Analysis of Energy Consumption Performance for Electric Vehicle Considering Transmission Shifting Pattern

Ho-Chang Jung 1,2, Deok-Jin Kim 2*

1 School of Electronic and Electrical Engineering, Sungkyunkwan University, Suwon, 440-746, Korea
2Advanced Engine System R&D Center, Korea Automotive Technology Institute, Cheonan, 330-912, Korea, djkim@katech.re.kr, * Corresponding author

Abstract
Because the traction motors for powertrain systems of electric vehicles have a wide operating range, they are not equally efficient at every speed and torque condition. Typically, powertrain systems of electric vehicles consist of a traction motor and single speed gearbox; however, this configuration is inadequate to obtain optimal fuel economy and driving performance for real-world driving cycles which have different characteristics. A multi-speed configuration of a powertrain system can reduce the electric energy consumption without degrading the driving performance, even if the traction motor power is reduced.

Keywords: Electric Vehicle, Two-Speed Transmission, Traction Motor, Driving Cycle, Energy Consumption

1 Introduction
With the rise of stringent worldwide environmental regulations and increases in petroleum costs, high-efficiency environmentally friendly vehicles have been attracting considerable attention. Many studies and cases on conventional electric vehicles (EV) indicated that the greatest shortcoming of EVs is the limited driving distance achievable in one charge. Hence, improvements in energy consumption efficiency remain a critical requirement for EVs. Further, the lack of external electricity quick charge infrastructures, unlike in the case for existing internal combustion engine vehicles (ICEV), and the inconsistent performance characteristics of battery energy, make energy consumption management in EVs even more important. Moreover, the importance of high efficiency in the power systems of electric vehicles is set to gain even more prominence in the years to come.

In most cases, using an electric motor as the main drive system when driving allows for a relatively wider range of driving speeds. Moreover, the high efficiency region is generally distributed in the medium speed, high load region. Thus, if the driving system is composed of an electric motor installed with a fixed ratio decelerator, electric energy consumption efficiency may greatly vary according to the driving pattern. In general, ICEVs undergo a process of calibration with respect to driving mode characteristics for transmission shifting pattern optimization. This calibration method can also be effectively utilized in EVs having traction motors of two speeds or more. Therefore, in the present study presents an analysis of the improvements in electric energy consumption efficiency for various driving modes when a two-speed traction motor is used in an electric driving system in place of a one-speed traction motor.
2 Vehicle Simulation
AVL cruise was used to model the vehicle system and construct the interpretation environment for various driving conditions for the vehicle simulation.

2.1 Driving Mode for Simulation
The driving modes reviewed in this study are the European NEDC (New European Driving Cycle), the chassis dynamometer vehicle driving mode, the urban driving mode FTP75 (2 UDDS, Urban Dynamometer Driving Schedule), the high-speed driving mode HFEDS (Highway Fuel Economy Driving Schedule), the harsh driving mode US06, and the driving mode for air conditioning device impact analysis SC03, which is composed of five cycles in the U.S.

As Figures 1 and 2 show, the average speed of the FTP75 mode, which represents urban driving characteristics, is 34.12 km/h; it has a relatively higher rate of stops. The high-speed driving mode HFEDS shows a high average speed of 77.7 km/h, while US06, the harsh high-speed driving mode, records a maximum speed of 129.2 km/h and an average speed of 77.9 km/h.

2.2 Modeling of the Electric Driving System

2.2.1 Transmission Modeling
1) 1-Speed Transmission (1-STM)
For the 1-STM model, a simplified model, in which the gear ratio, power transmission efficiency, and the input and output inertia moment can be adjusted, is shown in Figure 3. A separate transmission control logic is not required in this case. This model was composed to share the basic power system model of 1-STM with that of the 2-STM model using the system multi-layout management function of AVL cruise.
2) 2-Speed Transmission (2-STM)

While the same simplified model used for 1-STM, in which the gear ratio, power transmission efficiency, input and output inertia moment could be adjusted, was used for the 2-STM model, the modeling also reflected a virtual clutch model to simulate a transmission process and transmission control logic that controls this process. The model was also fabricated to share the power system model. 2-STM EV Model is shown in Figure 4.

![Figure 4: 2-STM EV Model](image)

The transmission control logic was composed such that the ideal reward and synchronization of the inertia moment of the electric motor could occur within the targeted transmission time using the PID controller, and the inertia moment of the virtual clutch was adjusted such that dynamic properties such as clutch response and shock could be ignored because the performance of the dynamic properties of the traction motor applied to the electric motors was not the purpose of the present study.

![Figure 5: 2-STM Transmission Process](image)

2.2.2 Electric Motor Modeling

In this study, an electric motor model was developed for the interpretation study through an appropriate down scaling method for simulating reduced capacity electric motors using performance curves and efficiency maps of an 80 kW electric motor. The following figure shows a concept map of down scaling.

![Figure 6: Electric motor model for reference EV model and scaling method](image)

2.2.3 Other Modeling

Vehicle dimensions were set to 1,190 kg as empty vehicle weight and 1,570 kg as maximum vehicle weight, which is similar to 1.6 L compact cars. The rolling resistance coefficient of the tire model and the inertia mass of the rotating unit was used for equal driving resistance. The battery was set to a 69 kWh Li-ion, a relatively large capacity battery, to minimize the impact of capacity limitations. Constraint conditions were removed for vehicle brakes to ensure maximum electric energy recovery through the electric motor’s regenerative breaking. The regenerative breaking control logic was composed such that breaking using mechanical brakes could occur in case additional breaking power was required.

<table>
<thead>
<tr>
<th>Category</th>
<th>Set value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission time(sec)</td>
<td>-</td>
<td>Fixed</td>
</tr>
<tr>
<td>Transmission speed(km/h)</td>
<td>80</td>
<td>Fixed</td>
</tr>
<tr>
<td>Motor capacity(kW)</td>
<td>80</td>
<td>Fixed</td>
</tr>
<tr>
<td>Deceleration ratio (first gear/second gear)</td>
<td>5 - 11/(-) Variable</td>
<td></td>
</tr>
<tr>
<td>Regenerative breaking</td>
<td>Max</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: Interpretation Conditions
3 Vehicle Analysis Result

3.1 1-STM EV energy consumption performance

3.1.1 Energy consumption performance according to gear ratio changes

When applying 1-STM according to the vehicle simulation interpretation conditions as shown in Table 1, to calculate the gear ratio for optimal energy consumption, the electric motor was fixed as an 80 kW class motor and the energy consumption was calculated by varying the gear ratio from 5 to 11 in the maximum regenerative condition. Transmission time and speed have no impact because the 1-STM model is used. Figure 7 shows the interpretation results. Improvement rates for each ratio were obtained relative to a gear ratio value of 9.3, which was set as the reference point.

![Figure 7: Energy consumption performance per driving mode for 1-STM gear ratio changes](image)

Each driving mode shows different gear ratio at the best energy consumption rate. For urban driving characteristics such as FTP75, maximum energy consumption improvement rate was recorded at around gear ratio 8. Maximum energy consumption improvement rate appeared at a relatively lower gear ratio for the US06 mode, which reflects harsh driving characteristics, and the HFEDS mode, which reflects highway driving characteristics.

The NEDC mode, which is a combination of the ECU mode, has low-speed driving characteristics, and the EUDC mode, which has high-speed driving characteristics, displayed, unlike other driving modes, two maximum energy consumption improvement inflection points. However, among the two inflection gear ratio points the lower gear ratio had a relatively higher energy consumption improvement rate.

Such results are caused by differences in the electric energy consumption efficiency according to operating area distribution changes of the electric motor for each driving mode; in other words, different EV driving energy consumption results were calculated for different driving modes. This result concurs with the aforementioned statement that, similar to general ICEV, optimal driving conditions for energy consumption improvement also exists for EV.

In addition, in the case of simple 1-STM EV, energy consumption deviation may greatly vary for different vehicle driving patterns. Further, because simultaneous energy consumption improvement for both low-speed and high-speed regions is impossible, a 2-STM, at the least, must be applied for improving energy consumption deviation for different driving patterns.

3.1.2 Energy consumption performance according to gear ratio changes when reducing motor capacity

Electric motor capacity determination is also a very important design variable in EVs. Permanent magnetic electric motors have high rare earth dependency; therefore, weight reduction through reduction in the permanent magnet attrition by determination of the optimal capacity can be achieved.

In Fig. 8, the improvements in energy consumption for changes in the gear ratio per driving mode when the electric motor was a 60 kW class were analyzed and compared to the results for the 80 kW class electric motor previously interpreted.

![Figure 8: Energy consumption performance according to gear ratio changes per driving mode when applying a 60 kW class motor](image)
Improvement rates were calculated relative to the reference gear ratio value of 9.3 for the 80 kW class 1-STM. Overall improvements were observed for the 60 kW class electric motor in the case of the five driving modes stated earlier for gear ratios 7~10.5. 9.3 was confirmed as the appropriate ratio when determining high-speed driving energy consumption gear ratio while ignoring minimum required acceleration performance and hill-climbing performance using the European NEDC mode and the American FTP75 mode as reference. Moreover different maximum energy consumption variations were observed for low-speed and high-speed driving modes even when the 60 kW class electric motor was applied. This case, however, does not consider reductions in power performance due to reductions in motor capacity. In such a case, a problem arises in that the power performance required in vehicles cannot be procured from the electric motor with reduced output without employing additional variable transmission.

3.2 Energy consumption performance of 2-STM EV

As was confirmed in the energy consumption characteristics per driving mode of the with 1-STM EV previously considered, the possibility of improving driving energy consumption by implementing adequate transmission was reviewed using the results. Hence, the present section studied changes in energy consumption characteristics per driving mode when implementing 2-STM.

3.2.1 Energy consumption performance according to changes in gear ratio for the first-gear

The interpretation study was conducted using the conditions described in Table 2 to analyze the energy consumption performance for changes in the gear ratio of the first-gear of the 2-STM traction motor. The transmission time was fixed to within 0.8 s, the speed to 80km/h, the electric motor capacity to an 80 kW class, and the regenerative breaking to maximum available conditions. Energy consumption characteristics per driving mode was analyzed by first fixing the gear ratio of the second gear to 8.59, and then varying the gear ratio of the first gear from 9 to 11. The condition for the 9.3 gear ratio of 1-STM was set as the reference point for relative comparison.

Table 2: Interpretation Conditions

<table>
<thead>
<tr>
<th>Category</th>
<th>Set Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission time(sec)</td>
<td>0.8</td>
<td>Fixed</td>
</tr>
<tr>
<td>Transmission speed(km/h)</td>
<td>80</td>
<td>Fixed</td>
</tr>
<tr>
<td>Motor capacity(kW)</td>
<td>80</td>
<td>Fixed</td>
</tr>
<tr>
<td>Deceleration ratio (First gear/second gear)</td>
<td>(9-11)/8.59</td>
<td>First gear variable/second gear fixed</td>
</tr>
<tr>
<td>Regenerative breaking</td>
<td>Max</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 9 shows the comparison results of the energy consumption improvement rate per driving mode for 2-STM, 80 km/h transmission speed, and 80 kW motor capacity. Unlike the results of 1-STM, where the best energy consumption gear ratio location varied overall between the low-speed and high-speed mode, the maximum energy consumption gear ratio location changed relatively similarly in this case. In other words, the operating area of the electric motor, which was completely separated into the low-speed and high-speed areas, had shifted due to two-speed transmission.

Moreover, slight energy consumption improvements could be observed in all driving modes except the SC03 mode despite the 2-STM composition not being optimized. In SC03, the transmission speed is 80km/h, which is relatively high; further, SC03 has relatively smaller areas when driving speed exceeds 80km/h, the energy consumption rate slightly decreased compared to when applying deceleration of the single gear ratio of 9.3. For the other four driving modes, the US06
mode with harsh driving characteristics had the highest energy consumption improvement while no improvements were observed in FTP75. This is due to the transmission reference speed being set to 80km/h. High energy consumption improvements can be expected for the single driving mode if the optimal transmission reference speed is set as the estimated midpoint between the average speeds of the low- and high-speed sections.

3.2.2 Energy consumption performance per driving mode for changes in gear ratio when reducing motor capacity

Motor capacity reduction possibilities can be estimated within an allowable range for hill-climbing performance and acceleration performance when applying 2-STM. Using the 1-STM conditions, which set the transmission reference speed at 60 and 80 km/h and utilize an 80 kW motor as the comparison reference, performance analysis per driving mode was conducted for fixed second gear ratio and varying first gear ratio when the motor capacity was reduced to 60kW for 30% hill-climbing performance and acceleration within 13 s conditions. The improvement rate when changing the gear ratio of the first gear from 9 to 15 under 2-STM, transmission speed 80km/h, and motor capacity 60kW standards, was analyzed and compared with the energy consumption of a 1-STM vehicle with 80 kW class motor and a 9.3 gear ratio; it is shown in Figure 10.

![Graph showing energy consumption improvements per driving mode for gear ratio change of the first gear of 2STM with fixed motor standard as 60kW class](image)

When referencing the NEDC mode as the priority standard, the gear ratio, for which the best energy consumption was observed, was 10. More than 2.7% energy consumption improvements were observed in the other driving modes for the same gear ratio condition. However, when fabricating the electric driving system using 2-STM and the reduced capacity electric motor, the transmission gear ratio and transmission control map must be optimized according to the driving pattern. The present study aims to study transmission gear ratio. Transmission control optimization per electric energy consumption efficiency per driving mode of 2-STM EV remains as future work.

4 Conclusion

The present study analyzed the improvements in the electric energy consumption efficiency per driving mode when applying 2-STM to an electric driving system in place of 1-STM.

The electric energy consumption efficiency of EV installed with 1-STM, i.e., a simple decelerator with a fixed deceleration rate, was different for different driving modes. The study confirmed that appropriate additional system implementation is required for optimal driving that utilizes the high efficiency area of electric motors. Electric energy consumption efficiency deviations caused by varying average speed and operating area distribution characteristics for different driving modes could be reduced by implementing 2-STM. The research studied whether an optimized electric driving system that satisfies both the vehicle power performance requirements (acceleration and hill-climbing) and improves energy consumption when reducing electric motor capacity could be realized.

For a traction motor design that considers the operating area distribution characteristic per driving mode and the electric motor efficiency area, control strategy optimization may be additionally required when implementing 2-STM.

Acknowledgments

This work was supported by the Industrial Strategic Technology Development Program (10033101, Development of Performance Analysis and Evaluation Technology for Heavy Duty Hybrid System) funded by the Ministry of Trade, Industry & Energy(MOTIE, Korea).
References


Authors

Ho-Chang Jung is a senior researcher in Advanced Engine System R&D Center of Korea Automotive Technology Institute. His main research interests include simulation and evaluation for main component and vehicle of Environmentally friendly vehicle.

Deok-Jin Kim is a team leader in Advanced Engine System R&D Center of Korea Automotive Technology Institute. His main research interests include simulation and evaluation for main component and vehicle of Environmentally friendly vehicle.