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RESEARCH ARTICLE

Multi-Speed Transmission Optimization of Electric Vehicles Based on Shifting Pattern Considering Dynamic Inertia Efficiency

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ABSTRACT Multi-speed transmissions for electric vehicles (EVs) can achieve superior economic and dynamic performances than single-speed transmissions. Since gear shifting causes an equivalent inertia variation in multi-speed transmissions, the optimal shifting pattern should be determined by considering the inertia variation effect to maximize EV performances. To consider the dynamic inertia variation effect owing to gear shifting, the equivalent inertia for each speed gear and dynamic inertia efficiency are mathematically derived. An EV analysis model is constructed to evaluate the EV performances, and energy efficiency and acceleration ability are adopted as quantification measures for economic and dynamic performances, respectively. The result comparison of the optimal shifting patterns when considering and not considering the dynamic inertia efficiency exhibits the importance of the optimal shifting pattern considering the dynamic inertia efficiency for the superior transmission design of EVs. A multi-objective optimization problem is formulated that includes the design variables as gear ratios and shifting patterns and the objective functions as energy efficiency and acceleration ability. As an alternative to the excessive calculation burden of conducting multi-objective optimization, an artificial neural network (ANN)-based multi-objective optimization process is utilized. To verify the importance of the dynamic inertia efficiency on economic and dynamic performances, the gear ratios and shifting patterns are optimized by considering the dynamic inertia efficiency and none. The different optimum solutions and objective function values demonstrate the necessity of considering the dynamic inertia efficiency owing to gear shifting; the economic and dynamic performances are improved from 2.7% to 7.8% and 2.8% to 3.0%, respectively.

INDEX TERMS Electric vehicle, two-speed transmission, dynamic inertia efficiency, shifting pattern, ANN-based optimization.

ABBREVIATION

EV	Electric vehicle.
ANN	Artificial neural network.
DCT	Dual-clutch transmission.
UDDS	Urban dynamometer driving schedule.
HWFET	Highway fuel economy test.
NEDC	New European driving cycle.
WLTP	World harmonized light-duty vehicles test procedure.
EFF	Energy efficiency of EV.
SOC	State of charge of battery.
WOT	Wide-open throttle.
APS	Accelerator pedal sensor.
NSGA	Non-dominated sorting genetic algorithm.
NRMSE	Normalized root mean square error.

I. INTRODUCTION

The electric vehicle (EV) market has been rapidly growing in the automotive industry as an alternative to vehicles that

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consume fossil fuels [1]. In an EV powertrain, a transmission that converts the torque and speed of an electric motor into wheels generally employs a single-speed gear because it has a simple structure with no gear shifting, enabling excellent high transmission efficiency and drivability [2]. However, compared to multi-speed transmissions, single-speed transmissions have several drawbacks in terms of economic and dynamic performance [3], [4], [5]. For economic performance, even if a motor drives in the low powertrain efficiency region under a specific vehicle driving condition, a single-speed transmission cannot control the motor operation because the motor torque and speed are determined by a fixed transmission gear ratio and the requested vehicle speed and force [6], [7]. However, a multi-speed transmission allows the motor to operate in a high-efficiency region with appropriate gear shifting depending on the vehicle's driving conditions [8]. For dynamic performance, the vehicle traction force is represented by the product of the motor torque and gear ratio, and the vehicle speed is expressed as the motor speed divided by the gear ratio. Therefore, it is appropriate to use high and low gear ratios to satisfy high traction force and vehicle speed, respectively.

Multi-speed transmissions are more advantageous than single-speed transmissions for EV performance because selecting the desired speed gear with an appropriate gear ratio among various speed gears is possible. The gear shifting allows the motor to operate in areas with high powertrain efficiency and increases the traction force and available vehicle speed. Since multi-speed transmissions are more complex than single-speed transmissions, design optimization of the transmission is essential to find an optimal solution that maximizes the economic and dynamic performances of EVs [9]. Gear ratio optimization is essential because the critical design parameter of a multi-speed transmission is the gear ratio of each speed [10]. However, the gear-shifting pattern controls the driving gear according to the vehicle driving conditions; therefore, optimizing the shifting pattern is also significant. Several previous studies have proposed shifting patterns for multi-speed EVs.

These studies revealed the following: First, the shifting pattern generally focuses on economic performance, and the optimal pattern is determined primarily to maximize only motor efficiency [11], [12], [13], [14], [15], [16]. Second, some studies have conducted gear ratio optimization simultaneously because the optimal shifting pattern depends on the combination of gear ratios [10], [17], [18], [19], [20]. Thus, to effectively optimize the shifting pattern, economic and dynamic performances should be considered in the shifting pattern optimization since both are equally important. Some studies have proposed a shifting pattern that focuses on both performances [10], [17], [18], [21], [22]. However, these studies have practical limitations because the shifting patterns differ for each performance rather than the integrated pattern. Moreover, increased speed gears should reduce the transmission efficiency because of additional shifting components [23]. Therefore, it is necessary to consider the transmission efficiency that varies with the gear shift to further accurately optimize the shifting pattern as well as the motor efficiency [19]. In addition, optimizing both gear ratios and shifting patterns can potentially improve the economic and dynamic performances of EVs. In summary, the gear-shifting pattern for EVs should be elaborately designed to improve their economic and dynamic performances, considering variations in the motor and transmission efficiencies with gear ratio optimization.

When a vehicle is driven, translational and rotational motions exist in various vehicle components. Based on the law of conservation of kinetic energy, these motions can be represented by the motion of equivalent inertia, which is virtual inertia, and its kinetic energy is equal to the sum of the kinetic energies of each vehicle component [24]. Therefore, the translational motion of body mass and the rotational motion of powertrain component inertias can be integrated into one virtual inertia for vehicle analysis. The equivalent inertia of the input side (motor and part of the transmission) differs according to the driving gear ratio. Assuming that the vehicle travels at a constant speed, the operating speed of the motor using a high or low gear ratio of the transmission is high or low, respectively. As the kinetic energy is proportional to the square of the rotational speed, using a high gear ratio increases the equivalent inertia of the vehicle. This effect is negligible as vehicle acceleration approaches zero. However, it significantly affects the requested motor power as vehicle acceleration increases. For economic performance, up- or down-shifting can improve the motor and transmission efficiencies by changing the motor torque and speed. However, the gear shift entails an additional inertia effect on the input side under acceleration conditions. Although the motor and transmission efficiencies after the gear shift are higher or lower than the previous gear, the total energy consumption rate may be reversed by considering the variation in inertial energy due to vehicle acceleration. For dynamic performance, using a high gear ratio can multiply the input torque more than that when using a low gear ratio. Although a significant increase in the input torque ensures a high acceleration of the vehicle, a high acceleration also involves a large inertia resistance. Therefore, using a high gear ratio increases the equivalent inertia of the input side, which may result in negative effects on vehicle acceleration. In summary, the equivalent inertia variation in the speed gear selection process should be considered to maximize the economic and dynamic performances of EVs.

Previous studies have determined the gear-shifting pattern based on static characteristics, such as constant input torque and speed. However, to derive a further optimal shifting pattern, it should be expressed by including the dynamic characteristic of the equivalent inertia variation. Therefore, the shifting pattern should be optimized according to the degree of vehicle acceleration to reflect the inertia variation effect for each speed gear. In addition, the optimal shifting pattern and gear ratios can ensure excellent economic and dynamic performances. However, their enhancement is challenging because of the trade-off relationship meaning that optimizing the shifting pattern and gear ratios for economic performance can diminish the dynamic performance [10], [19]. Therefore, a multi-objective optimization method can be an alternative to this problem by providing a Pareto front consisting of diverse optimal design solutions [25].

To overcome the aforementioned research limitations on the transmission optimization of EVs, this study proposes an effective optimization method of multi-speed transmission for EVs considering the effect of equivalent inertia variation on the gear-shifting pattern. A reference powertrain configuration of a two-speed transmission EV was introduced to analyze the equivalent inertia for each speed. Based on this, the equivalent inertia was mathematically derived and an EV analysis model was developed to evaluate the economic and dynamic performances of EVs. To verify the importance of the inertia variation effect, a dynamic inertia efficiency, which quantifies this inertia variation effect, was mathematically derived. The optimal shifting patterns with dynamic inertia efficiency and nothing were obtained, and the performance results were compared. To address the trade-off relationship between economic and dynamic performance, a multi-objective optimization problem was formulated that included the design variables as gear ratios and shifting patterns and the objective functions as energy efficiency and acceleration ability. As an alternative to the excessive calculation burden needed for performing the multi-objective optimization, this study utilized an artificial neural network (ANN) to predict the relationship between the design variables and objective functions and implemented an adaptive sampling method to minimize the samples to construct the ANN model. The optimization results presented different Pareto fronts as the optimal solutions based on the shifting pattern from the dynamic inertia efficiency. These optimization results demonstrate the necessity of considering the inertia variation effect in the design of gear-shifting patterns. The contributions of this study can be summarized as follows:

1) By referring to the limitations of previous studies on the multi-speed transmission optimization of EVs, this study conducted an integrated optimization of gear ratios and shifting patterns considering both economic and dynamic performances and variable efficiencies of the motor and transmission.
2) Unlike the previous studies on shifting pattern optimization, this paper proposed an optimization process of the shifting pattern, including inertia variation for each speed, to confirm the importance of the equivalent inertia effect on energy efficiency and vehicle acceleration. The comparison results of economic and dynamic performances in consideration of dynamic inertia efficiency or none quantitatively exhibited the effect of inertia variation on EV performances.

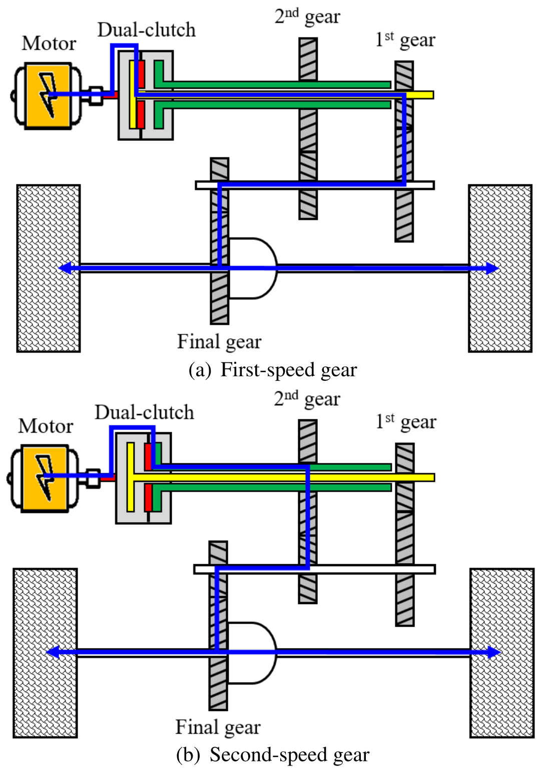


FIGURE 1. Power flows of DCT for each driving gear.

3) The different optimization results of the gear ratios and shifting patterns according to the equivalent inertia variation showed better objective values of the optimal design based on the inertia variation effect. Therefore, it verifies the performance superiority of the transmission design considering the equivalent inertia variation due to the gear ratios and shifting.

II. ANALYSIS OF MULTI-SPEED EV

An EV model employing multi-speed transmission was developed to analyze the economic and dynamic performances. Previous studies on multi-speed EVs have proposed various powertrain configurations. In the gear-shifting process, gear-shifting events generally occur more when vehicle acceleration is considered than when not considered. Since frequent gear-shifting causes poor drivability, the multi-speed transmission structure should address this shortcoming appropriately. Therefore, this study adopted a dual-clutch transmission (DCT) that exhibits high transmission efficiency and stable drivability [26].

The equivalent inertia for each driving speed gear can be derived from the powertrain configuration equipped with the DCT. To analyze the equivalent inertia of EV, the reference inertia component is determined. Several studies have calculated the equivalent inertia by referring to the wheel, which converts the rotational motion to the translational motion of a vehicle. Figure 1 shows the power flow of each driving-speed gear. Although the transmission consists of various rotational

TABLE 1. Inertia values of each component.

Component		Symbol	Value (kg $\cdot$m^2)
Motor		J_m	0.0650
First clutch		J_{c1}	0.0098
Second clutch		J_{c2}	0.0172
First speed	Gear	J_{g1}	0.0019
	Pinion	J_{p1}	0.0001
Second speed	Gear	J_{g2}	0.0009
	Pinion	J_{p2}	0.0002
Final	Gear	J_{gf}	0.0413
	Pinion	J_{pf}	0.0002

components, such as clutches, gears, bearings, and shafts, this study considers clutches and gears to calculate the equivalent inertia for the transmission because the inertia values of other components are negligible compared to those of clutches and gears. The inertia values of each component are summarized in Table 1 and determined from the component specifications introduced in [27]. Considering motor, transmission, and vehicle inertias, the equivalent inertia at the wheel driven by the first-speed gear ($J_{eq.1}$) can be expressed as follows:

$$J_{eq.1} = \left(J_m + J_{c1} + J_{p1}\right) \cdot \left(r_1 r_f\right)^2 + \left(J_{g1} + J_{g2} + J_{pf}\right) \cdot r_f^2 + J_{p2} \cdot \left(\frac{r_1 r_f}{r_2}\right)^2 + J_{gf} + MR_t^2 \tag{1}$$

where M is the mass of the vehicle, and R_t is the effective tire radius. Likewise, the equivalent inertia at wheel driven by the second-speed gear ($J_{eq.2}$) can be expressed as follows:

$$J_{eq.2} = \left(J_m + J_{c2} + J_{p2}\right) \cdot \left(r_2 r_f\right)^2 + \left(J_{g1} + J_{g2} + J_{pf}\right) \cdot r_f^2 + J_{p1} \cdot \left(\frac{r_2 r_f}{r_1}\right)^2 + J_{gf} + MR_t^2 \tag{2}$$

Using the equivalent inertia (J_{eq}), vehicle acceleration (a) and speed (v) are determined as follows:

$$a = \frac{T_{whl} R_t}{J_{eq}}, \quad v = \int a \, dt \tag{3}$$

where T_{whl} is the wheel torque, represented by the driving (T_{drv}) and resistance (T_{res}) torques ($T_{whl} = T_{drv} - T_{res}$). T_{drv} can be expressed as follows:

$$T_{drv} = T_m r_i r_f \cdot \eta_t \tag{4}$$

where T_m is the motor output torque, r_i is the speed gear ratio (r_1 or r_2), and η_t is the transmission efficiency. Here, η_t is determined by considering the losses of the clutch, gear, bearing, and concentric shaft in a DCT [19]. T_{res} can be expressed as follows:

$$T_{res} = R_t \left[\frac{1}{2}\rho c_d A_f v^2 + Mg\left(\mu_r \cos\theta + \sin\theta\right)\right] + T_{brk} \tag{5}$$

where ρ is the air density, c_d is the drag coefficient, A_f is the frontal area, g is the acceleration owing to gravity, μ_r is the rolling resistance coefficient, θ is the road slope, and T_{brk} is the braking torque. T_{brk} can be classified into mechanical (T_{mec}) and regenerative torques, as follows:

$$T_{brk} = T_{mec} - T_m r_i r_f \cdot \eta_t \tag{6}$$

Here, T_{mec} is generated by the mechanical brake, and T_m is the negative value determined by the regenerative braking torque distribution, as mentioned in [28].

Energy efficiency and acceleration ability were adopted as quantitative measures to evaluate the economic and dynamic performances of the EVs. For energy efficiency, many vehicle manufacturers have presented official efficiency values based on various standard driving cycles, such as the urban dynamometer driving schedule (UDDS), highway fuel economy test (HWFET), new European driving cycle (NEDC), and world harmonized light-duty vehicles test procedure (WLTP). The energy efficiency of an EV (EFF) means the distance that can be driven using 1 kWh of energy and it is calculated as follows:

$$\mathrm{EFF} = \frac{d_{cyc}}{C_{bat} \cdot \mathrm{dSOC}} \tag{7}$$

where d_{cyc} is the driving cycle distance, C_{bat} is the battery capacity, and dSOC is the state of charge (SOC) consumption. The dSOC is calculated from the analysis of the battery equivalent circuit. The battery voltage (V_{bat}) was derived using the circuit voltage equation, as follows:

$$V_{bat} = V_{OCV} - R_i I_{bat} \tag{8}$$

where V_{OCV} is the open-circuit voltage, R_i is the internal battery resistance, and I_{bat} is the battery current. Here, I_{bat} is determined by the battery charging and discharging conditions using the mechanical-electrical power relationship, as follows:

$$I_{bat} = \begin{cases} \dfrac{T_m \omega_m}{\eta_m \eta_i V_{bat}} & \text{if } T_m \geq 0 \text{ (discharging)} \\[2ex] \dfrac{\eta_m \eta_i T_m \omega_m}{V_{bat}} & \text{if } T_m < 0 \text{ (charging)} \end{cases} \tag{9}$$

where ω_m is the motor speed, and η_m and η_i are the motor and inverter efficiencies, respectively. dSOC is calculated by integrating I_{bat} as follows:

$$\mathrm{dSOC} = \frac{V_{OCV} \cdot \int I_{bat} \, dt}{C_{bat}} \tag{10}$$

The EV analysis model was built by MATLAB/Simulink, as shown in Figure 2.

For dynamic performance, the 0–100 km/h acceleration time, maximum speed, and ascendable gradient have been generally employed as evaluation measures in several studies. These measures can be determined under different vehicle

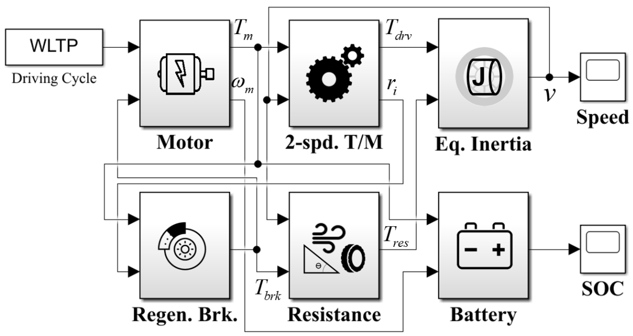


FIGURE 2. 2-speed EV analysis model.

speed conditions. Under a wide-open throttle (WOT) condition, the 0−100 km/h acceleration time (t_a) satisfies the following equation:

$$v = \int_0^{t_a} a \, dt = 100 \text{ km/h} \tag{11}$$

Next, the maximum speed (v_{max}) can be theoretically determined as follows:

$$v_{max} = \frac{\omega_{max}}{r_2 r_f} R_t \tag{12}$$

where ω_{max} denotes the maximum motor speed. However, the driving torque (T_{drv}) must be greater than the resistance torque (T_{res}) at this speed. Otherwise, v_{max} is determined at a speed that satisfies the condition $T_{drv} > T_{res}$. Lastly, because the ascendable gradient (θ_{grad}) considers the drivable condition ($v > 0$), assuming that the vehicle speed is zero, it can be determined as a gradient value equalizing T_{drv} and T_{res}. Therefore, θ_{grad} satisfies the following equation:

$$T_{max}(0) \cdot r_1 r_f = R_t M g \left(\mu_r \cos\theta_{grad} + \sin\theta_{grad} \right) \tag{13}$$

where T_{max} is the maximum motor torque, which varies with the motor speed. Here, if θ_{grad} is large, $\mu_r \cos\theta_{grad}$ is negligible. Therefore, θ_{grad} can be expressed as:

$$\theta_{grad} = \sin^{-1}\left(\frac{T_{max}(0) \cdot r_1 r_f}{R_t M g} \right) \tag{14}$$

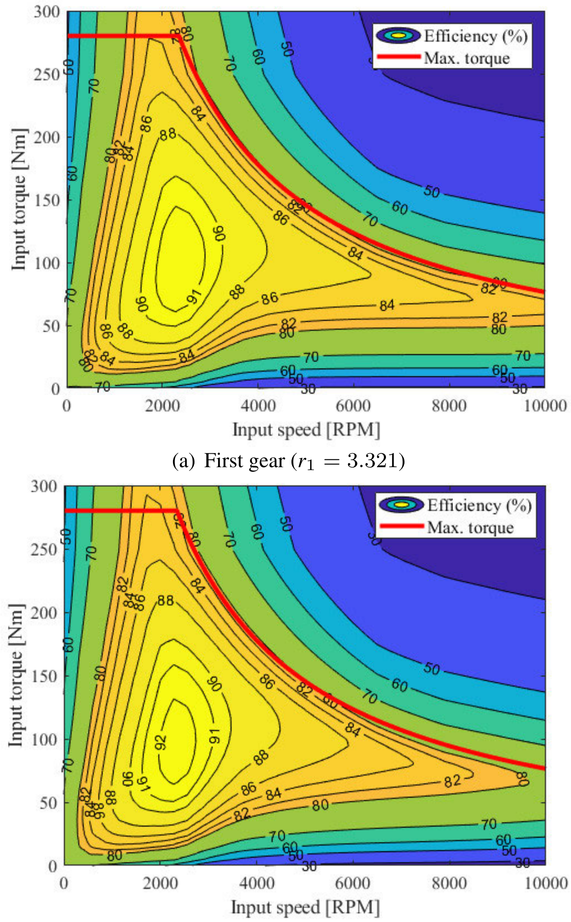
The significant parameter values of a reference EV are summarized in Table 2.

III. EFFECT OF DYNAMIC INERTIA EFFICIENCY ON OPTIMAL SHIFTING PATTERN

The economic and dynamic performances vary considerably depending on the gear ratio used under certain driving conditions. Therefore, the design of the gear-shifting pattern is as important as that of the gear ratios. The gear-shifting pattern determines the speed gear according to the accelerator pedal sensor (APS) and vehicle speed values, which represent the driver's request and vehicle status, respectively. In the two-speed transmission, the shifting pattern represents an up- or down-shift, meaning the first to the second gear shift, or vice versa. Since the up-shift occurs mainly under vehicle

TABLE 2. Specifications of reference EV.

Item		Specification
Vehicle mass		1,605 kg
Drag coefficient		0.29
Frontal area		2.27 m^2
Rolling resistance coefficient		0.01
Tire radius		0.323 m
Final gear ratio		4.058
Motor	Maximum torque	280 Nm
	Maximum power	80 kW
	Maximum speed	10,000 RPM
Battery	Open circuit voltage	350 V
	Internal resistance	0.1 Ω
	Capacity	60 kWh



(a) First gear ($r_1 = 3.321$)

(b) Second gear ($r_2 = 1.681$)

FIGURE 3. Powertrain efficiency ($\eta_m \eta_t$) maps for each driving gear.

acceleration, the shifting pattern is generally determined by considering the optimal up-shift conditions, and the down-shift is determined by offsetting the vehicle speed on the up-shift to avoid frequent gear shifts [21].

With respect to economic performance, a gear shift should be performed to minimize the required motor power

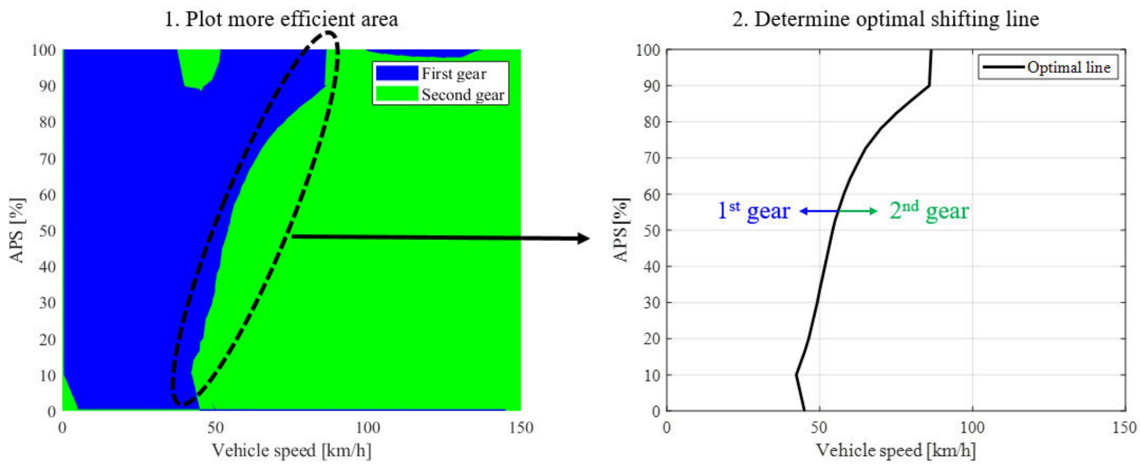


FIGURE 4. **Optimal shifting pattern for economic performance.**

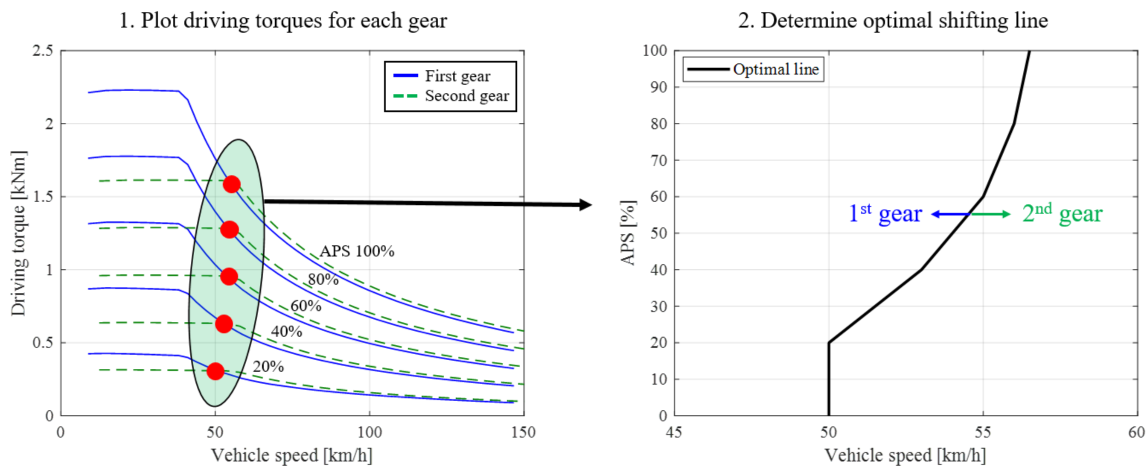


FIGURE 5. **Optimal shifting pattern for dynamic performance.**

under the same wheel power, represented as the product of wheel torque and speed, which maximizes the motor and transmission efficiencies. Although the motor efficiency (η_m) is determined only by the input torque and speed, the transmission efficiency (η_t) additionally varies with the driving gear. Therefore, the powertrain efficiency expressed as the product of the motor and transmission efficiencies ($\eta_m \eta_t$) is different for each driving gear, as shown in Figure 3. These efficiency maps can be converted equally into efficiency values according to the APS and vehicle speed, and an optimal shifting line can be determined by selecting a gear in a more efficient area when driven with each gear, as shown in Figure 4. Based on this shifting line, the optimal shifting pattern can be determined to maximize the economic performance of the EV.

With respect to dynamic performance, a gear shift should be performed to maximize the output torque according to the vehicle speed. Therefore, the driving torques (T_{drv}) of each speed gear were calculated for the APS values from 0% to 100%, and the gear-shifting speeds were determined from the cross-torque points, as shown in Figure 5. From the mentioned optimal shift pattern determination methods for economic and dynamic performances, they utilize only the static characteristics of efficiency and output torque to determine the gear-shifting pattern. Although many previous studies have used these methods, they are not the best under dynamic conditions such as vehicle acceleration. To obtain a more optimized shifting pattern for EVs, the static and dynamic characteristics should be considered together in the optimal shifting pattern process as follows.

When the vehicle is accelerating, the acceleration resistance torque on the wheel can be calculated as follows:

$$T_{acc} = J_{eq} \cdot \alpha_{whl} \tag{15}$$

where α_{whl} denotes the angular acceleration of the wheel. From the equivalent inertia of first- and second-gear sides mentioned in Eqs. (1) and (2), respectively, the equivalent inertia variation (J_{var}) caused by the gear shifting between the first and second gear drives can be derived by subtracting $J_{eq.2}$ from $J_{eq.1}$ as follows:

$$J_{var} = \left[J_m \left(r_1^2 - r_2^2 \right) + J_{c1} r_1^2 - J_{c2} r_2^2 + J_{p1} r_1^2 - J_{p2} r_2^2 + \frac{J_{p1} r_1^2}{r_2^2} - \frac{J_{p2} r_2^2}{r_1^2} \right] r_f^2 \tag{16}$$

When the gear ratios (r_1, r_2) are fixed, J_{var} is determined as a constant value. In addition, a large difference in gear ratios also increases the inertia variation, indicating that the equivalent inertia depending on the gear shift significantly affects vehicle performance. Therefore, the method proposed in this paper considers the motor and transmission efficiencies for the optimal gear-shifting pattern, as well as the inertia efficiency, which indicates the requested torque variation from the inertia effect by the gear shift as follows.

For economic performance, the shifting pattern optimization problem considering only the static characteristic can be formulated to maximize the powertrain efficiency ($\eta_m \eta_t$) according to the APS and vehicle speed (v) as follows:

$$\begin{aligned} &\underset{\mathbf{P}}{\text{maximize}}\, f_E(\mathbf{P}) = \eta_m \eta_t\,(\text{APS}, v) \\ &\text{where } \mathbf{P} = \left[v_{opt}^i, \cdots, v_{opt}^N \right], \quad i = 1, \cdots, N \end{aligned} \tag{17}$$

where $\mathbf{P}$ is the shifting speed set, v_{opt} is the optimal shifting speed, and superscript i is the total number of APS cases (0−100%). Here, $\mathbf{P}$ is for the up-shifting process, and the shifting speeds for the down-shifting process are determined by offsetting from the speed values of $\mathbf{P}$ [21]. The shifting pattern optimization that considers dynamic characteristics can be defined by including the acceleration resistance torque variation effect to Eq. (17).

The motor torque (T_m) by APS is expressed as follows:

$$T_m = T_{max}(\omega_m) \cdot \text{APS} \tag{18}$$

T_{max} is the variable value according to the motor speed (ω_m) and can be determined by the vehicle speed and driving gear as follows:

$$\omega_m = \frac{v}{R_t} \cdot r_i r_f \tag{19}$$

Therefore, T_m can be determined if APS and v are provided. Because of $r_1 > r_2$ in the gear ratio design, from Eqs. (1) and (2), $J_{eq.1}$ is always greater than $J_{eq.2}$. Hence, although driving with the first gear accelerated is more advantageous than driving with the second gear because a large gear ratio can significantly multiply the motor torque transmitted to the wheel, in contrast, it is disadvantageous in terms of inertia resistance. To compare the inertia effect with the motor and transmission efficiency, the inertia resistance torque can be converted into an expression in a unit of efficiency expression using the ratio of the resistance torque to the motor torque (T_m) as follows:

$$\eta_{in} = \frac{J_{var} \alpha_{whl}}{r_2 r_f T_m} \tag{20}$$

where η_{in} is the dynamic inertia efficiency, which is the difference in efficiency when shifting from the first-speed gear to the second. Since η_{in} is the relative value of the first gear when driving in the second gear, as expressed in Eq. (17), it is subtracted from $f_E(\mathbf{P})$ when only the first-speed gear is driven. Therefore, the objective function $f_E(\mathbf{P})$ can be revised by considering the inertia variation effect, as follows:

$$f_E(\mathbf{P}) = \begin{cases} \eta_m \eta_t\,(\text{APS}, v) - \eta_{in}\,(\alpha_{whl}) & \text{if } r_i = r_1 \\ \eta_m \eta_t\,(\text{APS}, v) & \text{if } r_i = r_2 \end{cases} \tag{21}$$

For the value of f_E, considering the dynamic inertia efficiency under acceleration conditions ($f_E = \eta_m \eta_t - \eta_{in}$) is necessarily lower than the value of considering only the static characteristics ($f_E = \eta_m \eta_t$) when driving with the first-speed gear, which means that the up-shifting is performed at a lower speed than considering only the static characteristics.

For dynamic performance, the shifting pattern optimization problem considering only the static characteristic can be formulated to maximize the driving torque (T_{drv}) according to the APS and vehicle speed (v) as follows:

$$\begin{aligned} &\underset{\mathbf{P}}{\text{maximize}}\, f_P(\mathbf{P}) = T_{drv}\,(\text{APS}, v) \\ &\text{where } \mathbf{P} = \left[v_{opt}^i, \cdots, v_{opt}^n \right], \quad i = 1, \cdots, N \end{aligned} \tag{22}$$

From this optimization problem, the optimal $\mathbf{P}$ can be easily obtained by combining the values of T_{drv} for each speed gear. Using the first gear during low-speed driving is generally advantageous in vehicle traction because a high motor torque is multiplied by a large gear ratio. However, an evaluation of dynamic performance should be conducted by considering the inertia variation effect because the acceleration that occurs under dynamic performance is greater than that in the economic performance evaluation. Therefore, when the acceleration is large, even at a low speed, the gear up-shift (first to second) may be advantageous because it can significantly reduce the inertia resistance torque.

Unlike maximizing the efficiency for economic performance, the analysis of dynamic performance, such as acceleration ability, should consider the time-variant behavior of the vehicle. Therefore, it is advisable to directly evaluate the acceleration ability through simulations using the developed EV model. To consider T_{drv} with the inertia effect for the optimal gear-shifting pattern, the optimization problem can be expressed using Eq. (11) as follows:

$$\begin{aligned} &\underset{\mathbf{P}}{\text{minimize}}\, f_P(\mathbf{P}) = t_a \\ &\text{subject to } \int_0^{t_a} a\, dt = v_{tar} \end{aligned} \tag{23}$$

where v_{tar} is the speed of the target vehicle. In several previous studies, v_{tar} was adopted at 100 km/h, and the acceleration time (t_a) was evaluated under WOT conditions. Therefore, Eq. (23) is acceptable for obtaining an optimal gear-shifting speed at an APS of 100%.

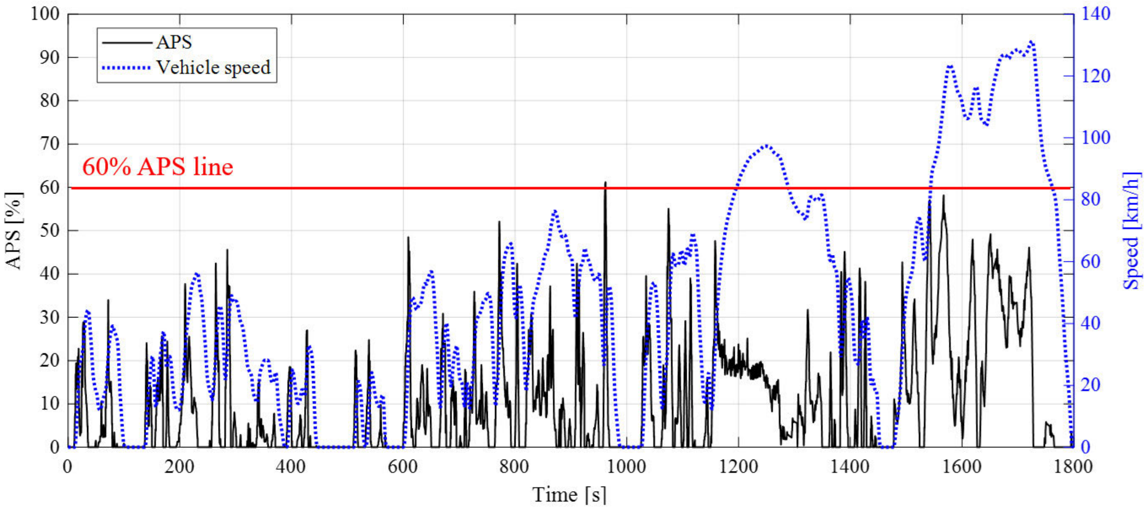


FIGURE 6. Example of APS values under the WLTP driving cycle.

Most APS values did not exceed 60% in the standard driving cycle, as shown in Figure 6. Therefore, to obtain an optimal shifting pattern that considers economic and dynamic performance, the optimal shifting speeds can be determined by focusing on the economic and dynamic performance at low and high APS values, respectively. Optimization problem that integrates Eqs. (21) and (23) can be formulated as follows:

$$\mathbf{P} = \begin{cases} \underset{\mathbf{P}}{\text{maximize}} \quad f_E(\mathbf{P}) & \text{if APS} \leq 60\% \\ \underset{\mathbf{P}}{\text{minimize}} \quad f_P(\mathbf{P}) & \text{if APS} = 100\% \end{cases} \tag{24}$$

Here, optimal shifting speeds between 60% and 100% APS were obtained using the interpolation method. Since $\mathbf{P} = \left[v^i_{opt}, \cdots, v^n_{opt}\right]$ must consist of ascending speeds, along with an increase in APS because of the drivability problem, it should satisfy the following constraint:

$$v^{i-1}_{opt} \leq v^i_{opt}, \quad i = N, \cdots, 2 \tag{25}$$

An example of optimal shifting patterns based on Eqs. (24) and (25) considering dynamic inertia efficiency, is shown in Figure 7. As the wheel acceleration (α_{whl}) increases, the optimal shifting lines gradually move toward the low-speed side. Since a high α_{whl} involves a large inertia resistance when driven by the first gear, the up-shifting is performed rapidly with increasing vehicle speed to reduce the inertia resistance even in areas where the powertrain efficiency ($\eta_m\eta_t$) of the second gear is lower than that of the first gear. In addition, the shifting speed of the WOT condition (100% APS) is constant regardless of α_{whl} because this speed already considers the inertia variation effect at full acceleration based on Eq. (23). Table 3 compares the results of applying the optimal shifting pattern considering dynamic inertia efficiency with those not considering it. These results demonstrate the importance of the inertia variation effect of gear-shifting in obtaining optimal shifting patterns for the energy efficiency (EFF) and acceleration time (t_a) for the economic and dynamic performances of EVs, respectively.

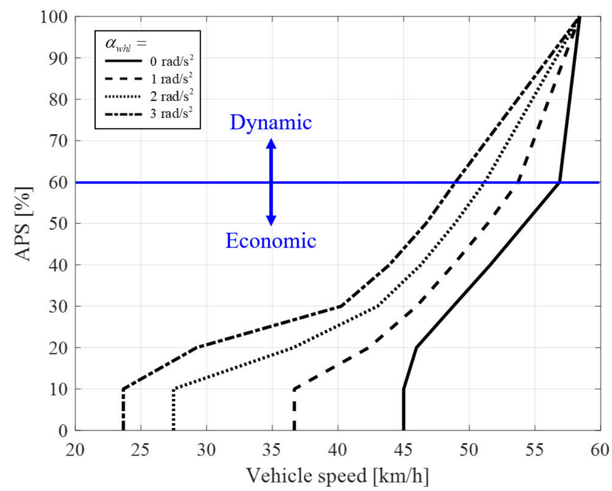


FIGURE 7. Example of optimal shifting patterns according to wheel acceleration ($r_1 = 3.321$, $r_2 = 1.681$).

TABLE 3. Comparison of results for economic and dynamic performances.

Dynamic inertia efficiency	Performance measure	
	EFF (km/kWh)	t_a (s)
Consideration	6.35	10.69
None	6.24	10.99
Improvement (%)	1.83	2.74

IV. OPTIMIZATION RESULTS OF TWO-SPEED TRANSMISSION

To maximize the economic and dynamic performances of EVs, it is appropriate to utilize multi-objective optimization methods that can address the trade-offs between performance

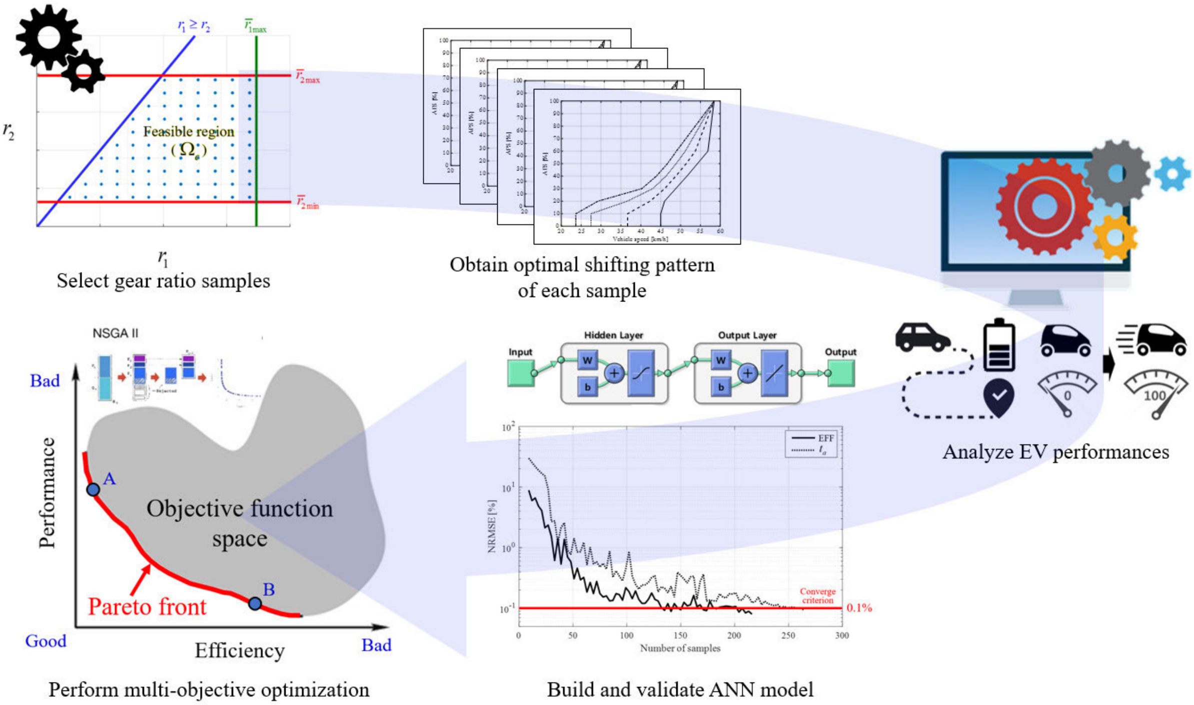


FIGURE 8. ANN-based multi-objective optimization process.

objectives. The critical design parameters for optimizing a two-speed transmission of an EV are the gear ratios of each speed and shifting pattern. In particular, since the optimal shifting patterns for each combination of gear ratios are different, they should depend on the gear ratios. Therefore, the multi-objective optimization problem is formulated by employing the objectives of EFF and t_a as follows:

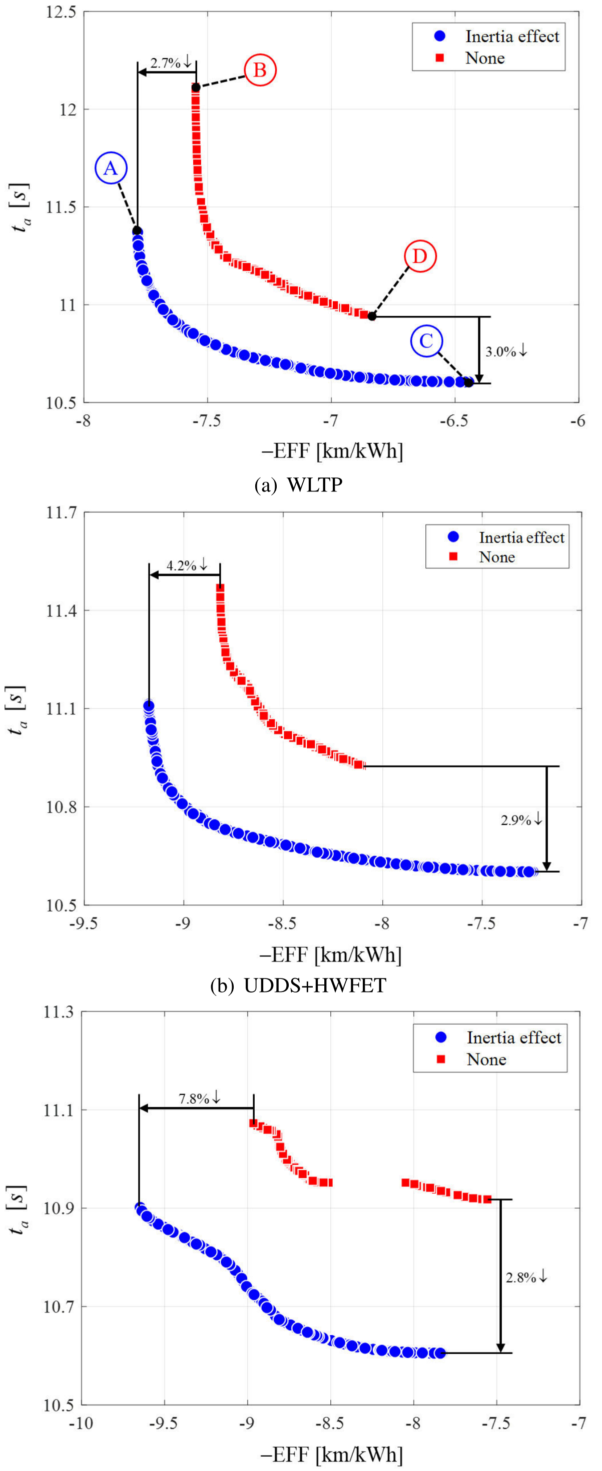
$$\begin{aligned} &\underset{\mathbf{r},\mathbf{P}}{\text{minimize}}\, \bar{f}(-\text{EFF}, t_a) \\ &\text{subject to } \mathbf{r} \in \Omega_c \end{aligned} \tag{26}$$

where $\mathbf{r} = [r_1, r_2]$ is the vector of gear ratios and Ω_c is the feasible region of gear ratios from the dynamic constraints. Here, the dynamic constraints are adopted with a maximum speed (150 km/h) and an ascendable gradient (40%), as determined by Eqs. (12) and (14), respectively. In addition, because a large step ratio (r_1/r_2) results in shifting difficulties [29], the step ratio was limited to three or less. In the objective function, EFF is expressed as a negative value (−EFF) because the optimization problem is formulated to minimize the objective function values, although EFF should be maximized for better economic performance.

The results of multi-objective optimization are displayed as the Pareto front, which is a set of optimal solutions. Because the multi-objective optimization algorithm should update many solutions simultaneously, performing this process requires significant computational effort [30]. Therefore, solving multi-objective optimization problems is more challenging compared to single-objective optimization problems.

In addition, to solve the multi-objective optimization problem in Eq. (26), this study employs a non-dominated sorting genetic algorithm (NSGA) [31], which has been used for various multi-objective optimization problems in the engineering field. Here, a genetic algorithm in the NSGA requires numerous calculations of objective functions compared to gradient-based algorithms. Therefore, an ANN-based multi-objective optimization method is used as an alternative to the excessive calculation problem [32]. The ANN algorithm trains the given sample results to derive the relationship between the input (design variable) and output (target) [33] and builds a predictive model which estimates the objective function values from the given design variable values of transmission without analyzing the EV model. Therefore, it can significantly decrease the calculation effort owing to the excessively iterative calculations in the multi-objective optimization process using the NSGA.

The overall optimization process is illustrated in Figure 8. First, the sample points are selected in a feasible region of the gear ratios, and the optimal shifting pattern of each sample is determined by Eq. (24). Next, the EV performances are analyzed using the gear ratio samples and optimal shifting patterns, and the ANN model is constructed using the analysis results of the samples. Here, the cross-validation method is utilized to validate the ANN model accuracy, and if the constructed ANN model does not satisfy an acceptable normalized root mean square error (NRMSE), the new sample points are added to the previous sample points and the ANN model is reconstructed. After the construction of the ANN model satisfying the criteria of NRMSE is complete,

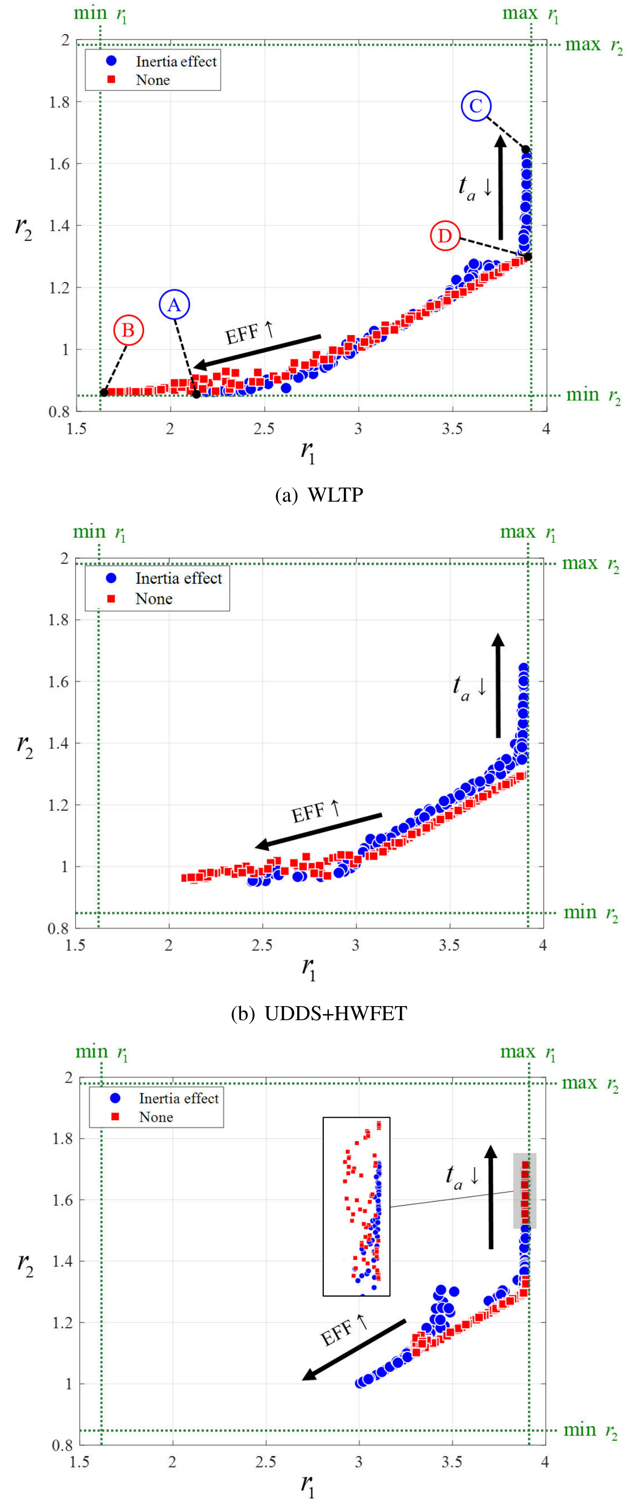


(a) WLTP

(b) UDDS+HWFET

(c) NEDC

FIGURE 9. Comparison of Pareto fronts for each cycle.



(a) WLTP

(b) UDDS+HWFET

(c) NEDC

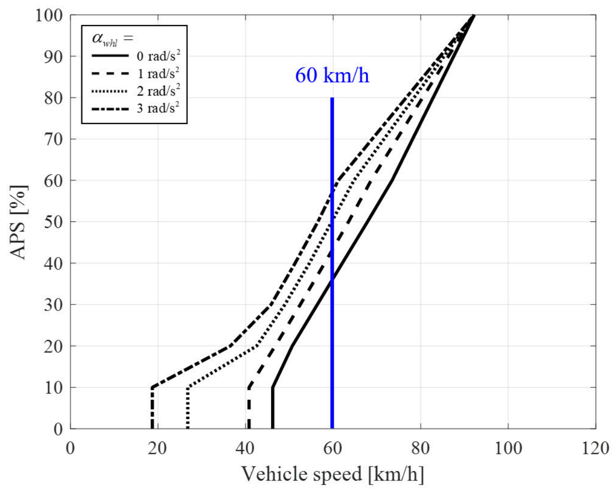
FIGURE 10. Comparison of the optimum gear ratios for each cycle.

a multi-objective optimization is finally performed using the NSGA and the ANN model to obtain a Pareto front, which means a set of optimal solutions.

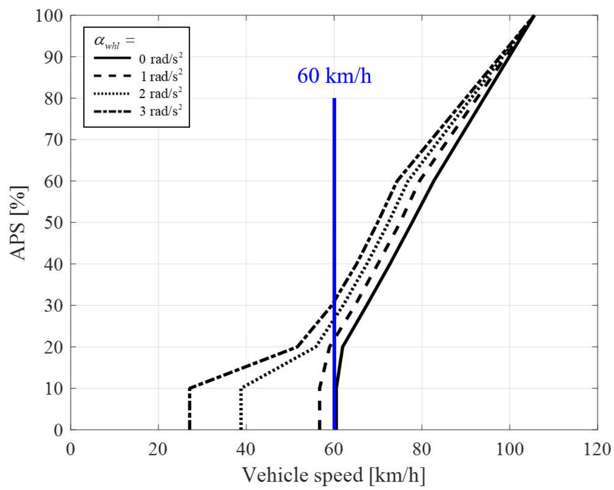
To confirm the inertia variation effect on the optimal gear-shifting pattern for economic and dynamic performance, multi-objective optimizations were conducted in two cases: i) considering the dynamic inertia efficiency and ii) not considering it. In addition, three cases (WLTP, UDDS+HWFET, and NEDC) were used for the driving cycles for economic performance evaluation to validate the effectiveness of shifting patterns considering dynamic inertia efficiency. The Pareto fronts of the two cases were compared from the optimization results for each driving cycle, as shown in Figure 9. These Pareto fronts depict the trade-off between economic and dynamic performances. For all driving cycles, the values of the optimum solutions show significant differences when the inertia variation effect is considered. Applying the optimal shifting pattern considering inertia variation substantially outperforms the energy efficiency (EFF) and acceleration time (t_a) compared to the case in which it does not. Therefore, these results demonstrate that the dynamic inertia efficiency should be reflected in the optimization of gear-shifting patterns.

Figure 10 illustrates the optimum gear ratios for each Pareto front, as shown in Figure 9. These results indicate the following. First, combining low and high gear ratios provides economic and dynamic performance advantages. A low gear ratio is generally beneficial for economic performance owing to its small equivalent inertia. However, the optimum gear ratios in Figures 10 (b) and (c) are not in the lowest gear ratio area. Therefore, while a low gear ratio ensures low equivalent inertia, it is more economically dominant in UDDS+HWFET and NEDC to improve the overall efficiency by changing the motor operating points, depending on the gear ratio and shifting pattern. For dynamic performance, a high gear ratio is generally helpful because it can significantly multiply the motor torque transferred to the wheels. However, the optimum gear ratios in Figure 10 are not in the highest gear ratio area. Since a high gear ratio exhibits high wheel torque and high acceleration resistance owing to the large equivalent inertia, considering only the wheel torque is not appropriate for the vehicle's acceleration ability.

Next, the distributions of the optimum gear ratios vary significantly depending on the optimal shifting pattern, considering or without considering the dynamic inertia efficiency. In particular, in Figures 10 (a) and (b), the optimum gear ratios derived by the optimal shifting pattern without considering the inertia effect are more distributed in the low gear ratio area than in the pattern considering the inertia effect, whereas the optimum gear ratios considering the effect are more distributed in the high gear ratio area than not considering the effect. This means that which shifting pattern is applied affects the EV performance and optimum gear ratios. For the WLTP case in Figure 10 (a), Table 4 compares the results of the best solutions for the economic and dynamic performances between the cases with and without the inertia effect. To confirm the effect of the optimal shifting patterns on the performance values when using different optimal shifting patterns that consider (Case 1) and do not consider (Case 2) the inertia effect, the performance values of each combination of gear ratios are evaluated. For economic and dynamic performances, when applying the Case 1 pattern, the EFF and t_a values of the gear ratios considering the inertia effect were superior to the values not considering the effect. However, when applying the Case 2 pattern, the EFF and t_a values indicated the opposite tendency.



(a) Solution A ($r_1 = 2.139$, $r_2 = 0.863$)



(b) Solution B ($r_1 = 1.649$,$r_2 = 0.863$)

FIGURE 11. Optimal shifting patterns for economic performance (A: inertia effect, B: none).

Figure 11 shows the optimal shifting patterns for the best solutions for EFF in Table 4. Solutions A and B have the same second gear ratio (0.863), whereas the first gear ratio of solution A (2.139) is greater than that of solution B (1.649). Due to the large step ratio of solution A, it is possible to change the motor operating points more than that of solution B by shifting the speed gear to improve the powertrain efficiency ($\eta_m \eta_t$). However, because the equivalent inertia of the first gear side of solution A is larger than that of solution B, it negatively affects the acceleration resistance of solution A, as expressed in Eq. (15). When comparing the optimal shifting patterns in Figure 11, the shifting speeds of solution A are more distributed on the left side (low speed) at 60 km/h than those of solution B. This means that the second-gear driving in solution A is more frequent than that in solution B. Since it reduces the

TABLE 4. Comparison of the best gear ratio solution results based on optimal shifting pattern in WLTP (Case 1: considering inertia effect, Case 2: not considering.)

Shifting pattern	Objective	Best solution (r_1/r_2)	Value	
			Case 1	Case 2
Inertia effect (blue)	EFF (km/kWh)	A: 2.139/0.863	7.78	7.51 (3.5%↓)
	t_a (s)	C: 3.894/1.636	10.61	10.94 (3.1%↑)
None (red)	EFF (km/kWh)	B: 1.649/0.863	7.67	7.55 (1.6%↓)
	t_a (s)	D: 3.894/1.298	10.67	10.91 (2.2%↑)

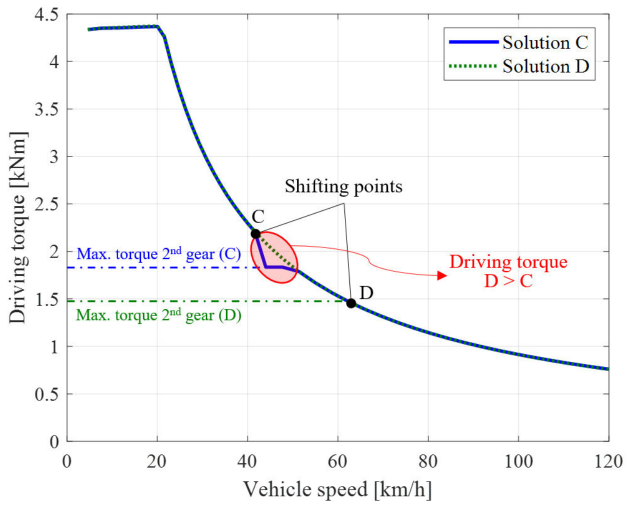


FIGURE 12. Comparison of driving torque for dynamic performance (C: inertia effect, D: none).

acceleration resistance by shifting the speed gear at lower speeds, solution A is superior to solution B in terms of EFF, despite the larger equivalent inertia of the first gear side.

Figure 12 shows the driving torque at WOT condition in the best solutions for t_a in Table 4. Solutions C and D have the same first-gear ratio (3.894), whereas the second-gear ratio of solution C (1.636) is greater than that of solution D (1.298). Since the equivalent inertia of the second gear side of solution C is larger than that of solution D, it has a negative effect on the acceleration ability of solution C. When comparing the optimal shifting speeds, solution C performs gear-shifting at a speed lower than solution D. In particular, the up-shifting of solution C is conducted before the driving torque of the first gear reaches the maximum driving torque of the second gear. Therefore, the total driving torque in the red-colored area is insufficient compared to that of solution D. However, although the T_{drv} of solution C is noticeably lower than that of solution D in the red-colored area, t_a of solution C is superior to that of solution D. For the acceleration ability, T_{drv} of solution C is a negative effect. In contrast, since the shifting speed of solution is significantly faster than that of solution D, the equivalent inertia of solution C is lower than that of solution D after gear shifting speed. It is advantageous for the acceleration ability and indicates that the equivalent inertia effect on the acceleration with a positive effect is greater than the negative effect of T_{drv} because t_a of solution C is faster than that of solution D. This demonstrates that the inertia effect on the acceleration ability is greater than that on the static driving torque. These results are particularly remarkable in designs with large gear and step ratios. In summary, the dynamic inertia efficiency, quantifying the equivalent inertia variation, should be considered in the design of the gear ratios and shifting patterns for the performance of EVs.

V. CONCLUSION

This paper proposes an effective optimization method for the multi-speed transmission of EVs considering the dynamic inertia efficiency for gear-shifting patterns. The equivalent inertia for each speed was analyzed from the power flow of each driving speed gear to confirm the equivalent inertia variation. An EV analysis model with variable motor and transmission efficiencies was constructed, and the quantitative performance criteria were determined to evaluate the economic and dynamic performances. From the EV analysis, the performance results based on the optimal shifting pattern, considering the inertia effect, were compared. These results demonstrate the importance of dynamic inertia efficiency, quantifying the inertia variation effect, by gear-shifting in obtaining optimal shifting patterns for the energy efficiency and acceleration time for economic and dynamic performances of EVs, respectively.

Due to the trade-off relationship between economic and dynamic performances, a multi-objective optimization problem, including the design variables such as gear ratios and shifting patterns and the objective functions of energy efficiency and acceleration time, was formulated. As an alternative to the excessive calculation burden needed for performing the multi-objective optimization using NSGA, the ANN-based multi-objective optimization method was utilized. In particular, to confirm the inertia variation effect on the optimal gear-shifting pattern, optimizations were performed by dividing the optimal shifting patterns considering the dynamic inertia efficiency and not considering it. In addition, various driving cycles (WLTP, UDDS+HWFET, and NEDC) were employed for economic performance evaluation to determine the effectiveness of shifting patterns considering equivalent inertia variation.

The optimization results demonstrate the importance of considering the dynamic inertia efficiency for the optimal shifting pattern. In each driving cycle, compared to the shifting pattern without the inertia variation effect, economic and dynamic performances were improved from 2.7% to 7.8% and 2.8% to 3.0%, respectively. In addition, the gear ratio values of the optimum solutions were obtained differently when the dynamic inertia efficiency was considered and not. Applying the optimal shifting pattern considering dynamic inertia efficiency substantially outperforms the energy efficiency (EFF) and acceleration time (t_a) compared with the case in which it does not. Therefore, these results demonstrate that the equivalent inertia variation effect should be reflected in the optimization of gear-shifting patterns. In conclusion, considering the dynamic inertia efficiency from gear ratios and shifting can achieve superior performance in the transmission design of EVs. In future work, we will demonstrate the effectiveness of this study by validating before and after optimization results through the experimental results. In addition, because the optimization results for each driving cycle are different, presenting the best solution considering the real-driving conditions is limited in this study. Therefore, we will study the method to represent the best optimal solution under various driving conditions and conduct the experiment on the presented solutions on a real-world system with variable parameters.

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(Kijong Park and Sang-Kil Lim contributed equally to this work.)

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