Research on Optimal Shift Control Strategy of Two-speed AMT based on Fuzzy Control

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Abstract. For a two-speed AMT pure electric commercial vehicle, the pros and cons of the shift control strategy directly determine the overall vehicle performance of the electric vehicle, such as power and economy. This article takes a certain type of commercial pure electric vehicle equipped with a two-speed automatic transmission as the research object, formulates a dynamic shift rule based on the torque map of the motor, structures an economic shift rule based on the efficiency map, and identifies road gradient and car load quality, comprehensive consideration of the car's loading quality, road slope, accelerator pedal opening, accelerator pedal opening change rate, vehicle speed and other parameters for optimal shift control strategy formulation. Comparing the dynamic shift strategy with the economic shift strategy, simulation analysis results show that the optimized shift control strategy can meet the requirements of dynamic performance and has the advantages of economy and energy saving.

1. Introduction
With the increase of people's awareness of energy saving and environmental protection, pure electric vehicles have developed extensively [1]. Pure electric vehicles use a drive motor as the power system to drive the vehicle. Its performance is mainly evaluated by the maximum speed, acceleration capability, climbing ability, and maximum cruising range [2], etc. And the transmission system layout, deceleration ratio selection and control strategy of pure electric vehicle directly affect the performance of electric vehicles. In order to adapt pure electric vehicles to complex driving conditions as well as drive motors to operate in high efficiency ranges, two-speed AMT is commonly used in China [3]. AMT has the advantages of simple structure, convenient control and high transmission efficiency [4]. The quality of its shift control strategy directly determines the power and economic performance of electric vehicles. Most of its control strategies are dynamic shift strategies, economic shift strategies or a comprehensive shift curve [5], but they can't intelligently take into account both dynamics and economy.

In the most common cases, the shift control strategy used by AMT is mainly based on two parameters: velocity and accelerator pedal opening. The velocity mainly reflects the current driving state of the vehicle, and the accelerator pedal opening degree mainly reflects the driving intention of the driver. However, under the premise of the complex and changeable driving environment, the shift control strategy formulated only according to the speed and accelerator pedal
opening cannot adapt to the complex and changeable driving conditions. In this paper, according to the road slope, the vehicle load mass, the change rate of accelerator pedal opening, etc., as well as based on the fuzzy control strategy to develop the optimal shift control strategy, we can better identify the complex and changeable driving environment. According to different driving environments, calculate the power demand factor of the car and formulate an optimal shift control strategy. Through MATLAB / Simulink and Cruise joint simulation, the dynamics and economics of pure electric commercial vehicles are compared under the optimized shift control strategy and economical and dynamic shift control strategies. Verify the superiority of the optimized shift control strategy. A simplified diagram of the optimized shift control strategy is shown in Figure 1.

![Figure 1. Optimized shift control strategy](image1)

| Table 1. Vehicle basic parameters |
|----------------------------------|
| **Parameter**                  |  **Number** |
| Curb weight $m_0$/kg          |  4100       |
| Gross weight $m$/kg           |  8275       |
| Frontal area A/m²             |  5.824      |
| Drag coefficient $C_D$        |  0.6        |
| Rolling resistance coefficient $f$ |  0.018  |
| Wheel radius $r$/m            |  0.36       |
| Transmission efficiency $\eta_t, \eta_0$ |  0.9  |
| Final ratio                   |  5.125      |
| First gear ratio              |  2.45       |
| Second gear ratio             |  1          |

2. AMT Shift Control Strategy Design

Shift control determines when and under what conditions the transmission will be shifted, whether the AMT can be controlled to shift at the best shift point, and whether the electric vehicle can meet the power and economic requirements.

2.1. Formulation of Optimal Dynamic Shift Rules

Dynamic performance is an extremely important standard in the evaluation of automobile performance. The shift rule that makes the car always work in the most powerful state is called the optimal dynamic shift rule [6]. In order to formulate the optimal dynamic shift rule, the intersection points of the acceleration curves corresponding to the first gear and the second gear is taken as the gear shift points.

The car driving equation is:

$$ T_{iq}i_qi_0 \frac{r}{\eta_t} = mgf + mgsin\alpha + C_D A u_2^2 + \delta \frac{du}{dt} (1) $$

The vehicle's longitudinal acceleration is:

$$ a = \frac{1}{\delta m} \left( T_{iq}i_qi_0 \frac{r}{\eta_t} - mgsin\alpha - C_D A u_2^2 \right) (2) $$

Where the $T_{iq}$ is motor torque; $i_q$ is transmission reduction ratio; $i_0$ is main reduction ratio; $\eta_t$ is mechanical efficiency of transmission system; $m$ is total vehicle mass; $r$ is wheel rolling radius; $f$ is rolling resistance coefficient; $\alpha$ is Road slope angle; $C_D$ is air resistance coefficient; $u_2$ is vehicle speed; $a$ is vehicle acceleration; $A$ is air resistance coefficient; $\delta$ is coefficient of vehicle rotation mass conversion.

According to the speed-torque curve of the motor, the acceleration curves of the first and second gears with different accelerator pedal openings are plotted, as shown in Figure 2. The intersection
points of the acceleration curves of the first gear and the second gear under different pedal openings were fitted as the best dynamic shift points. When the vehicle is running under actual driving conditions, power interruption will occur during AMT shift, and power interruption will cause the vehicle speed to drop by 1 to 2 km/h. A downshift speed difference of 2 to 8 km/h is usually set [7], which can eliminate the possibility of frequent gear shift. The best dynamic shift curve is obtained by fitting the intersection of the first-speed and second-speed acceleration curves of different pedal openings, as shown in Figure 3.

![Figure 2. Acceleration curves of the first and second gears with different accelerator pedal openings](image)

![Figure 3. Optimum dynamic shift curve of two-speed AMT](image)

### 2.2. Formulation of Optimal Economic Shift Rules

The best economical shift rule is to make the drive motor work in the high-efficiency region as much as possible, which means that the power consumption per 100 kilometers is the smallest [8].

For pure electric commercial vehicles, economy is a relatively important indicator. The quality of the economy determines the level of energy consumption during the use of pure electric commercial vehicles, and it also determines the level of operating costs. For pure electric commercial vehicles, improving economy can promote the cruising range of pure electric vehicles, improve the service life of power batteries, and reduce the manufacturing cost of complete vehicles. Therefore, whether it is power or economy, it is an important performance that pure electric commercial vehicles need to meet. According to the motor efficiency, the motor efficiency corresponding to the next gear and the second gear for different accelerator pedal openings is plotted, as shown in Figure 4.

The economic shift curve is fitted according to the first and second gear efficiency diagrams, as shown in Figure 5.

![Figure 4. First gear / second gear motor efficiency](image)

![Figure 5. Economic shift rules](image)

### 2.3. Optimal Shift Control Strategy Formulation

The car is a dynamic system, and its driving conditions are complex and changeable. In order to better adapt to all kinds of complicated drivers and meet the dynamic requirements of vehicles while driving,
as well as to save energy as much as possible, fuzzy control is adopted in this paper to formulate optimized shift control strategy. The road gradient $i$, the vehicle load $m$, and the acceleration pedal opening change rate $d_{acc}$ are selected as inputs, and normalized processing is performed, and the output is a dynamic demand factor $K$. The fuzzy subset of road slope $i$ is [NB, NS, F, S, B], which respectively represent road slope with large slope downhill, small slope downhill, flat road, small slope uphill, and large slope uphill. The fuzzy subset of the vehicle load $m$ is [E, H, F] which represents the vehicle's no-load, half-load, and full-load, respectively. The fuzzy subset of the accelerator pedal opening degree change rate $d_{acc}$ is [S, M, B], which respectively represent small, medium and large acceleration pedal opening degree change rates. Based on previous experience and a large number of simulation and comparison experiments, 21 rules of fuzzy control strategies are obtained, as shown in Table 2, where the output is the dynamic demand factor $K$ and the dynamic shift ratio coefficient. Its fuzzy subset is [Z, VS, S, M, B, VB], respectively, represent zero, small, small, medium, large, and large dynamic demand factors.

Table 2. Table of fuzzy rules

| Number | $i$ | $m$ | $d_{acc}$ | $K$ |
|--------|-----|-----|-----------|-----|
| 1      | B   | -   | -         | VB  |
| 2      | S   | E   | S         | VS  |
| 3      | S   | E   | M         | S   |
| 4      | S   | E   | B         | M   |
| 5      | S   | H   | S         | M   |
| 6      | S   | H   | M         | B   |
| 7      | S   | H   | B         | VB  |
| 8      | S   | F   | -         | VB  |
| 9      | F   | E   | S         | Z   |
| 10     | F   | E   | M         | VS  |
| 11     | F   | E   | B         | M   |
| 12     | F   | H   | S         | S   |
| 13     | F   | H   | M         | B   |
| 14     | F   | H   | B         | VB  |
| 15     | F   | F   | S         | B   |
| 16     | F   | F   | M         | VB  |
| 17     | F   | F   | B         | VB  |
| 18     | NS  | E   | -         | Z   |
| 19     | NS  | H   | -         | S   |
| 20     | NS  | F   | -         | B   |
| 21     | NM  | -   | -         | Z   |

Based on theoretical analysis and multiple simulation experiments, the membership function of the designed fuzzy variable is determined as shown in Figure 6.
3. Build Model and Simulation Analysis

3.1. Construction of Cruise / Simulink Joint Simulation Model
This article uses Cruise to build a pure electric commercial vehicle simulation model. Its structure is shown in Figure 7. The power battery provides power to the drive motor. Under the control of the motor controller, the drive motor provides the drive torque for the two-speed automatic transmission through the main deaccelerator and differential passing to the wheels. Use Matlab / Simulink to build an optimized shift control strategy, as shown in Figure 8. The optimized shift control strategy built by Matlab / Simulink is connected to Cruise through the Matlab DLL interface.

![Figure 7. Cruise / Simulink joint simulation model](image1)

![Figure 8. AMT optimized shift control strategy model](image2)

![Figure 9. Shift time for different strategies](image3)
3.2. Analysis of Simulation Results

For the optimized shift control strategy, dynamic shift control strategy, and economic shift control strategy, calculation tasks are set in the Cruise simulation. In this paper, a full acceleration calculation task of 0-100km/h is set up to obtain optimized shift and power. Dynamic shift curves of dynamic shift and economic shift are shown in Figure 9.

The simulation results show that under the control of optimized shift strategy, the time from the first gear to the second gear is between the dynamic and economic shift strategies. The 0-60km/h acceleration time of the vehicle under the control of the optimized shift strategy is compared with the dynamic and economic shift control strategy. The comparison results are shown in Table 3.

| Shift strategy     | Acceleration time (s) |
|--------------------|-----------------------|
| Optimized shift strategy | 8.92                  |
| Dynamic shift strategy   | 8.87                  |
| Economic shift strategy    | 9.16                  |

Table 4. NEDC cycle power consumption

| Shift strategy     | Energy consumption (kWh / 100km) |
|--------------------|----------------------------------|
| Optimized shift strategy | 37.01                          |
| Dynamic shift strategy   | 37.49                           |
| Economic shift strategy    | 36.89                           |

The NEDC circulation conditions calculate and compare optimized shift strategy, dynamic shift strategy, and economical shift strategy to control the overall economic performance of the vehicle. The simulation results are shown in Table 4.

According to Table 3, the acceleration time of the car under the control of the optimized shift strategy is 24.0s, which is not much different from the dynamic shift strategy, but it is much better than the economical shift strategy. It shows that optimized shift strategy can improve the dynamic performance of electric vehicles.

According to Table 4, in the NEDC operating condition simulation, the energy consumption of the vehicle under the control of the economic shift strategy is 30.15kWh/100km, which has the lowest energy consumption; the vehicle energy consumption under the control of the dynamic shift strategy is 37.49kWh/100km; the energy consumption of the vehicle under the control of the optimized shift strategy is 37.01kWh / 100km; with the comparison between the optimized shift strategy and dynamic shift strategy, the energy consumption is reduced by 0.48kWh/100km, and the economy is improved by 1.30%, while the reduced difference between the optimized shift strategy and the economic comparison is smaller, which indicates that optimized shift strategy can improve the economy of electric vehicles.

4. Conclusion

According to the theoretical and dynamic shift laws and economic shift rules, a two-speed AMT optimized shift control strategy is proposed for a pure electric commercial vehicle based on fuzzy control. The pure electric commercial vehicle model is built by using Cruise, and the shift control strategy is built by using Matlab/ Simulink. Joint simulations verify the power and economics of pure electric commercial vehicles. The simulation results show that the optimized shift control strategy can better identify driving intentions and road information, and better adapt to complex and changing driving conditions, thereby ensuring that electric commercial vehicles can improve economy while ensuring power.

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