

Downshifting Strategy Using Gear Skipping During Normal Braking in Electric Vehicles Equipped with AMT

Ryong Kim¹, Kyong Su Ri¹, Myong Ho Kwon¹, Jong Chol Kil^{1,*}

Abstract

In this paper, the regenerative braking method using optimal downshifting is investigated to increase the recovering energy during normal braking in an electric vehicle equipped with Automatic Manual Transmission (AMT). First, the modeling of the electric vehicle powertrain and consideration of brake force distribution was carried out. Based on these, the method to select general downshifting points was mentioned in the electric vehicle. Second, the effect of power interruption on the selection of the gear shifting points was considered, due to the power interruption during the downshift in the AMT. The necessity of gear skipping was considered because of the presence of energy that was not recovered during the gear shifting process. A reasonable downshifting strategy was established under normal braking condition. Then, using Isight and Matlab co-simulation, the optimal downshifting points were selected and the optimal shift gear order was determined to maximize the braking energy recovery in the given initial braking velocity and gears using shift gear order matrix. Finally, the simulation of the running process was carried out using Matlab/Simulink simulation interface, and a comparative analysis of the recovered energy was performed for the case of a sequential downshifting strategy and downshifting strategy with gear skipping in the normal braking condition. The simulation result shows that the proposed downshifting strategy increased 10.9% for the fixed initial braking speed and braking strength and 5.93% for the Urban Dynamometer Driving Schedule (UDDS) operating cycle condition compared to the sequential downshifting strategy. Through the simulation, it shows that downshifting strategy proposed in this paper can effectively recover the energy during braking process.

Keywords: AMT, gear skipping, regenerative braking, power interruption, electric vehicle

INTRODUCTION

Nowadays, rapidly appearance of electric vehicle plays a positive role to prevent air pollution and protect environment. But travelling distance of the electric vehicle (EV) is relatively short, so it is necessary to manage energy effectively in EV.

*Author for Correspondence

Jong Chol Kil
E-mail: JC.KIL@star-co.net.kp

¹Assistant Professor, Department of Mechanical Engineering, KimChaek University of Technology, Pyongyang, DPR Korea

Received Date: March 26, 2025

Accepted Date: June 04, 2025

Published Date: June 14, 2025

Citation: Ryong Kim, Kyong Su Ri, Myong Ho Kwon, Jong Chol Kil. Downshifting Strategy Using Gear Skipping During Normal Braking in Electric Vehicles Equipped with AMT. Journal of Automobile Engineering and Applications. 2025; 12(2): 8–19p.

As the law of conservation of energy states that energy cannot be created nor destroyed, but only change from one form to another. During conventional braking, kinetic energy of vehicle is converted into heat energy, this heat energy is wasted and dissipated into atmosphere. Regenerative braking makes restoration of kinetic energy possible [1].

EVs and hybrid electric vehicles (HEVs) are using regenerative braking method to save energy and increase lives, then several methods to increase braking energy recovery rate was proposed.

Braking system structure and mechanical design method to recover regenerative braking energy effectively was discussed by Bhandari et al. and Lakshmi et al. [2, 3]. Improving method of regenerative braking system (RBS) was discussed, focusing on decreasing weight and increasing efficiency of RBS by Patil et al. [4]. Pusztaï et al. [5] used regenerative braking method based on torque optimization model. In literature by Mamur and Candan [6], detailed simulation method of motor using regenerative braking was discussed.

EVs mostly rely on driving method by gearbox which has fixed gear ratio. But in heavy EVs, this method cannot provide sufficient performance of vehicle. Hence, Automatic Manual Transmission (AMT) is used in heavy EVs and this influences the performance of RBS. In EVs equipped with AMT, using downshifting during regenerative braking, allows the motor to work in high-efficiency range.

Braking of electric vehicles was classified as emergency braking and normal braking. Downshifting strategy was made to improve safety of vehicles in emergency braking and increase the energy recovery rate in normal braking. Sequential downshifting strategy was used and the number of shift times was limited, considering the effect of frequent gear-shifting on energy recovery [7].

Sequential downshifting strategy was designed to recover braking energy in hybrid electric vehicles. Downshifting point was chosen as shifting velocity, recovering the maximum energy in the velocity region between two adjacent gears, but the effect of frequent shifting on energy recovery was not considered [8].

Due to the presence of power interruption during gear-shifting, the amount of recovered energy depends on the shift times, braking strength, and initial braking speed. Therefore, sequential downshifting strategy cannot maximize the recovered energy. Also, limiting the number of shift times cannot sufficiently recover the braking energy in the low gears. To recover braking energy effectively, factors which are affected to downshifting must be analyzed.

The aim of this paper is to recover braking energy effectively using downshifting strategy that can recover maximum braking energy at any braking strength and initial braking speed during normal braking. To practice this aim, analysis about the effect of power interruption during gear shifting process is carried out.

This paper is organized as follows: First, electric powertrain modeling is carried out and the braking force distribution principle of the composite brake system is given. Also, the effect of power interruption in the downshifting process is analyzed to design the downshifting strategy, and based on this, a method for developing a reasonable downshifting strategy during normal braking is discussed. Then, analysis of the results is carried out. Finally, conclusions are drawn.

MODELING OF ELECTRIC POWERTRAIN

The general structure of an electric vehicle is shown in Figure 1. There are two subsystems in Figure 1, one is electric propulsion and the other is energy storage system. Electric propulsion subsystem comprises of the electric motor, inverter and the controller while the energy storage subsystem includes the battery, Battery Management System (BMS) and charger circuitry [9].

Motor Model

The general motor model is constructed as follows:

$$\begin{cases} U_a = L_a \frac{dI_a}{dt} + R_a I_a + E_b \\ E_b = K_e \frac{d\theta_m}{dt} \\ J_m \frac{d^2\theta_m}{dt^2} = T_m - T_f - T_L \\ T_m = K_T I_a \end{cases} \quad (1)$$

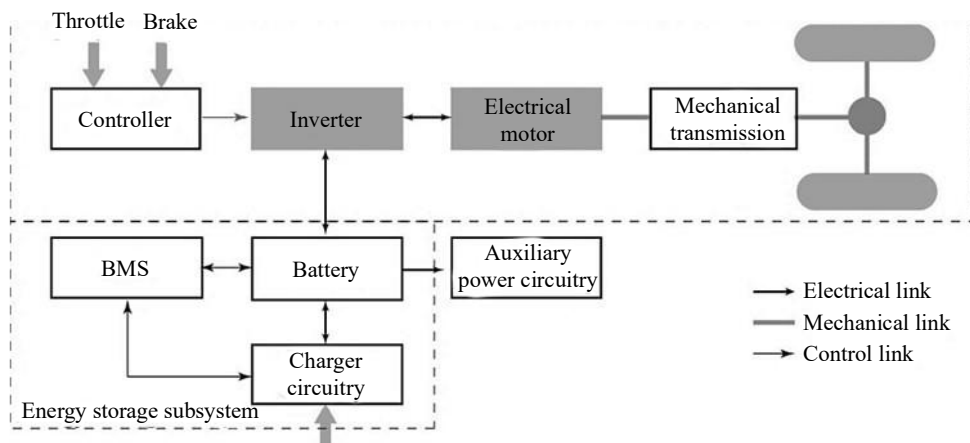


Figure 1. General structure of electric vehicles.

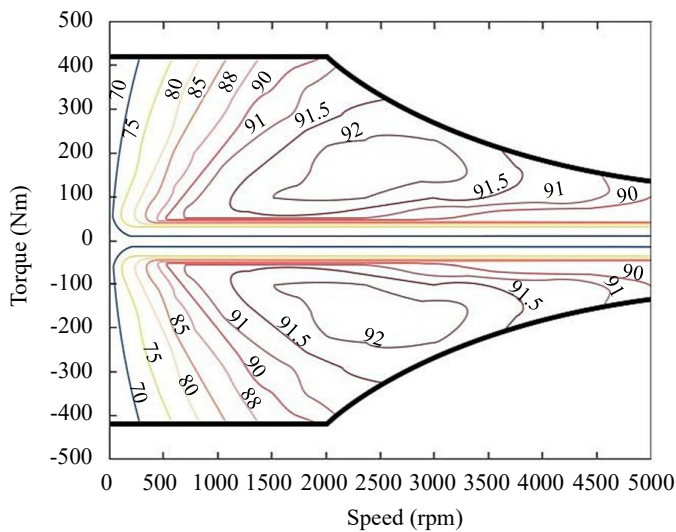


Figure 2. Motor efficiency map.

Where, U_a , L_a , I_a and R_a are motor armature voltage, inductance, current, and resistance, respectively, E_b is the back electromotive force (EMF), K_e and K_T are the back EMF constant and torque constant, respectively, θ_m is the motor rotation angle, J_m is the moment of inertia of the motor, T_m , T_f and T_L are electromagnetic torque, friction torque, and load torque of the motor, respectively [10].

The motor can work in two modes: drive mode and power generation mode.

In both cases, the output power of the motor can be expressed as

$$P_m = \frac{T_m \cdot n_m \cdot \eta_m^{-\text{sgn}(T_m)}}{9550} \quad (2)$$

Where, P_m is the power of the motor, n_m is speed of the motor, respectively, and η_m is the motor efficiency [11].

Figure 2 shows the efficiency curve of the motor.

Also, $\text{sgn}(\cdot)$ is a sign function that can be defined as follows:

$$\text{sgn}(T_m) = \begin{cases} 1 & T_m \geq 0 \\ -1 & T_m < 0 \end{cases} \quad (3)$$

The maximum braking torque of the motor is

$$T_{m,\max} = \begin{cases} \frac{9550P_0}{n_b} & n_m \leq n_b \\ \frac{9550P_0}{n_m} & n_m > n_b \end{cases} \quad (4)$$

Where, P_0 is motor rated power (kW) and n_b is motor base speed (rpm).

Battery Model

The characteristics and state of the battery in regenerative braking of electric vehicles also affect the energy recovery.

The power charged to the battery during braking can be expressed as follows:

$$P_b = \begin{cases} P_m \cdot \eta_b & SOC \leq 0.8 \\ 0 & 0.8 < SOC < 1 \end{cases} \quad (5)$$

Where, P_b is the power charged to the battery (kW) and η_b is the energy conversion efficiency.

The overcharging negatively affects the battery performance and service life.

Therefore, it is generally recommended that the state of charge (SOC) does not exceed 80%.

Vehicle Model

The forces acting in the braking process of EVs include the force generated by the regenerative braking of the motor, the force generated by the frictional brake, the air resistance force of the vehicle, the rolling resistance force of the vehicle, and the inclined resistant force. Therefore, the vehicle dynamics equation can be expressed as

$$\delta ma = - \left(F_{fb} + F_{mb} + \frac{1}{2} C_d \rho A v^2 + \beta G \right) \quad (6)$$

Where, a is the acceleration of the vehicle (m/s^2), m is the mass of the vehicle (kg), G is the weight of the vehicle (N), β is the terrain coefficient, ρ is the density of the air (kg/m^3), C_d is the drag coefficient, A is the front area of the vehicle (m^2), v is the velocity of the vehicle (m/s), F_{fb} is the frictional braking force (N), δ is the mass factor and F_{mb} is the regenerative braking force (N).

Then, the regenerative braking force can be calculated as follows:

$$F_{mb} = \frac{T_m i_t i_f \eta_t \eta_f}{r} \quad (7)$$

Where, η_t is the efficiency of the transmission, η_f is the efficiency of the final drive, i_t is the gear ratio of the transmission, i_f is the gear ratio of the final drive, r is the tire rolling radius.

BRAKING FORCE DISTRIBUTION OF COMPOSITE BRAKING SYSTEM

Electric vehicles have two braking systems from their inherent characteristics: The regenerative braking system and the friction braking system. In this paper, the rear driving vehicle is used, so the regenerative braking force is activated on the rear axle.

Since, the regenerative braking force varies according to the driving conditions, the proper distribution of the regenerative braking force and the friction braking force is important. It can increase the vehicle safety and braking performance. The braking force distribution strategy of the composite braking system includes series braking strategy, parallel braking strategy, etc. [9].

In this paper, a downshifting strategy, which is mainly focused on recovering more braking energy, is used. In braking force distribution, priority is given to regenerative braking system, while the friction braking system is used to compensate for the rest of braking force [7].

At that time, braking torque of the motor is as follows:

$$T_m = \begin{cases} T_{req}, T_{m,max} > T_{req} \\ T_{m,max}, T_{m,max} \leq T_{req} \end{cases} \quad (8)$$

Where, T_{req} is the required braking torque (Nm).

The required braking torque of the vehicle can be expressed as

$$T_{req} = mgz \quad (9)$$

Where, z is braking strength.

At low motor speeds, the electromotive force that is generated is very low leading to charging of cells at low voltages and high currents. At low motor speeds, because the charging and discharging cycles are very short, it can affect the life of the battery. Hence, the minimum speed at which regenerative braking can be achieved in each gear is chosen [9].

EFFECT OF POWER INTERRUPTION IN THE SHIFT PROCESS ON THE DESIGN OF DOWNSHIFTING STRATEGY

The following relationship is established between the motor speed and the vehicle speed:

$$n_m = \frac{i_t i_f}{0.377r} v_a \quad (10)$$

Where, v_a is the vehicle speed (km/h).

In the case of $T_{m,max} > T_{req}$, regenerative power of the motor can be calculated as follows from Eq. (2), (8)–(10):

$$P_m = \frac{mgv_a}{0.377r\eta_t\eta_f} \eta_m \quad (11)$$

Also, in the case of $T_{m,max} \leq T_{req}$, regenerative power of the motor can be calculated as follows from Eq. (2), (4), (8)–(10):

$$P_m = \begin{cases} \frac{P_0\eta_m}{\eta_b} \cdot \frac{i_t i_f v_a}{0.377r}, n_m < n_b \\ P_0\eta_m, n_m \geq n_b \end{cases} \quad (12)$$

As shown in Figure 2, the efficiency of the motor at high rotational speed is higher than that at low rotational speed.

From Eq. (10)–(12), it can be seen that the higher the gear ratio, the higher the speed of the motor and the higher the regenerative power.

Hence, to increase the energy recovery, downshifting should be performed during braking.

Figure 3 shows the regenerative power curve of motor at different gears. As shown in Figure 3, it can be seen that at the given gear, the regenerative power increases initially and then decreases with the efficiency characteristics of the motor. In the high-speed range of the motor, decrease of the regenerative power is due to the rapid increase in motor losses with increasing speed.

If there is no gear-shifting transient process in the vehicle during normal braking, the shifting point will be the intersection point between the two adjacent gears. If there is no intersection, the minimum speed of the high gear will be the shifting point.

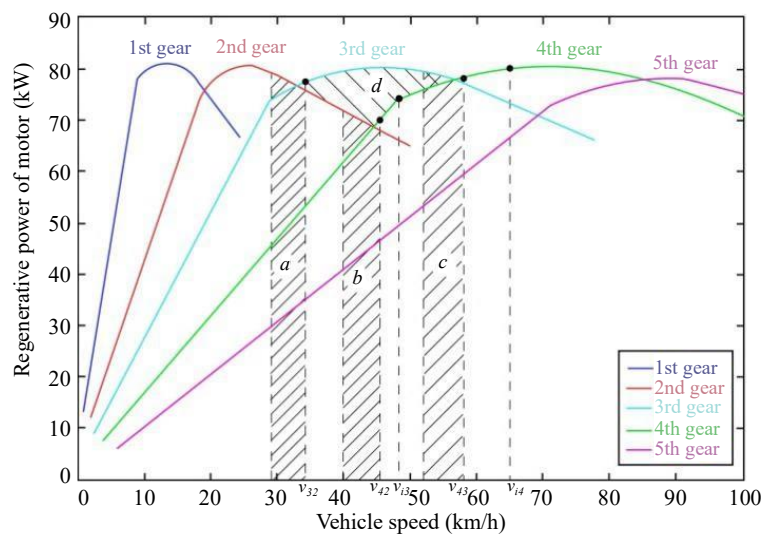


Figure 3. Regenerative power curve at different gears.

However, as discussed above, there exists power interruption during gear-shifting (e.g., gear shift between 4th gear and 3rd gear). Therefore, there exists the region (c) that does not recover the braking energy. This region (c) depends on the braking strength, the time of the gear-shifting, and how the shift point is chosen.

To recover the braking energy effectively, the amount of the energy that is not recovered in region (c) should be minimized. Hence, the intersection between the two adjacent gears cannot be considered as the reasonable shifting point, and the power interruption in the shifting process will affect the selection of the shifting point.

Effect of Power Interruption in the Shifting Process on the Determination of Shift Gear Order

In the designing of the downshifting strategy, the number of shift times must be considered. Frequent shift affects the life time of the gear shifting system and also negatively affects the performance of the composite braking system. Hence, the number of shift times should be reduced as much as possible.

Sequential downshifting was used for regenerative braking [7, 8]. In Figure 3, when the vehicle is running at 4th gear and it uses sequential downshifting, gear-shifting is performed at speeds v_{43} , v_{32} . In that case, due to the power interruption, braking energy in regions (b) and (c) cannot be recovered. However, in the case of gear skipping, gear shift will be performed at the shifting point between 4th gear and 2nd gear, and the braking energy cannot be recovered in region (a) and region (d).

If the energy not recovered in region (a) and region (c) is equal or greater than in region (b) and region (d), gear skipping will be more effective in terms of both reduction in the number of shift times and braking energy recovery. The quantitative relationship of such energy is also related to the initial state of the vehicle braking.

Depending on the driver's driving intention and driving conditions, the gear corresponding to one speed is not constant. Hence, the existence range of each gear in the whole speed range is relatively large and there may be several gears according to one vehicle velocity.

If the energy not recovered in regions (a) and (c) is less than the energy not recovered in regions (b) and (d), the initial state of vehicle braking does not affect the shift gear order since the vehicle initial braking speed in Figure 3 is constant and there is no change in the quantitative relationship of the energy when the vehicle is running at 4th gear.

However, if the initial braking speed is v_{i3} and vehicle is running at 4th gear, the additional unrecoverable region (d) will be significantly reduced, resulting in the change in the quantitative relationship of energy. The quantitative relationship of such energy will have the direct impact on the determination of the shift gear order, and there will be the reasonable speed for energy recovery to perform gear skipping. Thus, to recover more braking energy, one must use gear skipping during the downshifting.

REASONABLE DOWNSHIFTING STRATEGY UNDER NORMAL BRAKING CONDITION

Considering the effect of power interruption during gear-shifting, an optimal downshifting strategy during normal braking can be designed. As mentioned in Figure 3, the power interruption during gear-shifting affects the selection of the shifting point and the determination of the shift gear order. During gear-shifting, the motor has speed and torque due to its inertia. Hence, it can recover energy. However, the amount of this energy is very small, and hence, for simplicity of problem, it is assumed that there is no energy recovered during gear shift process [8].

The braking energy charged to the battery at i^{th} gear per unit time is:

$$dE_b = \frac{T_m n_m}{9550} \eta_m \eta_b dt = \frac{3.6 T_m n_m}{9550 a_i} \eta_m \eta_b dv_a \quad (13)$$

Where, a_i is the acceleration of the vehicle at i^{th} gear.⁵

Consider the downshift from the i^{th} gear to the j^{th} gear.

The regenerative braking energy in the speed range of the j^{th} gear can be expressed as

$$E_b = \int_{v_{ij}}^{v_{j,\max}} \frac{3.6 T_m n_m}{9550 a_i} \eta_m \eta_b dv_a + \int_{v_{j,\min}}^{v_{ij}} \frac{3.6 T_m n_m}{9550 a_j} \eta_m \eta_b dv_a \quad (14)$$

Where, v_{ij} is the speed of shifting point between i^{th} gear and the j^{th} gear, v'_{ij} is the vehicle speed after the gear-shifting, $v_{j,\min}$, $v_{j,\max}$ is minimum and maximum speed of j^{th} gear, respectively, and a_j is the acceleration of the vehicle at j^{th} gear.

v'_{ij} can be expressed as follows:

$$v'_{ij} = v_{ij} + \int_0^{\tau_{ij}} a_{ij} dt \quad (15)$$

Where, a_{ij} is the acceleration of the vehicle during gear-shifting, and τ_{ij} is the shifting time (s) between i^{th} gear and j^{th} gear.

Using an Isight and Matlab co-simulation, we can obtain the speed of shifting point between two gears where Eq. (14) is maximized. The downshifting schedule between the shift gears can be obtained by connecting the shifting points at different braking strengths.

Figure 4 shows the downshifting schedule obtained using the co-simulation. In Figure 4, (a) is the sequential downshifting schedule, and (b) is the downshifting schedule with the gear skipping.

When vehicle is running, use of gear skipping is related on detailed running condition. In other words, shift gear order should be determined in the running process.

In this paper, the shift gear order matrix is constructed for the selection of the downshifting schedule constructed. According to the obtained shift gear order, it can be determined whether or not gear skipping is performed. The shift gear order matrix can be written as

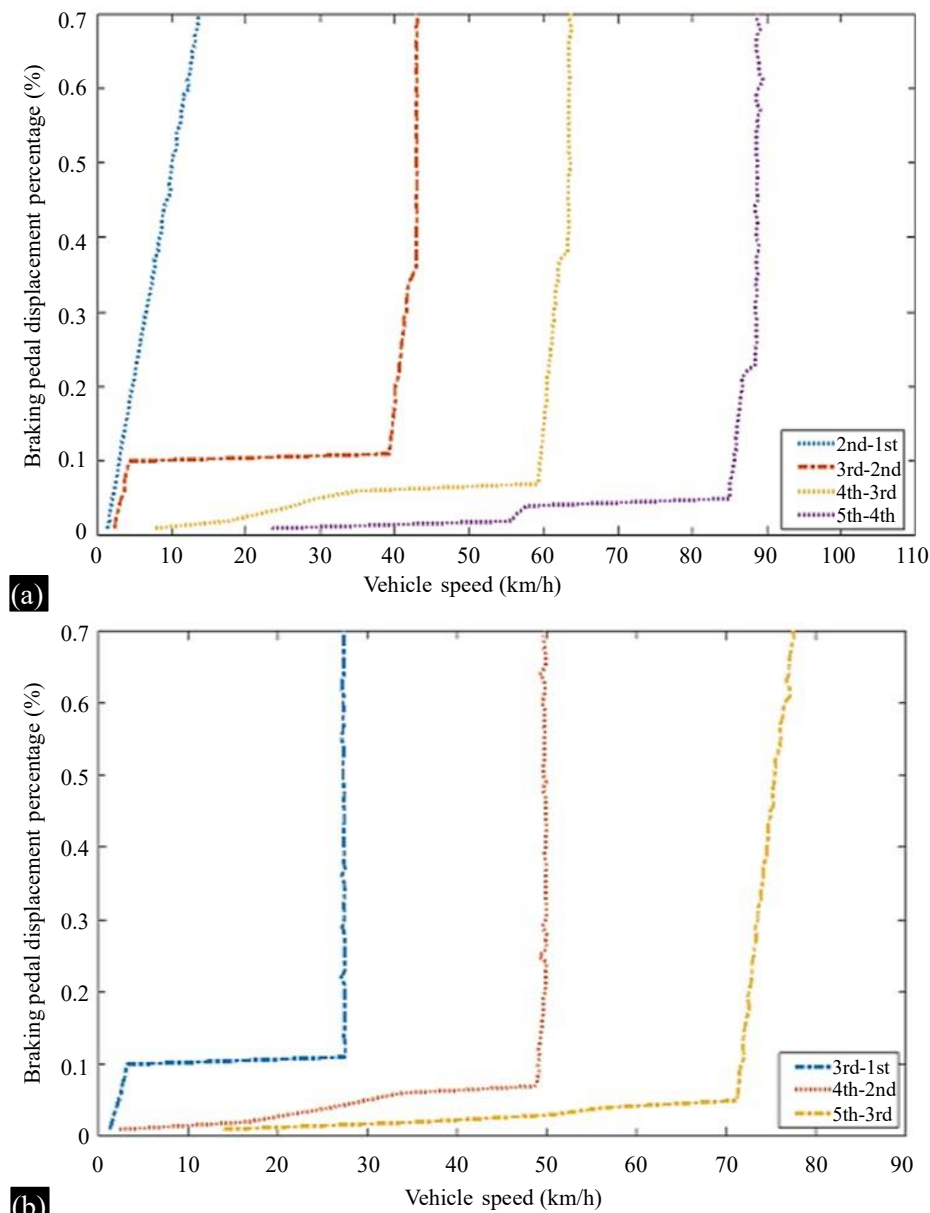


Figure 4. (a) and (b) downshifting schedule.

$$\begin{matrix}
 & 5 & 4 & 3 \\
 & 5 & 4 & 2 \\
 & 5 & 3 & 2 \\
 & 5 & 3 & 1 \\
 Shift_seq = & 5 & 2 & 1 \\
 & 5 & 4 & 0 \\
 & 5 & 3 & 0 \\
 & \vdots & \vdots & \vdots \\
 & 2 & 1 & 0
 \end{matrix} \tag{16}$$

In the matrix, zero means the neutral gear. Given the initial braking speed and shifting gear, the partial matrix for each gear can be obtained. Through the simulation, it can be determined that the shift gear order in which the braking energy recovered among each shift gear order of the partial matrix is maximized. The obtained shift gear order with varying initial braking speed and braking pedal displacement percentage is shown in Figure 5.

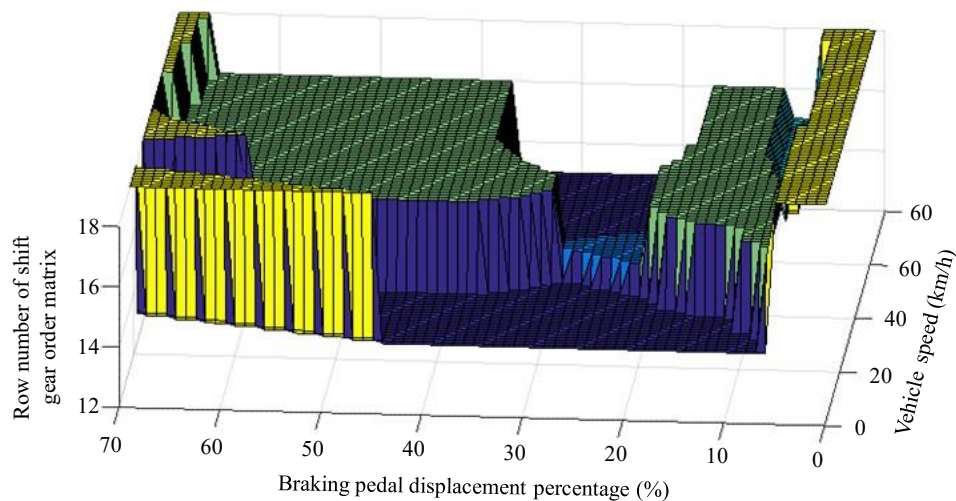


Figure 5. Shift gear order with initial braking speed (initial gear-4th gear).

Table 1. Design parameters of the vehicle.

Parameter	Description/Value
Vehicle	Mass 10000 kg, Terrain coefficient 0.01, Front area 6.9 m^2 Drag coefficient 0.536, Rolling radius 0.43 m, density of air 1.293 kg/m^3 Final drive gear ratio 4.875 Final drive efficiency 0.98 Mass coefficient (1.58 1.2 1.12 1.06 1.03)
Transmission	Gear ratio (6.02 3.3.2 2.07 1.4 1) Efficiency 0.96
Motor	Rated power 90 kw Peak torque 430 Nm Peak rational speed 5000 rpm
Battery	Capacity 200Ah Rated voltage 354V

As shown in Figure 5, depending on the braking strength and the initial braking speed of the vehicle, the optimal shift gear orders are not constant. Likewise, for the other gears, optimal shift gear orders can be obtained depending on the initial braking speed and braking strength. Therefore, next shifting gear and gear-shifting point can be determined using the data of the optimal shift gear orders according to the initial braking speed, braking strength and initial gear number.

SIMULATION RESULTS

To verify the effect of the proposed downshifting strategy, the simulation analysis using Matlab/Simulink simulation interface was carried out. The design parameters of the vehicle used in the simulation are shown in Table 1.

Figure 6 shows the simulation results in the case of the braking strength of 0.2, initial speed of 70 km/h. At this time, initial gear is 5th. As can be seen from Table 2, when the downshifting strategy proposed in this paper is adopted, the recovered braking energy is increased by 10.9% compared to the sequential downshifting strategy. Also, the number of shift times was reduced compared to the sequential downshifting strategy.

Therefore, it can be seen that the proposed downshifting strategy can not only increase the recovered braking energy but also reduce the negative effect on brake system and brake performance by reducing the number of shift times.

Figure 7 shows the simulation results in the case of the UDDS cycling condition. As can be seen from Table 2, under UDDS cycling condition, the proposed downshifting strategy increased 5.93% of the recovered braking energy compared to the sequential downshifting strategy. The simulation results showed that the downshifting strategy using gear skipping can effectively recover the braking energy.

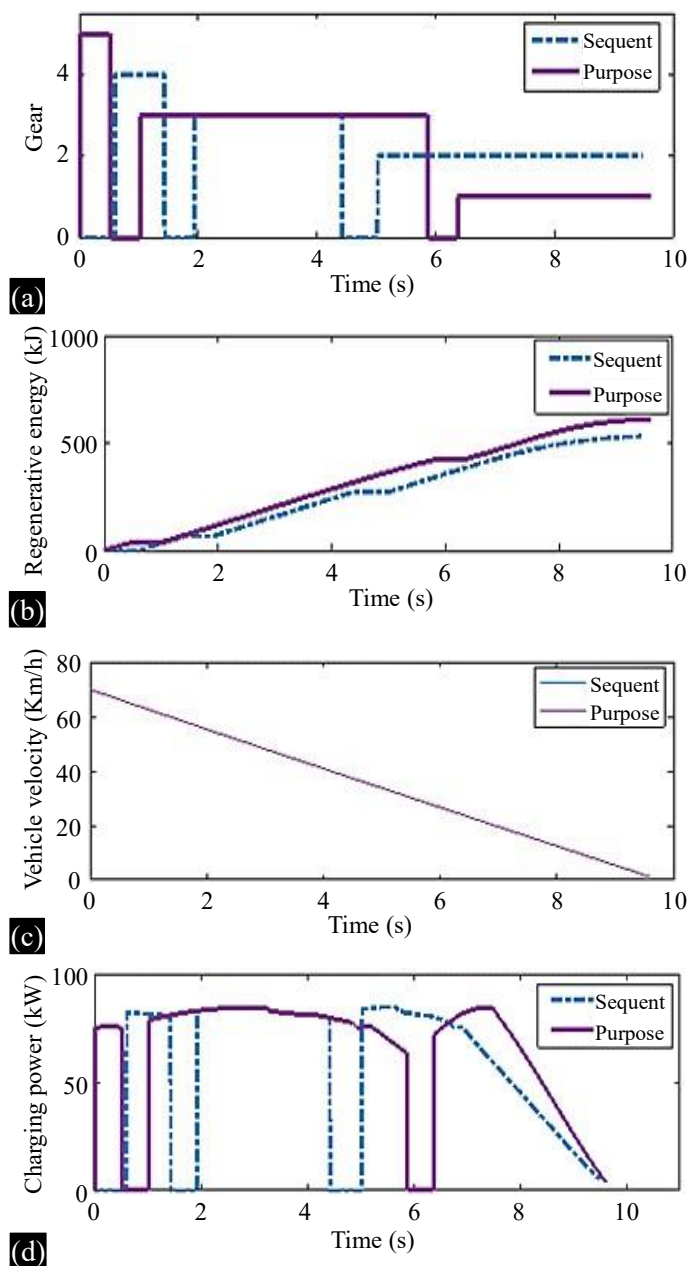
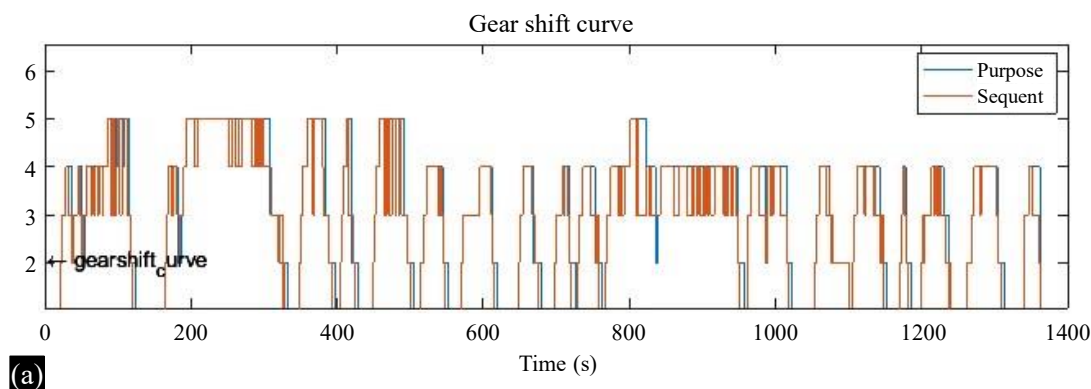


Figure 6. Simulation results under normal braking condition: (a) transmission gear curve; (b) regenerative energy curve (kJ); (c) vehicle velocity curve; (d) charging power curve (kW).



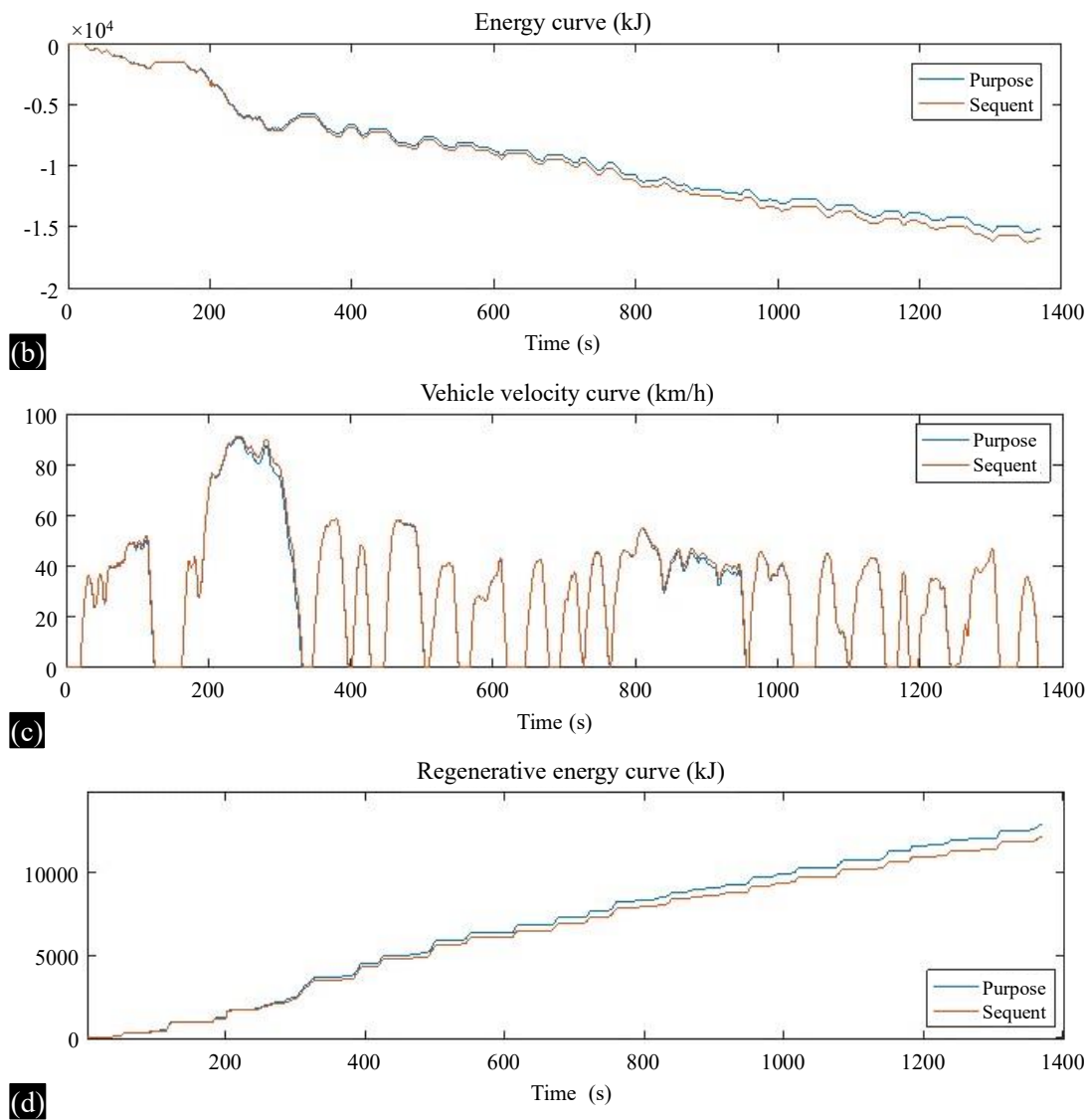


Figure 7. Simulation results of composite braking system under UDDS cycling condition; (a) transmission gear curve; (b) consumption energy curve (kJ); (c) vehicle velocity curve; (d) regenerative energy curve (kJ).

Table 2. Simulation result.

	$z=0.2, v=70 \text{ km/h}$	UDDS
Increasing rate of energy (%)	10.9	5.93
Reduction of shifting times	1	7

CONCLUSION

This paper proposed the downshifting strategy using gear skipping to increase the braking energy recovered under normal braking condition in EVs equipped with AMT. Also, using the Isight and Matlab co-simulation, the reasonable downshifting strategy using gear skipping was proposed and the shift gear order was determined based on initial velocity and gear number in braking condition.

Meanwhile, simulation study was conducted using the Matlab/Simulink. The proposed braking downshifting strategy was simulated under UDDS cycling condition. Also, in the case of fixed initial braking speed and fixed braking strength, it was simulated and compared with simulation results for the sequential downshifting strategy. The recovered braking energy is increased by 10.9% in the case of

fixed initial braking speed and braking strength and 5.93% in the case of UDDS cycling condition, respectively, compared to the sequential downshifting strategy. Also, the number of shift times was reduced. Therefore, downshifting strategy using gear skipping proposed in this paper, can effectively recover braking energy under normal braking condition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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