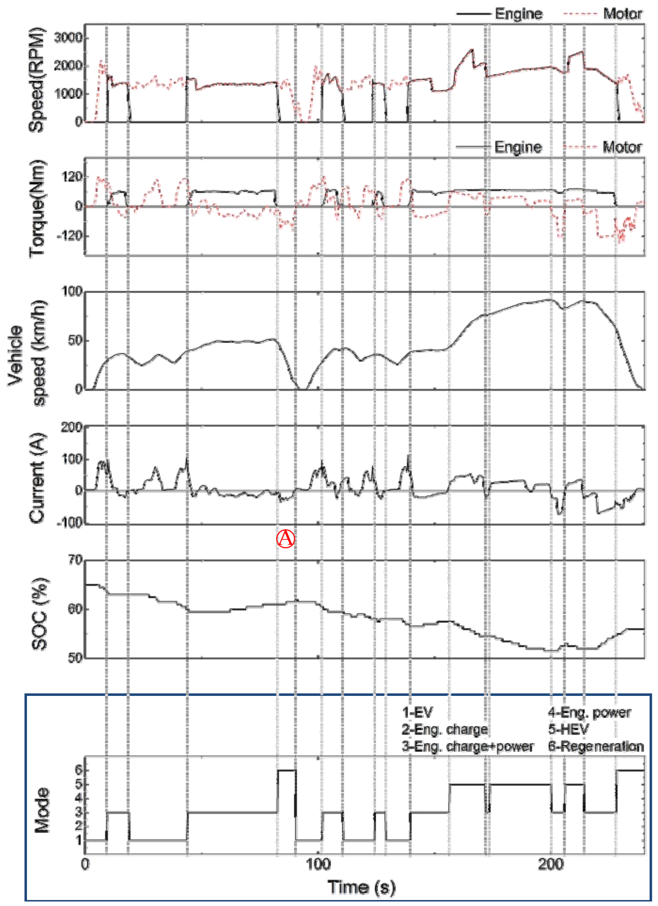

Figure 15: Six-driving modes characteristics at initial SOC of 65%.

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