Journal of Network Intelligence ©2019 ISSN 2414-8105 (Online)
Taiwan Ubiquitous Information Volume **4**, Number **3**, August **2019**

The Study of Dynamic Programming with Fuzzy Logic Energy Design and Simulation of Gear Shift for Electric Vehicles

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Received March 2019, Revision May 2019

Abstract. *An electric vehicle equipped with three-gear automatic transmission is studied. The motor is matched according to the given vehicle parameters, the driving and power efficiency and external characteristics of the motor are obtained, and a load characteristic diagram of the motor is created based on the accelerator pedal opening degree, motor speed, and the motor driving characteristics. According to the relevant automobile theory, the relationship among the acceleration under different gears, the accelerator pedal opening degree, the vehicle speed is determined, and a dynamic gear-shifting strategy is formulated based on the motor load characteristic diagram. Finally, a simulation platform is used to build a corresponding simulation model for the dynamic acceleration and deceleration shifting and the road adaptability of the shifting based on cyclic conditions. The results of dynamic acceleration and deceleration shifting show that the shifting control strategy designed can meet the dynamic power requirements of electric vehicles. The results of road adaptability of shifting based on cyclic conditions show that the shifting control strategy designed can improve the work efficiency of the motor. Taken together, the gear-shifting strategy designed can meet the requirements of road conditions and can be used as the basis for economic optimization.*

Keywords: electric vehicles; automatic transmission; gear-shifting strategy; simulation; design.

1. **Introduction.** Electric vehicles usually use the motor to directly drive because the motor has zero-speed start, step less speed change, wide speed range, and continuous torque output. However, electric vehicles that do not have a transmission will have disadvantages in terms of starting, high-speed cruising, and ramp start [1].For electric commercial vehicles that require high torque, the number of transmissions can be increased to reduce the peak torque demand of the motor, reduce the cost of the drive system, and achieve better power and economy.

Zhu et al. [2] proposed a gear-shifting planning algorithm for pure electric vehicles to demonstrate how to optimize the shifting point. The up shift and downshift lines were generated based on the motor efficiency diagram, and the simulation model of the pure electric vehicle was established. The simulation results show that the gear-shifting strategy can improve the working area of the motor as well as the dynamic performance and economy efficiency of the vehicle. Liu et al. [3] analyzed the advantages and disadvantages of the existing methods of analyzing automatic transmission vehicle gear shifting, proposed an optimal gear-shifting strategy based on fuzzy neural network, studied the structure and algorithm of the Takagi-Sugeno model, established the corresponding membership function and fuzzy logic rules, and modified them with an artificial neural network training mechanism based on experimental samples. The simulation results show that the shift scheduling method based on the Takagi-Sugeno model fuzzy neural network is feasible. Jiang et al. [4] used the dynamic programming algorithm to find the optimal driving position of the vehicle under ECE cyclic working conditions, modified the static economic gear-shifting strategy accordingly, established the electric vehicle simulation model under UDDC cyclic working conditions, and simulated the gear shifting before and after the modification was carried out. The results show that the improved gear-shifting strategy can effectively reduce the energy consumption of electric vehicles. In order to improve dynamic performance, Zhao [5] considered the influence of vehicle running load on the optimal gear position for parallel hybrid vehicles and proposed the energy-saving gear-shifting strategy, dynamic gear-shifting strategy, and comprehensive gear-shifting strategy with pedal, vehicle speed, and load factor as the control parameters. The results show that the proposed gear-shifting strategies are accurate and effective, the power performance of the vehicle is improved, and the energy consumption is reduced. Yang et al. [6] designed the gear-shifting strategy for the automatic transmission of plug-in hybrid electric vehicles (PHEVs), devised the torque distribution strategy between the engine and the motor, and tested the gear-shifting and control strategies with the established simulation model. The simulation results show that the gear-shifting and control strategies can ensure that the engine and motor can be in the optimal working range and improve the fuel economy of PHEVs in urban cyclic working conditions.

Zhao et al. [7] proposed a comprehensive gear-shifting strategy based on the dynamics and economy of the automatic transmission pure electric commercial vehicle during the shifting time. This strategy introduced load detection to improve work adaptability and utilized some control parameters to identify working conditions, such as brake pedal signal and accelerator pedal opening degree and its rate of change. Han et al. [8] proposed a gear-shifting strategy for pure electric vehicle dual clutch transmission (DCT) based on coordinated control of power. In order to verify the effectiveness of this gear-shifting strategy, some simulations were carried out. The results show that the gear-shifting strategy can improve the vehicle's dynamic performance. Yu et al. [9] proposed a gear-shifting strategy based on a dynamic programming algorithm for hybrid buses and presented the algorithm to solve the problem. Based on the typical urban cyclic working conditions in China, the optimal shifting point was obtained through the proposed gear-shifting strategy. Through comparison with the traditional two-parameter gear-shifting strategy and the optimal fuel economy gear-shifting strategy, it was proved that the best shifting point can significantly improve the fuel economy of the hybrid bus. Guo et al. [10] described an on-line gear-shifting optimization strategy; this strategy can improve the energy efficiency of the electric vehicle through double-speed automatic transmission. Hybrid cars cannot work at the optimal fuel economy point during the entire drive; Shen et al. [11] proposed a hybrid vehicle gear-shifting optimization method and the corresponding solution algorithm based on dynamic programming (DP) for this problem. The DP method was used to obtain the optimal shifting point and extract the gear-shifting patterns. Compared with the traditional two-parameter gear-shifting strategy in the simulation and real vehicle test, the extracted gear-shifting pattern has been proved to significantly improve the fuel economy of the hybrid vehicle.

To realize the automatic and rapid gear-shifting of the automatic transmission (AMT), Liu et al. [12] set the optimal dynamic gear-shifting strategy based on the optimization of the acceleration time and the economic gear-shifting strategy based on the optimal working efficiency of the driving motor. For the problem of the dynamic performance of the vehicle declining along with the change in vehicle quality, Liu et al. [13] built the corresponding simulation model and conducted the simulation test on the basis of the three dynamic parameters (speed, throttle opening, and acceleration) with additional quality control parameters. Gao et al. [14] established a pure electric bus power system model and verified the model by a real vehicle test, where the lowest energy consumption was the optimization goal under five different typical driving conditions, and the dynamic programming method was used to obtain the optimal gear-shifting strategy. Zhang et al. [15] studied personal cars and established a 12-degree-of-freedom vehicle ride dynamics model in order to analyze the simulation of human body vibration response at different positions under different vehicle speeds by getting the dynamic equation from the D'Alembert principle and building a human-vehicle-road simulation model in Simulink. Jensen et al. [16] proposed a hybrid vehicle parameter optimization method based on multi-cycle working conditions with the minimum vehicle fuel consumption as the optimization target and the power system parameters and control strategy parameters as optimized variables to establish the corresponding optimization simulation model. The simulation model optimizes the hybrid vehicle with single-cycle and multi-cycle working conditions. The simulation results show that the optimization based on multi-cycle can further improve the fuel economy of the vehicle. Based on a pure electric vehicle and its power and economic design requirements, Cui et al.

[17] completed the design and selection of the main component parameters of the power system through theoretical calculations and used CRUISE to build a vehicle model and conduct the power and economy simulation. Yang et al. [18] analyzed the optimal power gear-shifting strategy of pure electric vehicles by establishing numerical models of pure electric vehicle battery systems and motor systems. Then they developed a dynamic 3-parameter gear-shifting strategy and a 4-parameter gear-shifting strategy in which the maximum discharge power of the battery is greater or less than the maximum input power of the motor based on the characteristic that the maximum discharge power of the battery decreases as the battery SOC decreases.

Ding et al. 19] used the fuzzy reasoning method to identify the driver's intentions during a drive to address the problem of frequent gear-shifting and studied the shifting performance of the dual clutch automatic transmission under the traditional shifting control strategy. Based on the traditional shifting control strategy and driving intention identification of dual clutch automatic transmission, the fuzzy shifting control strategy of dual clutch automatic transmission was proposed, and the simulation model of fuzzy shifting control strategy of dual clutch automatic transmission based on MATLAB/Simulink was established. Compared with the simulation results of the dual clutch automatic transmission's shifting performance with the traditional shifting control strategy, the effectiveness of the fuzzy shifting control strategy for the dual clutch automatic transmission based on driving intention recognition was verified. The research results show that the shifting control strategy can effectively reduce the number of shifts of the vehicle, eliminate the frequent shifting phenomenon during the drive, and improve the comfort of the driver and the safety of driving.

This paper is aimed at three-gear automatic transmission, according to the longitudinal dynamics of automobile, the relationship among the acceleration under different gears, the accelerator pedal opening degree, the vehicle speed is determined, and a dynamic gear-shifting strategy is formulated based on the motor load characteristic diagram, the simulation model of shift schedule is established in Simulink to verify the reliability of shift schedule.

2. Gean-Shifting Strategy design.

2.1. Basic structure of pure electric vehicle. Compared with the structure of traditional fuel vehicles, the structure of pure electric vehicles is relatively simple, but the power systems of the two are quite different. The fuel vehicle is driven by the internal combustion engine. After the combustion process of mixture of fuel and air, the power generated from engine is transmitted to the flywheel and clutch and then to the drive train until vehicle is driven forward. The power system of a pure electric vehicle mainly consists of the electrical system and the mechanical transmission system. The controller of the power system can issue corresponding control commands to control the power converter according to the signals input by brake pedal and accelerator pedal. The function of the power converter is to adjust the power flow between the motor and the power supply, control the speed and torque of the drive motor in real time, and then the power output from the motor passes through the transmission transmission to drive the wheels according to the driver's request. The basic structure of the pure electric vehicle is shown in Fig. 1.

2.2. Research Basis. Urban commercial vehicles have always been indispensable means of transportation for urban development and normal operation.They can be divided into urban logistics trucks, city buses and city-specific vehicles according to different uses.Due to the increasingly serious environmental protection problems in the city and the rise of new energy vehicles in recent years, the commercial vehicles driven by traditional internal combustion engine are replaced by vehicles in hybrid or pure electric mode gradually . Therefore, this paper uses an 8.5m long pure electric urban logistics ruck equipped with a three-gear automatic transmission as the research object. The basic parameters of the vehicle are shown in Table 1.

2.3. Map and External Characteristics of the Drive Motor. The parameters of the drive motor are selected to be rated power 48 kW, peak power 85 kW, and peak torque 600 N_m. The maximum speed is 3000 r/min. The driving and power generation efficiency and external characteristics of the driving motor are shown in Fig. 2 and Fig. 3, respectively. The horizontal axis in Fig. 2 represents the work range of the motor speed, and the vertical axis represents the work range of the driving torque of the motor (indicated by a positive number). The black curve is the driving efficiency curve of the motor, the data label represents the driving efficiency value (in%) of the motor at the current speed, and the blue line represents the external characteristic curve of the motor. The motor speed and torque do not exceed this curve range because when the motor is on, the torque decreases as the rotational speed increases,

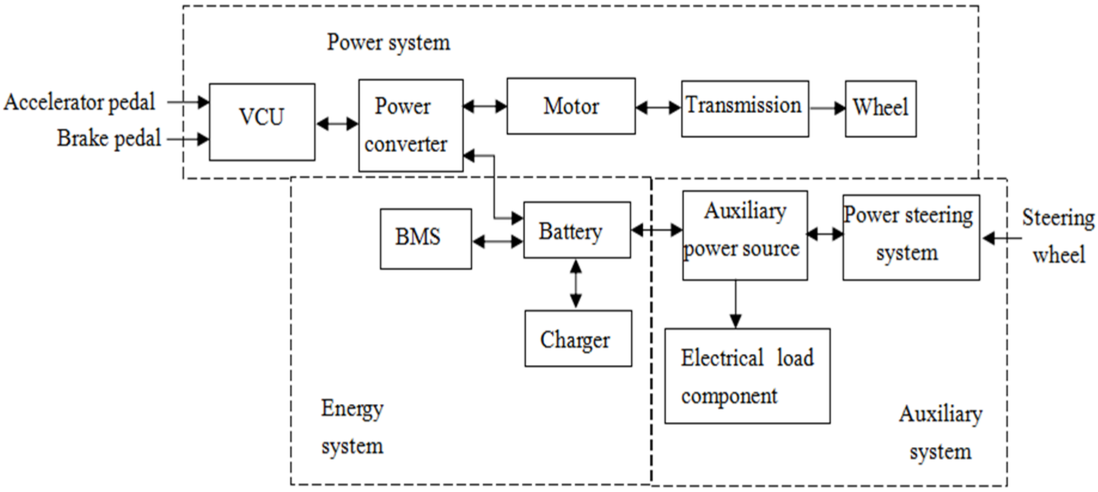

FIGURE 1. Basic structure of pure electric vehicle

Parameter	Value
Tire radius r (mm)	478
Maximum total mass m (kg)	13000
Final driver ratio i_0	6.14
Transmission ratio i_g	i_{g1}=3, i_{g2}=1.5, i_{g3}=1
Windward area A (m^2)	6
Drag coefficient Cd	0.65
Rolling resistance coefficient f	0.0085
Transmission efficiency η_t (%)	0.95
Correction coefficient of rotating mass δ	1.05

TABLE 1. Basic parameters of vehicle

so the external characteristic curve is in a downward trend. Same as Fig. 2, the horizontal axis in Fig. 3 represents the work range of the motor speed, the black curve is the driving efficiency curve of the motor, the data label represents the driving efficiency value (in%) of the motor at the current speed, and the blue line represents the external characteristic curve of the motor, which is the critical line of the motor speed torque, but the rotor is reversed when the motor is in the state of power generation. Thus, the vertical axis represents the work range of the driving torque of the motor (indicated by a negative number), and the external characteristic curve is increasing.

2.4. **Load Characteristic Design.** Like a fuel car, the electric vehicle also uses the vehicle controller to sense the accelerator pedal opening for torque output, but the drive motor can output torque from speed zero. However, the power source output torque, t_m , can also be determined by the accelerator pedal opening degree, α , and the driving motor speed, n_m . Also, in order to prevent excessive sensitivity, the accelerator pedal can reserve a free stroke, α_Δ . When the pedal opening degree is greater than α_Δ , the output torque should satisfy the sum of the resistance during travel, t_{res} (assuming the road grade is 0). The above can be represented by Equation (1).

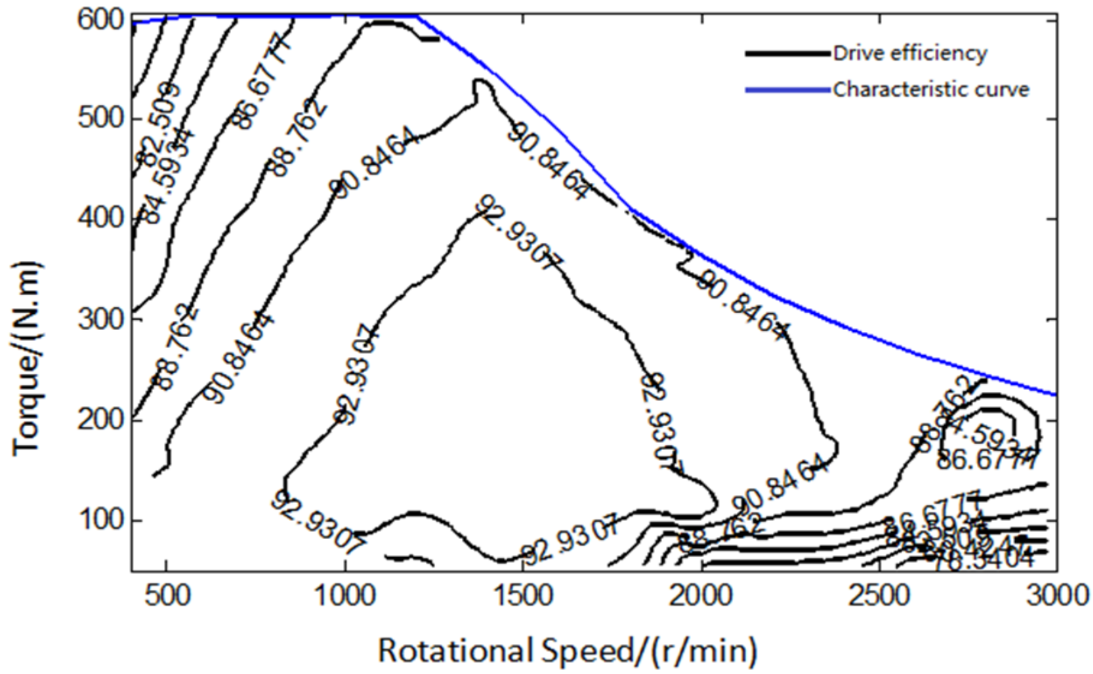

FIGURE 2. Driving characteristics of the drive motor

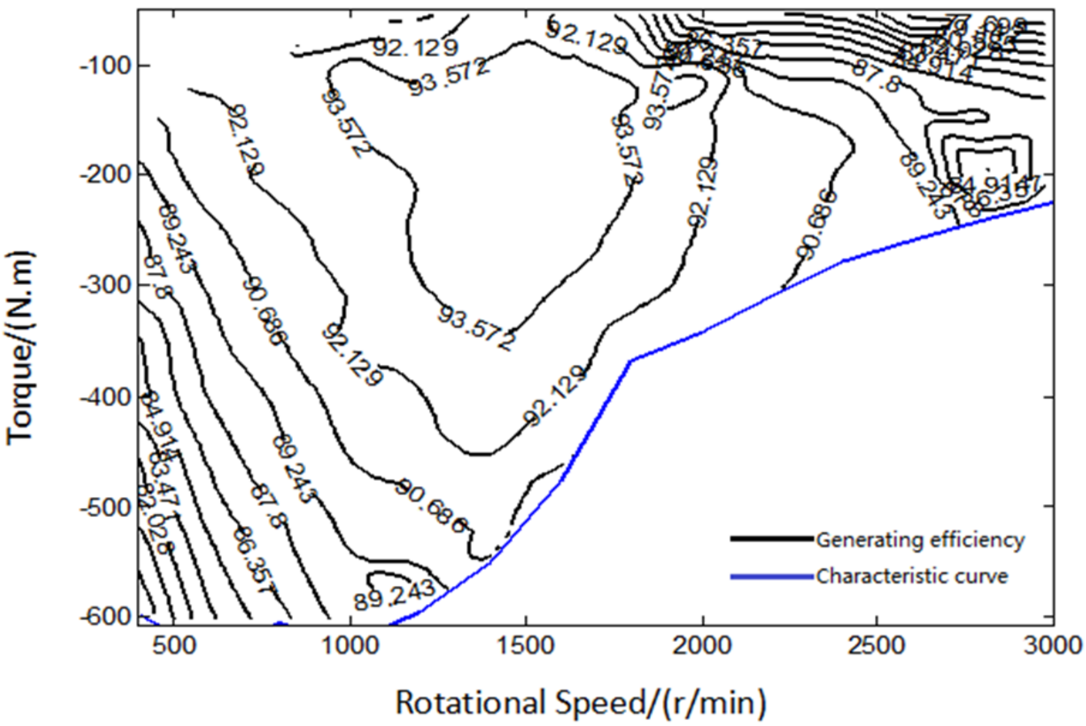

FIGURE 3. Drive motor power-generation characteristics

$$\begin{cases} t_m = f(\alpha, n_m) \\ t_m = f(\alpha, n_m) = 0, \alpha \leq \alpha_\Delta \\ t_m = f(\alpha, n_m) \geq t_{res}, \alpha \triangleright \alpha_\Delta \end{cases} \tag{1}$$

The load characteristic diagram of the motor can be determined by Equation (1) combined with the characteristic data of the motor in Fig. 2. As shown in Fig. 4, the x-axis represents the motor speed,

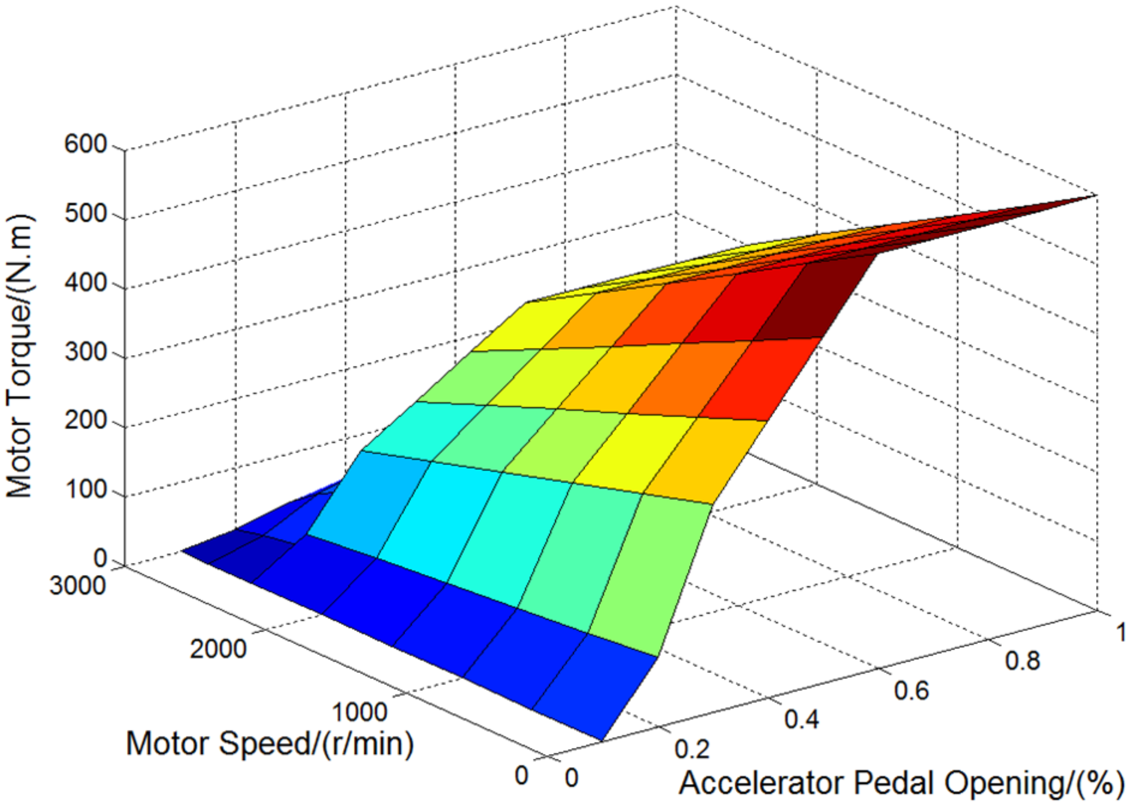

FIGURE 4. Motor load characteristics

the y-axis represents the accelerator opening degree, and the z-axis represents the output torque of the motor. Motor speed and accelerator pedal opening degree determine the output torque of the motor. When the motor speed is at 0–1500 r/min and the accelerator pedal opening is at 0.6–1

2.5. **Gear-Shifting Strategy Design.** The accelerator pedal on an electric car is essentially a sensor that transmits the current driver's driving intention—the desired target speed and the time it takes to get the target speed which also called the acceleration. These two parameters could reflect in the rate of change of opening of pedal and opening of pedal respectively. At present, the commonly used gear-shifting strategy is based on two-parameter shifting, that is, the shifting timing is determined according to the current accelerator pedal opening degree and the current vehicle speed. The gear-shifting strategies are divided into dynamic shifting and economic shifting according to the goal. In this paper, the gear-shifting strategy is designed with the aim of power. The dynamic gear-shifting strategy is to determine the switching timing for different gears in order to achieve the minimum acceleration time. According to the theory of the automobile [20], there is an inherent mathematical relationship between the motor speed and the vehicle speed, as seen in Equation (2). The resistance during the runtime of the vehicle can be simplified to Equation (3). Combined with Equation (1), and the relationship between acceleration, accelerator opening, and vehicle speed with different gear positions can be expressed as Equation (4).

$$u = 0.377 \frac{n_m r}{i_0 i_g} \tag{2}$$

$$t_{res} = mgf \cos\beta + \frac{C_D A}{21.15} u^2 + mg \sin\beta \tag{3}$$

$$\delta m \frac{du}{dt} = \left(\frac{f(\alpha, u) i_g i_0 \eta_t}{r} - t_{res} \right) \tag{4}$$

In Equations (2)–(4), u is the speed of the vehicle, β is the road slope angle, and g is the acceleration constant of gravity.

Combined with Equation (4) and the relevant data in the motor load characteristics of Fig. (4), the graphical method and the MATLAB tool are used to draw the acceleration performance curve of the

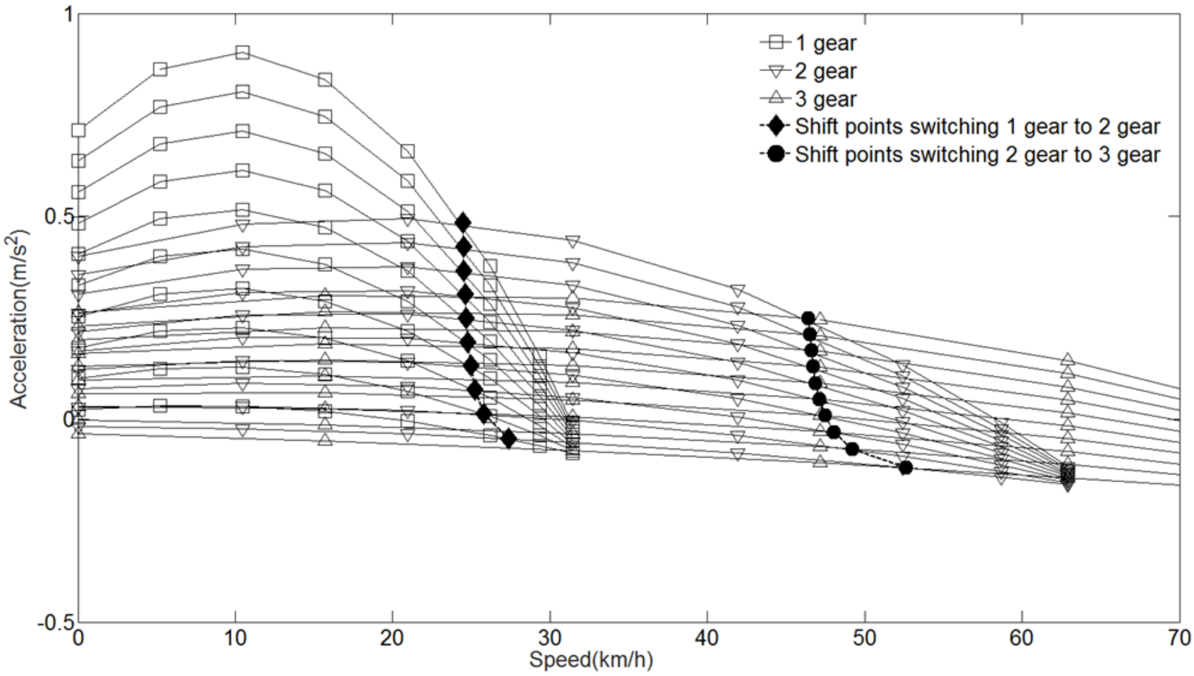

FIGURE 5. Acceleration capacity diagram at different gears

vehicle under different acceleration pedal opening degrees on different gear positions, as shown in Fig. 5. Each curve in the figure represents the vehicle acceleration under the current accelerator pedal opening. The curves are divided into three groups, and each group contains 10 curves. Each curve from left to right corresponds to 1st, 2nd, and 3rd gears. Under each gear position, each curve corresponds to the accelerator pedal from 0.1 to 1 from bottom to top with a tolerance of 0.1. A set of shifting points from 1st to 2nd gear can be obtained by connecting the intersection of the first set of curves and the second set of curves; a set of shifting points from 2nd to 3rd gear can be obtained by connecting the intersection of the 2nd set of curves and the 3rd set of curves.

Based on the results in Fig. 5, it is converted into the upshift strategy determined by the accelerator pedal opening degree and the current vehicle speed, and a reasonable downshift speed difference is created, so the gear-shifting strategy of the vehicle can be obtained. The vehicle dynamic gear-shifting strategy is shown in Fig. 6. The points on each curve in the figure indicate the vehicle shift timing (i.e., the speed point at which to shift) at different accelerator pedal opening degrees and different vehicle speeds, where the first two curves represent shifting from 1st gear to 2nd gear and shifting from 2nd gear to 1st gear at the vehicle speed of 20–30 km/h; the latter two curves represent shifting from 2nd gear to 3rd gear and shifting from 3rd gear to 2nd gear at the speed of 45–55 km/h. It can also be found that when the accelerator opening at the shifting point on each curve is in the range of 100–20%, the gear-shifting speed points are relatively close; when the accelerator pedal opening degree is in the range of 20–10%, the gear-shifting speed points between 1st and 2nd gear have a range of 2 km/h, and the gear-shifting speed points between 2nd and 3rd gear have a range of 3 km/h.

3. **Simulation Research.**

3.1. **Dynamic Simulation test.** After the completion of the shifting schedule, the shift control strategy needs to be transplanted into the vehicle model for verification.The simulation model of electric vehicle dynamic established is shown in Fig.7. The model is a simple simulation module for the vehicle dynamics. In this model, "Drive-pedal" is the module of analog output of acceleration and braking signal, "HCU" is the module of calculating vehicle's power , "calc-th" is the module of calculating gear ratio , "shift-logic" is the shift logic module, and "transmission" is the module of calculating output of transmission torque, "Out-model" module can output the required power parameters; the shifting control strategy model established as shown in Fig. 8, this figure is the shift logic diagram drawn by state-flow in Simulink environment . The "gear-state" monitors current gear status in simulation, the "selection-state" is the expression of the shifting condition and shifting process. The up-shift is performed, when the vehicle speed

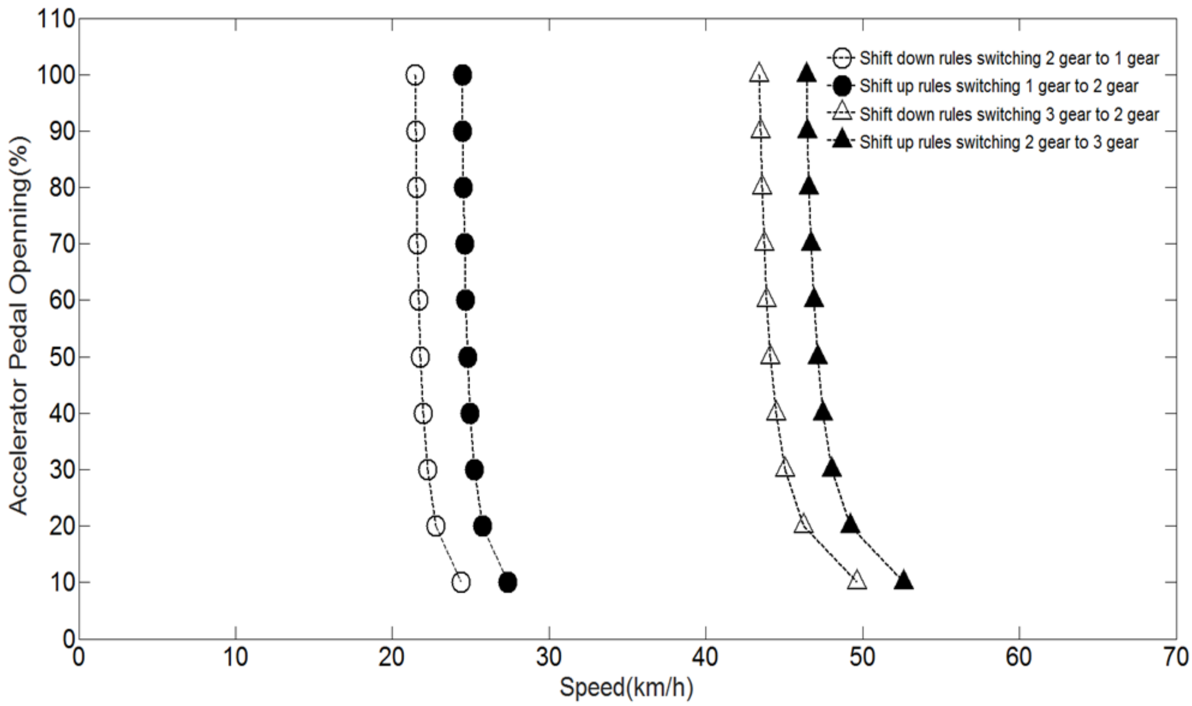

FIGURE 6. Dynamic gear-shifting strategy

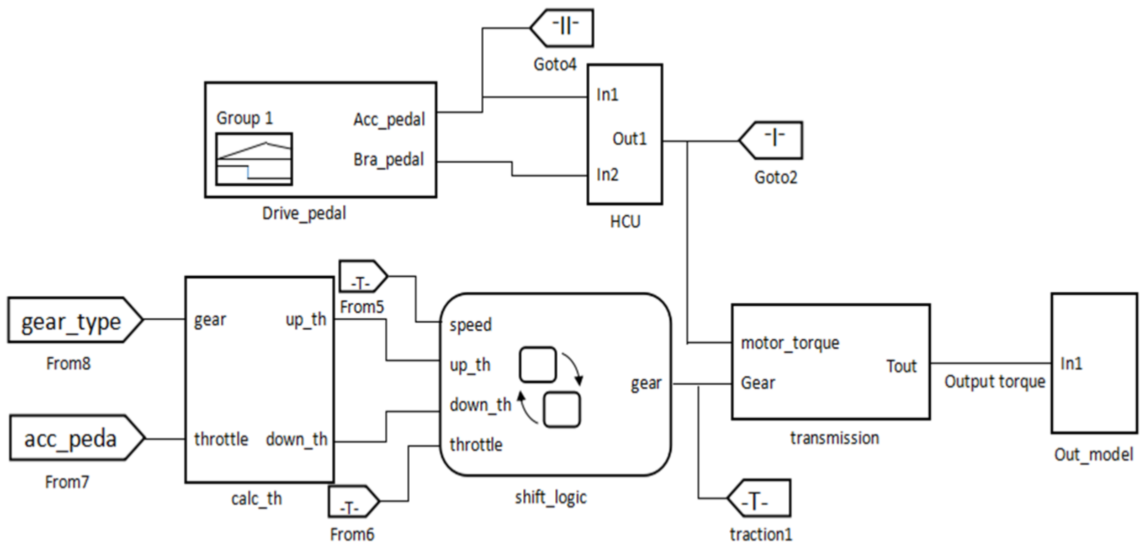

FIGURE 7. Dynamic simulation model

is greater than the up-shifting speed, similarly, when the vehicle speed is lower than the downshifting speed, the downshift is performed, and the shift has a delay of 1 second.

Assuming that the simulation time was 100 second, in "Driver-pedal" model, the accelerator pedal and brake pedal signals were used to make the vehicle accelerate and decelerate in the simulation, and the designed up shift and downshift control strategy was tested; the results are shown in Fig. 9. It was concluded that the transmission can be shifted well based on the designed gear-shifting strategy during the acceleration from a speed of 0 to the maximum speed (speed limit 70 km/h) and the deceleration to 0. In addition, according to the simulation results, the full-load acceleration time of 0-50 km/h was 23 second, and the maximum slope was 14%.

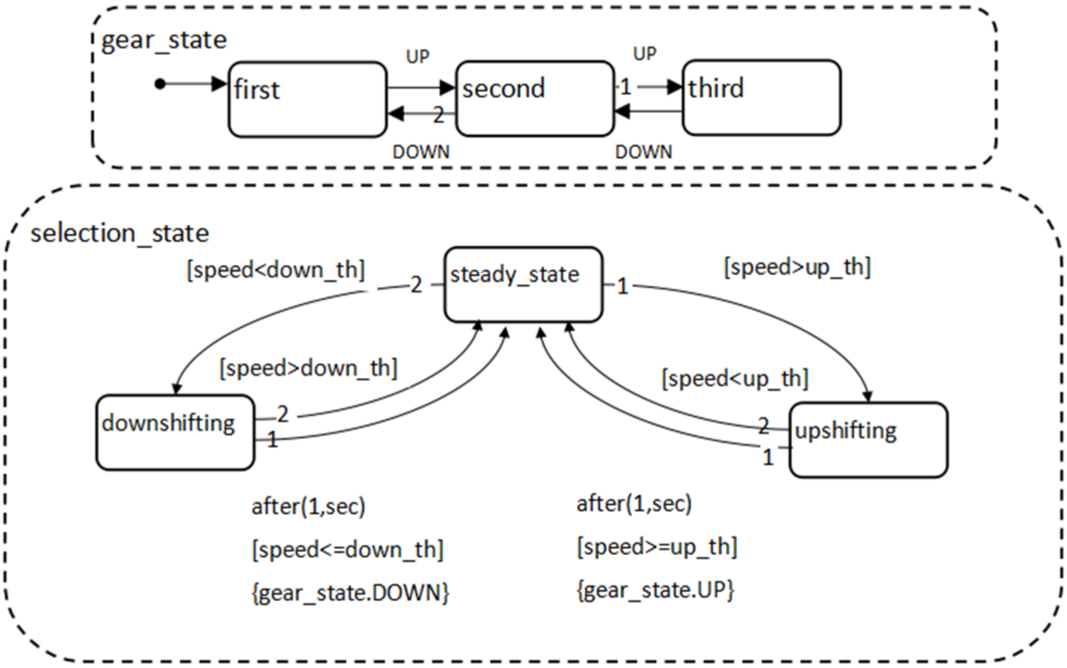

Figure 8. Model of shifting controlling strategy

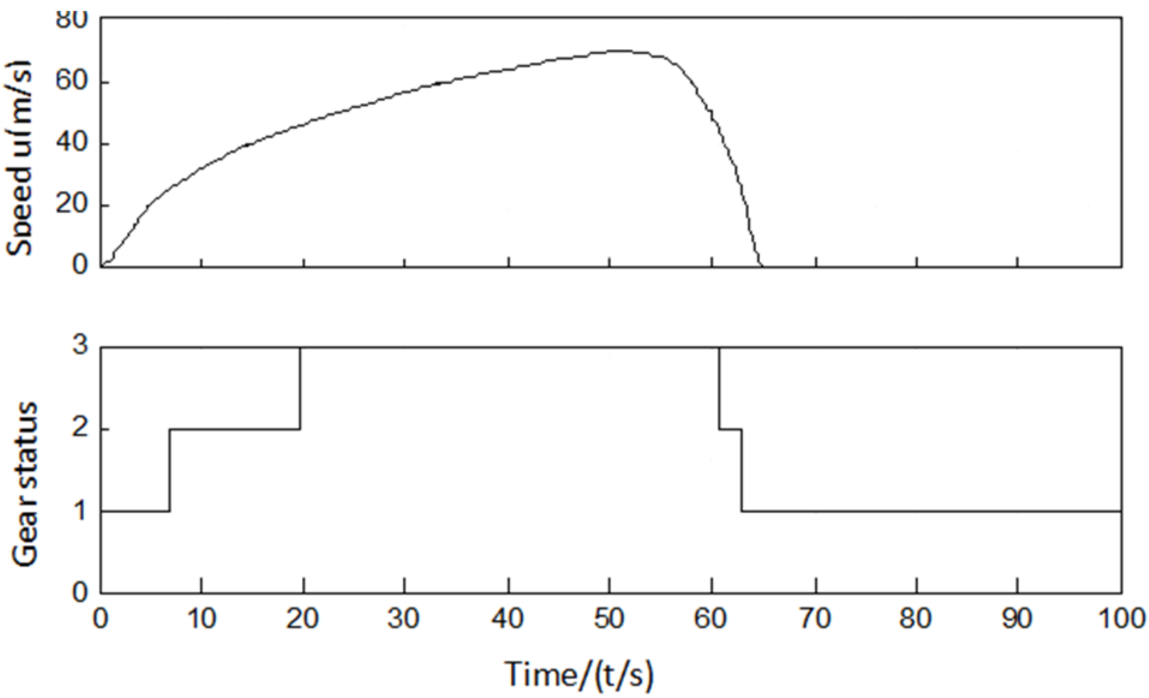

Figure 9. Gear change during acceleration and deceleration

3.2. **Simulation Study of Cyclic Working Conditions.** To test the designed shifting control strategy, the dynamic simulation should be combined with the cyclic working conditions to carry out the adaptability test of the shifting conditions and the economic analysis under the cyclic working conditions.

For the simulation of the cyclic working conditions, the simulation model in Fig. 6 needed to be improved. The cyclic condition model and the driver model needed to be added to complete the cycle of

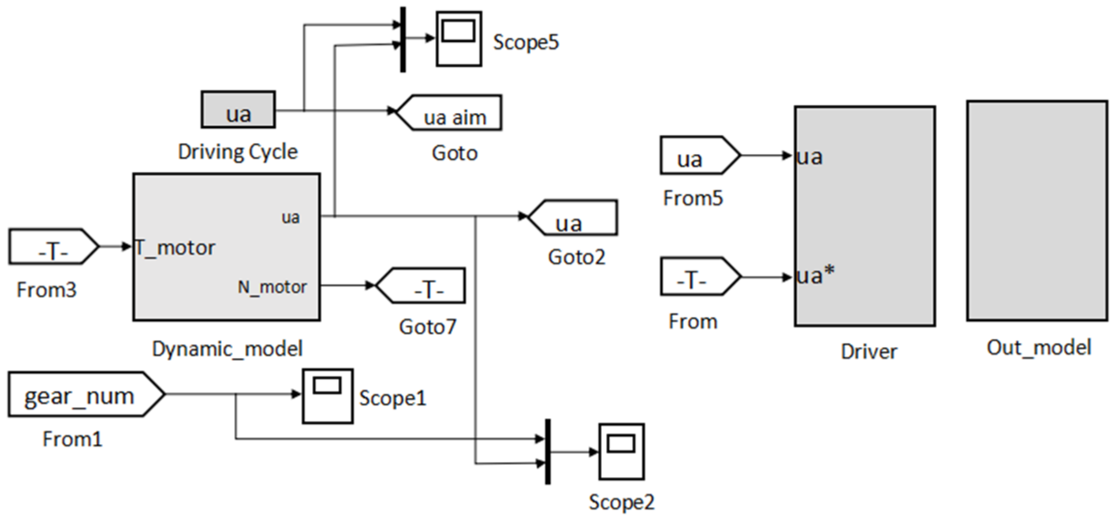

FIGURE 10. Model of cyclic condition

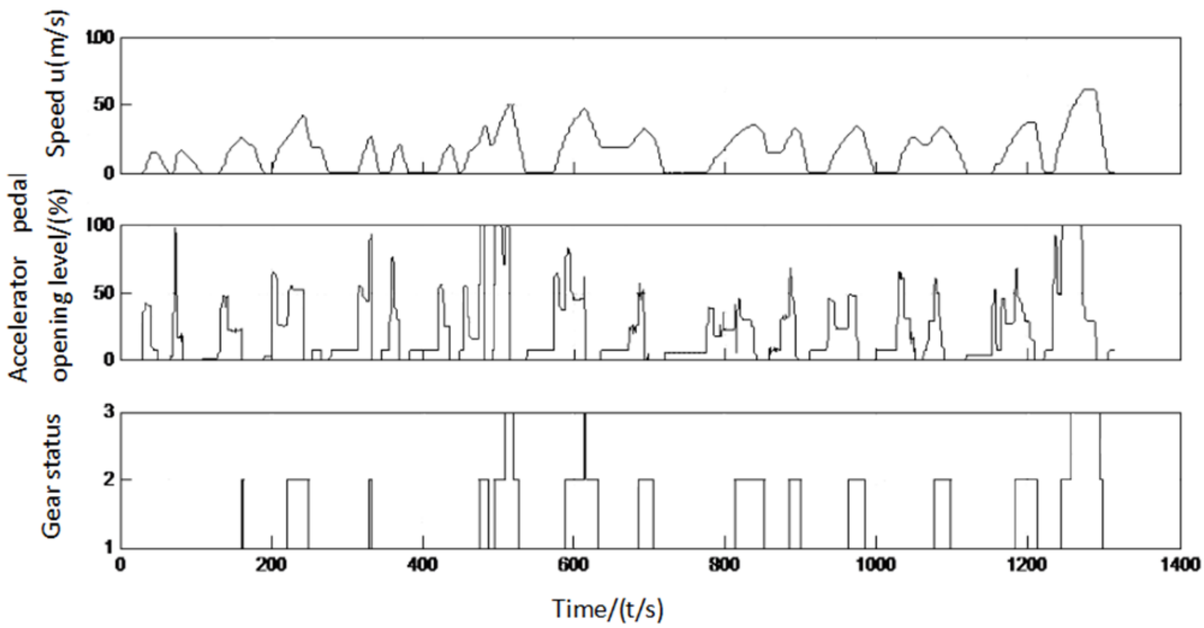

FIGURE 11. Accelerator pedal opening degree and gear change under cyclic working conditions

the working conditions, and the power and efficiency models of the motor and battery both needed to be added to complete the vehicle power limit and power consumption statistics. The simulation model of the improved cyclic working condition is shown in Fig. 10. In the figure, the "Dynamic-model" is the vehicle equivalent module. The "Driver" is the module of controlling the driver's operation under the simulated target condition through control of PI. The "Out-model" module is used to output the simulation result of vehicle economic.

The first two simulation results in Fig.11 turns out that the accelerator pedal opening is large and the change rate of pedal opening changes so much when vehicle accelerates. At this time, the shift mainly adopts dynamic shift schedule designed by this paper, which also meets demand for power during acceleration of vehicle;The analysis of cycle condition of gear state changing diagram turns out that there are sixteen upshift and sixteen downshift, and the time taken by portion of higher changing rate of pedal

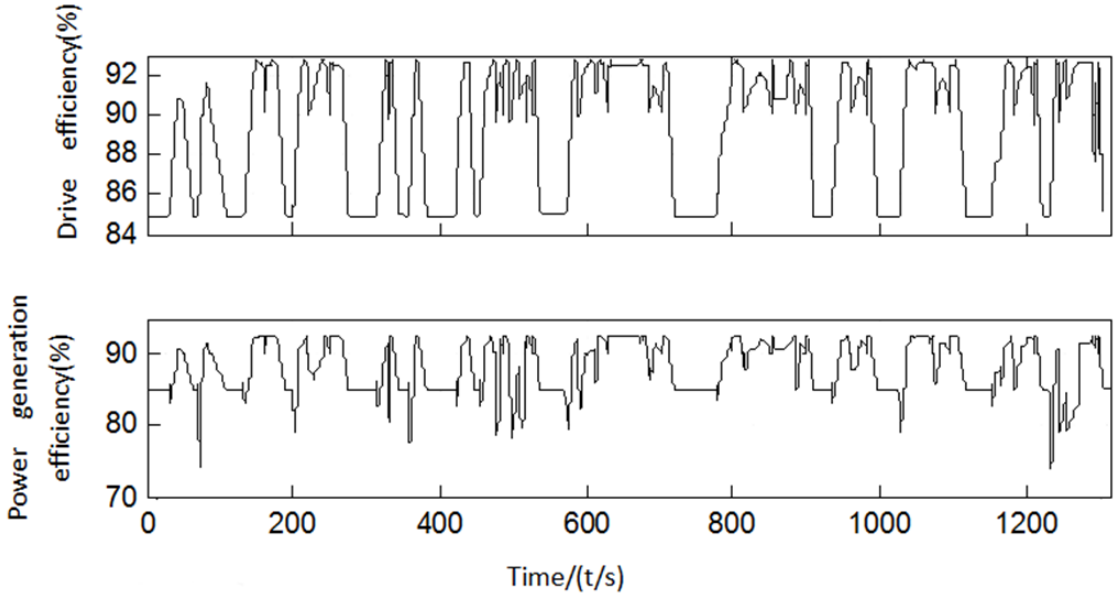

Figure 12. Driving and power-generation efficiency of motor under cyclic conditions

openning is less which meets need of economy driving of vehicle. In addition, during the whole cycle, the working efficiency of the motor can be counted as shown in Fig. 12.

It can be seen from Fig. 11 that the working efficiency of the motor is almost 85% or more, whether motor is in the working state of driving or generation. Under the action of the gearbox, the motor can work at higher speeds more often, widening the working range of the high-efficiency area of the motor. From the simulation results, the power consumption was 65.6 kwh/100 km. However, since this paper is based on the dynamic gear-shifting strategy, at the expense of a part of the power to optimize the shifting control strategy, the vehicle economy has much room for optimization.

4. **Conclusion.** The steps of developing the dynamic gear-shifting strategy are as follows:

(1) Determine the power source output torque according to the accelerator pedal opening degree and the speed of the driving motor.

(2) Formulate the load characteristic map of the motor combined with the characteristic data in the driving characteristic diagram of the selected driving motor.

(3) The acceleration performance curve of the vehicle is based on the motor load characteristic data and the relationship among acceleration, accelerator opening degree and vehicle speed, and it is drawn in MATLAB using the graphic method.

(4) Then in this curve, it is converted into the acceleration pedal opening degree and the gear upshift strategy at current speed, and the appropriate downshift strategy can be set to obtain the vehicle dynamic gear-shifting strategy.The shifting control strategy designed in this paper was integrated into the electric vehicle simulation model established in the Simulator MATLAB platform. The simulation results show that the acceleration time of the full-load vehicle from 0 to 50 km/h was 23 second, and the maximum slope was 14%. The simulation model was changed by selecting the typical bus conditions in Chinese cities to verify the adaptability of the shifting conditions and analyze the economics under this cyclic condition. The simulation results show that the converted electricity consumption per 100 kilometers was 65.6 kwh, and the motor drive and power generation efficiency diagrams for this cyclic condition were obtained, which show that the motor was in the 85% or more high efficiency operating range more often. The above two simulation results show that the designed gear-shifting strategy can be used in real vehicle running and provide a basis for optimizing the fuel economy of the vehicle in future studies.

Conflicts of Interest. This manuscript did not lead to any conflicts of interest regarding the publication.

Acknowledgment. This entire study works are sustained by Fujian Nature foundation No. 2016J01039 and Xiamen City foundation No. 3502Z20173037.

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