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Comparative Study of Powertrain Loss and Efficiency for the Electric Vehicle and Internal Combustion Engine Vehicle

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전기차와 내연기관차의 파워트레인 손실 및 효율 비교

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ABSTRACT

In this paper, the component loss models of the electric vehicle(EV) and the internal combustion engine vehicle(ICEV) are developed to analyze the losses and efficiencies of these two types of vehicles. The EV powertrain efficiency decreases as the vehicle velocity increases over most of the vehicle velocity range because the battery efficiency decreases. Especially, the EV powertrain efficiency decreases significantly when the battery SOC is low. But the ICEV powertrain efficiency increases as the vehicle velocity increases. This is because the efficiencies of both the transmission and engine increases.

Keywords : Electric Vehicle(전기자동차), Internal Combustion Engine(내연기관), Powertrain(파워트레인), Energy Loss(에너지손실), Battery Efficiency(배터리 효율)

1. Introduction

An electric vehicle(EV) is propelled by an electric motor, having a battery as the power source. The battery is charged by the electricity produced from a power plant. Thus, energy consumption and energy generation can be separated. Under this separation, zero emission driving in an EV can make the air in urban areas cleaner than what it is now. Furthermore, the electric power for the EV can be generated by using renewable energy, such as wind, solar or biomass energy[1]. Many studies have been conducted to maximize the performance of the EV. To design a robust battery system, real world battery duty profiles and the relationship between battery state of charge (SOC) and motor efforts have been studied[2-3]. Also, the costs of 100, 75 and 50 mile range EVs were compared and the 50 mile range EV was considered the most cost effective vehicle[4]. For the above reasons, Nissan released in 2010 the EV “Leaf” showing 160km driving range under normal driving mode and up to 200 km driving range under ECO driving mode[5]. To maximize EV performance under limited battery performance, the small EV or hybrid EVs are developed[6-9]. The above researches showed

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that the limited range driving EV with its small size battery can satisfy current daily driving patterns, and its less driving power can provide higher EV efficiency and longer battery life. But, some analysis studies are required to know why the limited driving range and less driving power lead to better performance.

Thus, in this paper, the component losses and efficiencies of the EV are investigated. An EV component loss model is developed to analyze EV component losses in terms of driving velocity and battery SOC. Also, an internal combustion engine vehicle(ICEV) loss model is developed, and the component losses and efficiencies of the ICEV are compared with those of the EV.

2. Powertrain loss models

The EV is propelled by the electric motor, with the electric energy supplied by the battery. When power passes from the battery to the vehicle, power losses occur. The first power loss at the battery can be calculated by using the internal resistance and open circuit voltage of the battery, which change according to battery SOC. Fig. 1 shows the equivalent electric circuit of battery. Considering the electric circuit of the battery in Fig. 1, the battery output voltage is expressed by equation (1).

$$V_{out} = V_{OC}(SOC) - R_{int}(SOC) \cdot i \qquad (1)$$

where V_{out} is the battery output voltage, $V_{OC}(SOC)$ is the open circuit voltage, $R_{int}(SOC)$ is the internal resistance, and i is the current of the battery. The battery input and out power can be calculated by multiplying the battery current i to equation (1), as given in equation (2).

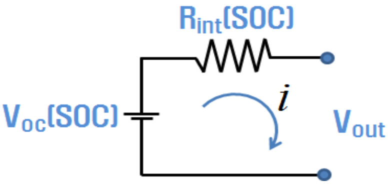

Fig. 1 Equivalent electric circuit of battery

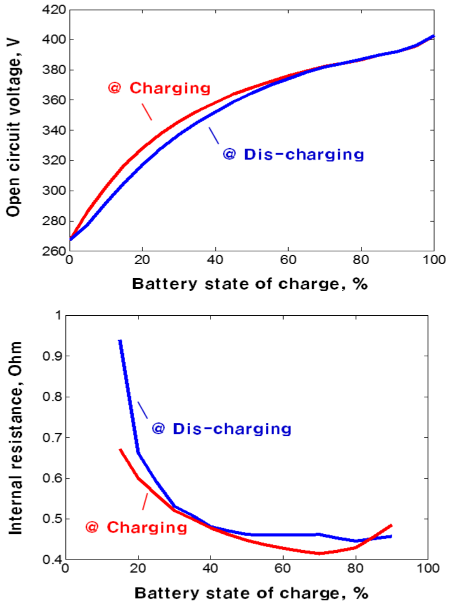

Fig. 2 Open circuit voltage and internal resistance curve

$$V_{out} \cdot i = V_{OC}(SOC) \cdot i - R_{int}(SOC) \cdot i^2 \qquad (2)$$

And, the battery input, output, and loss power are expressed as

$$V_{out} \cdot i = P_{battery} \qquad (3)$$

$$V_{OC}(SOC) \cdot i = P_{battery\_in} \qquad (4)$$

$$R_{int}(SOC) \cdot i^2 = P_{battery\_loss} \qquad (5)$$

where $P_{battery}$ is the battery output power, $P_{battery\_in}$ is the battery input power, and $P_{battery\_loss}$ is the battery loss power. Thus, equation (2) is expressed as

$$P_{battery} = P_{battery\_in} - P_{battery\_loss} \qquad (6)$$

by using equations (3) ~ (5). The internal resistance decreases and the open circuit voltage increases when the battery SOC increases as shown in Fig. 2. The higher open circuit voltage leads to lower current, and lower current and lower internal resistance results in small battery loss power. Thus, if the battery SOC increases, the battery loss power decreases. Because of the battery internal resistance, the battery input power is reduced as much as the battery loss power.

And the second loss occurs when the battery output power is delivered to the electric motor. The electric motor power loss can be calculated by considering the electric motor efficiency. In this paper, the motor power loss includes the inverter power loss. The inverter means the electric device which operates the electric motor. Electric motor efficiency varies with the operation point, which consists of the electric motor torque and speed. In the Fig. 3, the efficiency curve of the electric motor is shown. Using this efficiency curve, the electric motor output power and loss power are calculated as

$$P_{motor} = P_{battery} \cdot \eta_{motor} \tag{7}$$

$$P_{motor\_loss} = P_{battery} \cdot (1 - \eta_{motor}) \tag{8}$$

where P_{motor} is the electric motor output power, η_{motor} is the electric motor efficiency, and P_{motor_loss} is the electric motor loss power. The final electric motor output power is used to propel the vehicle.

In this study, the power losses of the EV are compared with those of the ICEV. Thus, an ICEV loss model is developed. The ICEV consists of an engine and transmission. In this study, the gasoline engine is considered; thus, the engine input power comes from the gasoline. As the gasoline power passes through the engine, power loss occurs, which can be calculated by considering engine efficiency.

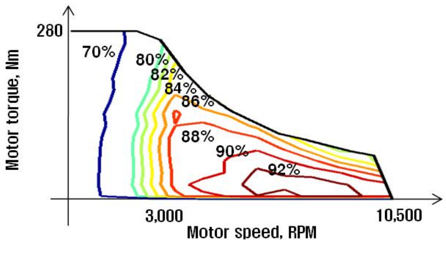

Fig. 3 Motor efficiency curve

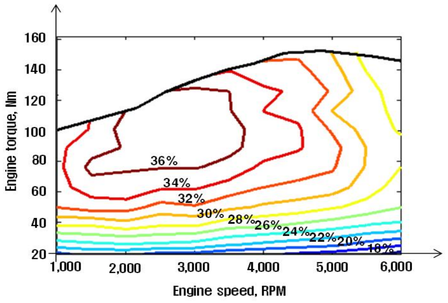

Fig. 4 Gasoline engine efficiency curve

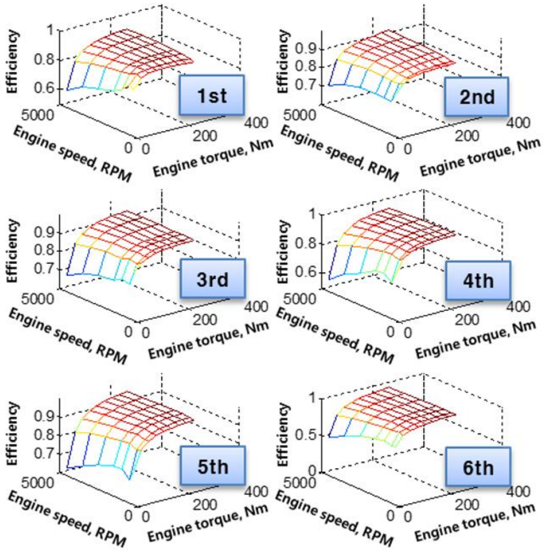

Fig. 5 Six speed automatic transmission efficiency curve

Engine efficiency varies with the engine operation point, which consists of the engine torque and speed. In Fig. 4, the efficiency curve of the ICEV engine is shown, from which the engine output power and power loss are calculated as

$$P_{engine} = P_{gasoline} \cdot \eta_{engine} \tag{9}$$

$$P_{engine\_loss} = P_{gasoline} \cdot (1 - \eta_{engine}) \tag{10}$$

where P_{engine} is the engine output power, $P_{gasoline}$ is the gasoline power, η_{engine} is the engine efficiency, and P_{engine_loss} is the engine power loss. And the second loss occurs when the engine output power passes through the transmission. The transmission power loss can be calculated by considering the transmission efficiency. The transmission is connected to the engine directly. Thus, the transmission input speed and torque are same as the engine speed and torque. The transmission efficiency varies with the transmission operation point, which consists of the engine torque and speed. In this speed, the six speed automatic transmission is considered. In Fig. 5, the efficiency curve of the transmission is shown, from which the transmission output power and power loss can be calculated as

$$P_{transmission} = P_{engine} \cdot \eta_{transmission} \tag{9}$$

$$P_{transmission\_loss} = P_{engine} \cdot (1 - \eta_{transmission}) \tag{10}$$

where $P_{transmission}$ is the transmission output power, $\eta_{transmission}$ is the transmission efficiency, and $P_{transmission\_loss}$ is the transmission power loss. The final transmission output power is used to propel the vehicle.

3. Analysis of EV and ICEV powertrain losses and efficiencies

In this study, the power losses of EV and ICEV are compared. Thus, the specifications of both the EV and ICEV are shown in table 1. Both vehicles have the same weight and aerodynamic parameters, which allow for a fair comparison. The EV has an 80kW electric motor and a 345 voltage lithium ion battery. The ICEV has a 91kW gasoline engine and a 6-speed automatic transmission, which can yield similar performance to that of the EV. Using these parameters, the powertrain losses of EV/ICEV are analyzed. The analyses are performed by changing driving velocity to changing driving power.

Table 1 Vehicle specifications

	EV		ICEV		
	Motor		Engine		
Type	AC synchronous		Gasoline (4 Cylinder, 1.8L)		
Max. Power	80kW @2,730-9,800rpm		91kW @6,000rpm		
Max, Torque	280Nm @0-2,730rpm		152Nm @4,600rpm		
Max RPM	10,390 RPM		6,000 RPM		
	Battery		Transmission		
Type	Laminated Lithium Ion		6 speed Automatic Transmission		
	Voltage	345 V	Gear ratio	1st	4.212
				2nd	2.637
	Capacity	24 kWh		3rd	1.8
				4th	1.386
	Number of Cells	192		5th	1.0
				6th	0.772
Final Drive Ratio	7.9377		3.32		
Driven Wheels	Front				
Tire Size	205/55R16				
Weight	1,525kg (Kerb Weight), 1,965kg (Gross Vehicle Weight)				
Cd	0.29				
Frontal Area	2.27m^2				

Fig. 6 shows the loss powers of the EV powertrain. The battery loss power varies with the battery SOC, but the motor loss power remains unchanged. The loss powers of both the motor and battery increase as the EV velocity increases. When the EV velocity is less than about 100 km/h, the battery power loss becomes smaller than the motor power loss. But, the motor power loss increases in the form of a first order, and the battery power loss increases in the form of a second order function. Thus, the battery loss power becomes larger than motor loss power when the EV velocity faster than

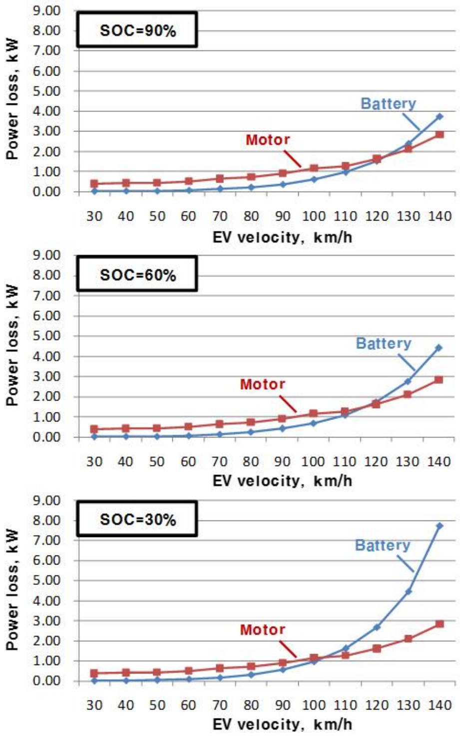

Fig. 6 Powertrain losses of the electric vehicle

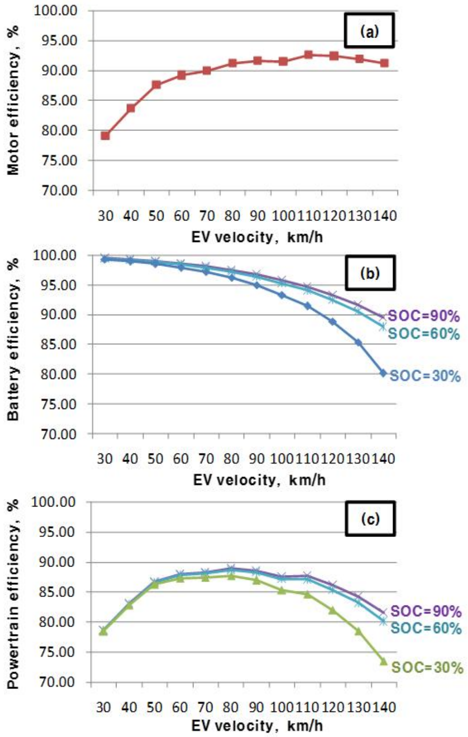

Fig. 7 Powertrain efficiencies of the electric vehicle

about 100km/h. And, the battery power loss increases rapidly when the battery SOC is a low value such as 30%, and the battery power loss at 30% SOC is about 8 kW, which is twice the battery power loss at 90% SOC when the EV velocity is 140km/h.

Fig. 7 shows the efficiencies of the EV powertrain. The motor efficiency does not change much after vehicle velocity of 60km/h in Fig. 7a, but remains at about 90 ~92 %. Thus, the motor power loss increases linearly with almost first order gradient in Fig. 6. But, the battery efficiency decreases as the vehicle velocity increases in Fig. 7b. Especially, the battery efficiency decreases in the form of a second order function and the slope increases as the battery SOC decreases. This is the reason why the battery power loss increases rapidly as the vehicle velocity increases and battery SOC decreases in Fig. 6. Fig. 7c shows the powertrain efficiency, which includes

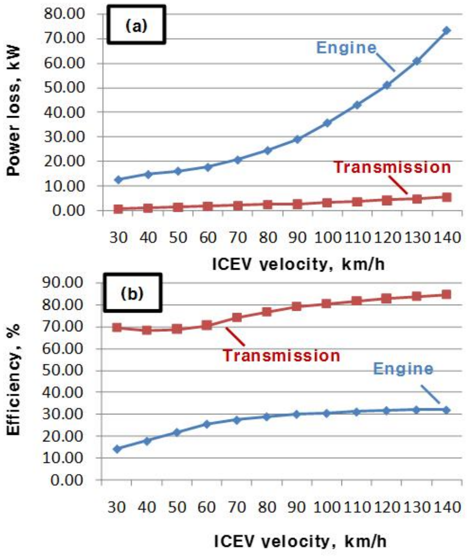

Fig. 8 Power losses and efficiencies of the internal combustion engine vehicle

the battery and motor efficiencies. The powertrain efficiency increases up to vehicle velocity of 50km/h because the motor efficiency increases and the battery efficiency does not decrease greatly. Above vehicle velocity of 50km/h, the powertrain efficiency is greatly affected by the battery efficiency, so it decreases with decreasing battery SOC.

Fig. 8 shows the power losses and efficiencies of the ICEV. In Fig. 8a, the transmission power loss shows a similar numerical range to those of the electric motor and battery power losses of the EV. But, the engine power loss is the biggest of all losses. Because the transmission efficiency shows a similar numerical range to that of the EV, the engine efficiency is about 15 ~ 32 % in Fig. 8b. This range is much smaller than the others, but it is typical of a gasoline engine. In Fig. 8b, both transmission and engine efficiencies increase as the ICEV velocity increases.

Fig. 9 shows the powertrain efficiencies of the EV and ICEV. The EV powertrain efficiency includes the electric motor and battery efficiencies, and the ICEV powertrain efficiency includes the engine and transmission efficiencies. The ICEV powertrain efficiency ranges 10 ~ 27%, and the EV powertrain efficiency ranges 73 ~ 90%, almost three times higher than that of ICEV. The ICEV powertrain efficiency increases as the vehicle velocity increases because both the transmission and engine efficiencies increase. But the EV powertrain efficiency decreases as the vehicle velocity increases in most of the vehicle velocity range because of the battery efficiency decreases. Especially, the EV powertrain efficiency decreases greatly as the battery SOC decreases.

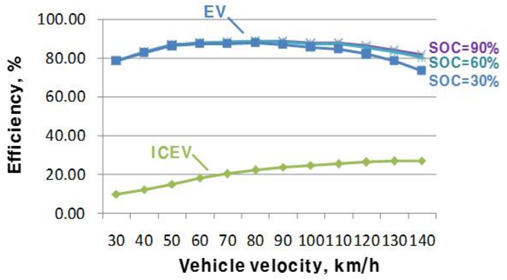

Fig. 9 Powertrain efficiencies of the EV and ICEV

4. Conclusion

In this study, the component loss models of the electric vehicle(EV) and the internal combustion engine vehicle(ICEV) were developed to analyze the losses and efficiencies of these two types of vehicles. The EV powertrain efficiency, which includes the efficiencies of the motor and battery, varied with the vehicle velocity and battery state of charge(SOC). The motor efficiency increased as the vehicle velocity increased. But the battery efficiency was affected by the vehicle velocity and battery SOC. The battery efficiency decreased as the vehicle velocity increased and the battery SOC decreased. The EV powertrain efficiency decreased as the vehicle velocity increased over most of the vehicle velocity range because the battery efficiency decreased. Especially, the EV powertrain efficiency decreased significantly when the battery SOC was low. But the ICEV powertrain efficiency, which includes the efficiencies of the engine and transmission, increased as the vehicle velocity increased. This is because the efficiencies of both the transmission and engine increased.

REFERENCES

1. Richardson, D. B., “Electric Vehicles and the Electric Grid: A Review of Modeling Approaches, Impacts, and Renewable Energy Integration,” Renewable and Sustainable Energy Reviews, Vol. 19, pp. 247-254, 2013.
2. Devie, A., Vinot, E., Pelissier, S. and Venet, P., “Real-world battery duty profile of a neighbourhood electric vehicle,” Transportation Research Part C: Emerging Technologies, Vol. 25, pp. 122-133, 2012.

3. Nasri, A. and Gasbaoui, B., “The slopped road angle effect on lithium ions battery behavior for the next future commercialized electric vehicle,” Journal of Electrical and Electronics Engineering, Vol. 4, No. 2, pp. 5-10, 2011.
4. Neubauer, J., Brooker, A. and Wood. E., “Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies,” Journal of Power Sources, Vol. 209, pp. 269-277, 2012.
5. Ohbu, K., Yamakawa, H., Hoshi, S., Kageyama, Y., Hisada, K. and Misawa, H., “Technology for distinctive handling performance of the newly developed Electric Vehicle,” SAE Paper, No. 2011-39-7207, 2011.
6. Na, Y. M. and Park, J. K., “Design and Fabrication of Single-person Neighborhood Electric Vehicle with Streamlined Car Body”, Journal of the Korean Society of Manufacturing Process Engineers, Vol. 17, No. 4, pp. 55-63, 2018.
7. Kim, J. M., “Comparative Study of Different Drive-train Driving Performances for the Input Split Type Hybrid Electric Vehicle”, Journal of the Korean Society of Manufacturing Process Engineers, Vol. 16, No. 4, pp. 69-75, 2017.
8. Sim, H. S., “A Study of on a Power Control System for a Solar-Electric Vehicle”, Journal of the Korean Society of Manufacturing Process Engineers, Vol. 13, No. 3, pp. 70-76, 2014.
9. Sim, H. S., “A Study on an Electric Power System Design of a Small Electric Vehicle”, Journal of the Korean Society of Manufacturing Process Engineers, Vol. 17, No. 1, pp. 89-94, 2018.