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CVT车辆爬长大坡道时的动力性和经济性控制策略

闫光辉[1,2],余 强[1],关志伟[2],杜 峰[2]
(1. 长安大学 汽车学院,陕西 西安 710064;2. 天津职业技术师范大学 汽车与交通学院,天津 300222)

摘 要: 分析了车辆爬长大坡道时的动力性、经济性与CVT传动比控制策略,在发动机最佳动力性和最佳经济性转速之间等间隔地选取多个工作点,研究了各工作点的传动比对车辆动力性和经济性的影响,通过Simulink仿真找出了车辆爬坡时兼顾动力性和经济性的CVT传动比最优控制策略。仿真结果表明:与最佳经济性传动比相比,采用最优控制策略时汽车的加速响应时间提高了1.2 s,与最佳动力性控制策略相比,采用最优控制策略时汽车的燃油消耗率下降了7.9%,且车辆加速度变化曲线平顺,并无明显拐点,因此,采用传动比最优控制策略可以有效改善车辆爬长大坡道时的动力性和经济性。

关键词: 汽车工程;无级变速器;传动比控制;整车仿真;长大坡道;动力性;经济性

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Control strategy of power performance and fuel economy for CVT vehicle on long uphill highway

YAN Guang-hui[1,2], YU Qiang[1], GUAN Zhi-wei[2], DU Feng[2]
(1. School of Automobile, Chang'an University, Xi'an 710064, Shaanxi, China; 2. School of Automobile and Transportation, Tianjin University of Technology and Education, Tianjin 300222, China)

Abstract: The control strategy of CVT transmission ratio, the power performance and fuel economy of vehicle on long uphill highway were analyzed. Multiple work points between the best dynamic and best economical rotational speeds of engine at equal interval were selected, and the influence of transmission ratio of every working point on the power performance and the fuel economy was studied. The optimal control strategy of CVT transmission ratio under considering the two properties was found by Simulink simulation. Simulation result indicates that the acceleration response time of the optimal control strategy decreases by 1.2 s compared with the best dynamic control strategy, the fuel consumption rate of the optimal control strategy decreases by 7.9% compared with the best economical control strategy, and the acceleration curve is smooth. Therefore, the two performances of vehicle on long uphill highway can be effectively improved by using the optimal control strategy of transmission ratio. 3 tabs, 12 figs, 14 refs.

Key words: automotive engineering; continuously variable transmission; transmission ratio

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Author Resume: YAN Guang-hui(1980-), Male, Suixi, Anhui, Lecturer of Tianjin University of Technology and Education, Doctoral Student of Chang'an University, Research on Automotive System Dynamics and Control, +86-22-88181104, yanguanghuiygh@sina.com.
Tutor Resume: YU Qiang (1961-), Male, Nanyang, Henan, Professor of Chang'an University, PhD, +86-29-82334315, qiangyu@chd.edu.cn.

control; whole vehicle simulation; long uphill highway; power performance; fuel economy

0 Introduction

The high automation and continuity of shift process are the pursuit goals of automobile transmission design. CVT transmission ratio changes continuous, which must make engine running condition match vehicle power performance more reasonable, so that engine works at the more ideal performance points, and has better fuel economy, emission performance and power performance[1]. At the same time, CVT transmission may change automatically according to driver's intention and vehicle running resistance, which makes vehicle have better steering stability and ride comfort. The control of CVT transmission ratio is the key factor to reach the above objectives.

However, in normal conditions, driver only choose E-economical mode or S-sport mode. Especially, in order to ensure the power performance, when vehicle is climbing up long uphill section, driver generally directly chooses the sport mode and ignores fuel efficiency. Therefore, we should discuss a control strategy to consider both power performance and fuel economy under long uphill section condition, and also pay attention to the smooth change of CVT transmission ratio.

In order to improve the work efficiency of torque converter and the fuel economy of CVT vehicle, He et al designed a PID controller, so that engine and torque converter can work in the optimal economy region by the adjusting function of CVT transmission ratio [2]. In order to study the CVT control strategies for engine brake of CVT vehicle on long downhill section, Dong et al established the comprehensive control strategy between engine and CVT on long downhill section with dynamic simulation, which verifies the correctness of the control strategy for engine brake of CVT vehicle on long downhill section, and improves the fuel economy and safety of vehicle[3]. Zhang et al set up a fuel economy model of engine, studied the matching strategy between CVT and engine, and determined the relationship between engine goal speed and vehicle speed. At the same time, they formulated the comprehensive control strategy from the demand of vehicle power performance under transient operating conditions and from fuel economy under steady operating conditions, so as to improve vehicle fuel economy under steady condition[4]. For CVT hybrid electrical vehicle, Zhang et al proposed a new algorithm of motor torque according to the control rules of CVT transmission ratio, and the simulation result showed that the algorithm can achieve the smoothness of mode switching of hybrid electrical vehicle[5]. Zhang et al determined the fuel consumptions at different transmission ratios under various slope-road conditions through a large number of simulation experiments, and made the fuel consumption reasonably match the power performance, so as to obtain the optimal control goals of CVT transmission ratio[6]. Lee et al proposed the theories of speed envelope strategy[7], the departure from practice strategy[8] and so on, which was aiming at the control of dynamic response speed for CVT vehicle. Ryu et al researched how to improve vehicle fuel economy by the methods to reduce the energy loss of CVT[9]. From the aspects of CVT structure, Liu et al researched the influence of the change of transmission ratio on CVT, the power performance and fuel economy of vehicle[10]. Yet all the theories do not precisely give the target control quantities and control methods of transmission ratio. The researches on the control strategies of CVT transmission ratio consideing both power performance and fuel economy on long uphill section are scarce. They almost researched how to control CVT transmission ratio under common working conditions for a single goal, and paid attention to the precision of transmission ratio control, but did not integratively consider the power performance, fule economy and ride comfort of vehicle.

In view of the above questions, this paper proposes CVT transmission ratio control strategy integrative considering the power performance, fuel economy and ride comfort of vehicle on long uphill section, and uses vehicle dynamic simulation models established in MATLAB/Simulink to precisely give the determination method of CVT transmission ratio control strategy considering both the power performance and the fuel economy on long uphill section and the method to calculate transmission ratio MAP chart.

1 CVT target transmission ratio

This paper sets engine rotational speed as n_e ($r \cdot min^{-1}$), the output rotational speed of CVT as n_{out} ($r \cdot min^{-1}$), then the real transmission ratio of CVT is

$$i = \frac{n_e}{n_{out}} \tag{1}$$

Due to

$$n_{out} = \frac{25vi_0}{3\pi r_d} = \frac{25n_w i_0}{3\pi} \tag{2}$$

$$P_e \eta = n_e T_e \eta = n_w T_w \tag{3}$$

the target transmission ratio of CVT is

$$i_t = \frac{3\pi T_w}{25 i_0 \eta T_e} \tag{4}$$

where v is vehicle speed ($km \cdot h^{-1}$); i_0 is the transmission ratio of vehicle main reducing gear; r_d is the rolling radius of wheel (m); n_w is the rotational speed of wheel ($r \cdot min^{-1}$); P_e is the output power of engine (kW); η is the transmission efficiency of drive system (%); T_e is the output torque of engine ($N \cdot m$); T_w is the resisting torque of wheel($N \cdot m$).

At the same throttle opening degree α, the working points of vehicle optimal fuel economy and optimal power performance are (n_{ee}, T_{ee}, i_{te}) and (n_{es}, T_{es}, i_{ts}) respectively, which correspond to the working point(n_e, T_e, i_t). Therefore, at present condition, the optimal economy transmission ratio of CVT is[6]

$$i_{te} = \frac{3\pi T_w}{25 i_0 \eta T_{ee}} \tag{5}$$

The optimal dynamic transmission ratio of CVT is

$$i_{ts} = \frac{3\pi T_w}{25 i_0 \eta T_{es}} \tag{6}$$

When the throttle opening degree continuously changes from small to large, engine has the optimal economy target speed and the optimal dynamic target speed at every throttle opening degree. For example, the engine is assembled in Nissan TIIDA, the optimal economy target speed and the optimal dynamic target speed at every throttle opening degree are shown in Tab. 1. With the interpolation method, the optimal economy working curve and optimal dynamic working curve of engine can be drawn and shown in Fig. 1.

Tab. 1 Optimal economical and dynamic speeds of engine

α/%	10	20	30	40	50	60	70	80	90	100
n_{ee}/($r \cdot min^{-1}$)	1 297	1 458	1 804	2 411	3 022	3 521	3 989	4 197	4 308	4 405
n_{es}/($r \cdot min^{-1}$)	1 343	1 754	2 799	3 497	3 992	4 498	4 876	5 078	5 156	5 189

2 Control strategy of CVT on long uphill section

2.1 Driving conditions of long uphill section

Generally, the range of long uphill gradient is $4\% \leqslant j \leqslant 10\%$, and slope length is more than 100 m. When vehicle runs on long uphill section, slope resistance increases, wheel resistance torque increases to T'_w and makes vehicle speed decrease. However, driver is not satisfied with the decreasing speed, so driver treads accelerator pedal at a certain rate to an objective position, making α increase to α', until the speed is stable at a satisfying value. Now, vehicle's best economical working point is (n'_{ee}, T'_{ee}, i'_{te}), and the optimal dynamic working point is (n'_{es}, T'_{es}, i'_{ts}), they correspond to the working point (n_e, T_e, i_t), so the optimal economical target transmission ratio of CVT is

$$i'_{te} = \frac{3\pi T'_w}{25 i_0 \eta T'_{ee}} \tag{7}$$

The optimal dynamic target transmission ratio is

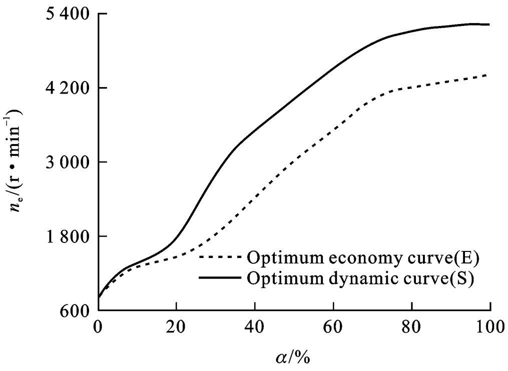

Fig. 1 Engine speed's adjustment characteristics

$$i'_{ts} = \frac{3\pi T'_w}{25 i_0 \eta T'_{es}} \tag{8}$$

If the slope changes continuously, driver will continuously tread the throttle pedal, therefore, the optimal economical and dynamic target transmission ratios constantly change.

2.2 Optimal control strategy

When vehicle climbs slope, because of the increase of vehicle resistance and ensuring good dynamic response and certain back-up power at α', vehicle shouldn't entirely work at the optimal economical point. At the same time, in order to ensure the ride comfort and the fuel economy, vehicle shouldn't entirely work at the optimal dynamic point. Therefore, when vehicle is climbing up long uphill section, the control principle to CVT is to guarantee the necessary power and simultaneously take fuel economy and smoothness into account. In the control method, the ideal working point (n_{em}, T_{em}, i_{tm}) between point (n'_{ee}, T'_{ee}, i'_{te}) and point (n'_{es}, T'_{es}, i'_{ts}) must be found. Furthermore, it should meet the conditions: $T'_{ee} < T_{em} < T'_{es}$ and $i'_{ts} < i_{tm} < i'_{te}$. At the point, vehicle can meet the dynamic requirement, it also can make vehicle run near the economical working point as much as possible.

2.3 Implementation of control strategy

In order to find a more ideal working point (n_{em}, T_{em}, i_{tm}), the method in this paper is taking the same throttle opening and slope as input signals, and choosing four engine working points with equal interval between point (n'_{ee}, T'_{ee}, i'_{te}) and point (n'_{es}, T'_{es}, i'_{ts}). The method of selecting engine working points is to choose four engine rotational speeds as engine target speeds at equal interval between engine optimal dynamic and economical speeds, then to put them into Eq. (4) and vehicle simulation model to simulate, so as to obtain the change curves of vehicle acceleration, fuel consumption and CVT transmission ratio at each simulation point.

During that vehicle starts to climb and throttle change completes till vehicle speed reaches stability, vehicle's dynamic response, smooth acceleration and lower fuel consumption are taken as targets, vehicle's ideal working point (n_{em}, T_{em}, i_{tm}) climbing up a certain slope at a certain α is gotten by the simulation method. If the working point is used for CVT transmission ratio control during vehicle climbing, vehicle dynamic performance will be better than that at the optimal economical working point, and vehicle will have stronger back-up power and the fuel consumption will be less. The ratio at the ideal working point is CVT ideal ratio when vehicle is climbing up long uphill section.

With the repeated simulation at different α and j, the best CVT transmission ratio control MAP is obtained, which is the optimal climbing control strategy. Therefore, vehicle simulation model is established firstly in this paper.

3 Simulation models

3.1 Engine model

According to the test bench experiment data of output torque and fuel consumption for Nissan TIIDA engine in Tab. 1, engine power performance and fuel economy are gotten by the 3-spline interpolation method and shown in Fig. 2 and Fig. 3 respectively. According to the experiment data, engine torque simulation model and fuel consumption(g_e) simulation model are established by the 2-dimension numerical table interpolation method in MATLAB/Simulink[11], and shown in Fig. 4 and Fig. 5 respectively.

3.2 Drive system model

The torque output by CVT is transmitted to drive system, simulation vehicle in this paper is front-

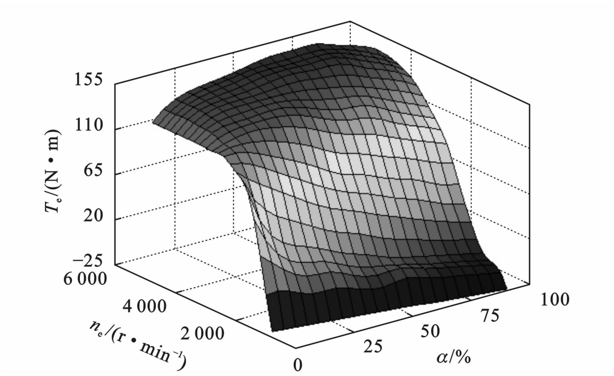

Fig. 2 Engine power performance

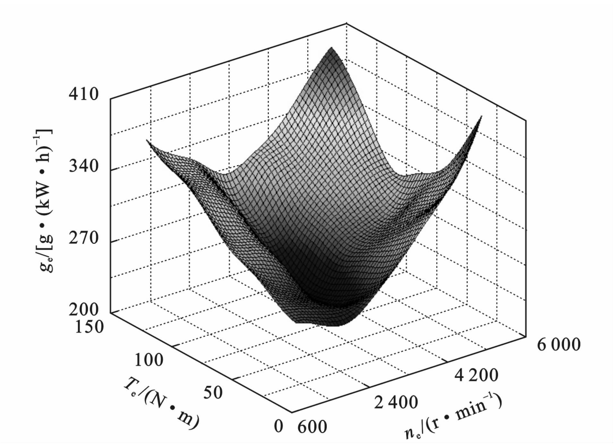

Fig. 3 Engine fuel economy

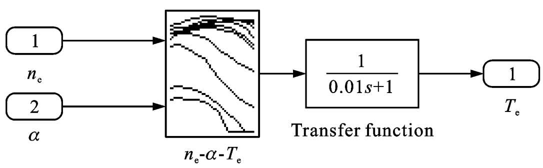

Fig. 4 Simulation model of engine torque

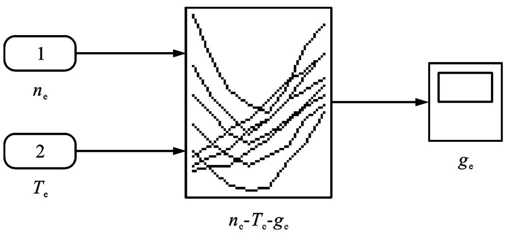

Fig. 5 Simulation model of fuel consumption

wheel drive, so its main reducer gear and CVT become an integral structure, and the drive shaft is differential shaft too. Considering the torsional rigidity and viscous damping of differential shaft, the torque transmitted by it is

$$T_{out} = K_a \theta_a l + C_a \dot{\theta}_a l \tag{9}$$

$$\dot{\theta}_a = \frac{\omega_{out}}{i_0} - \omega_w \tag{10}$$

where K_a is the torsional rigidity of differential shaft(N • m • rad^{-1}); C_a is the viscous damping of differential shaft(N • m • (rad • s^{-1})$^{-1}$); θ_a is the torsion angle of differential shaft (rad); l is the length of differential shaft (m); ω_{out} is the rotational speed of CVT output shaft(rad • s^{-1}); ω_w is the rotational speed of wheel(rad • s^{-1}).

3.3 Control method of CVT transmission ratio

Here, the specific implementation procedure of CVT transmission ratio control system is not considered, but CVT is thought as an ideal system that can achieve its own control goal[12]. PID control strategy is adopted in CVT control system, and the change rate of CVT transmission ratio is

$$\frac{di}{dt} = K_p(i_t - i) + K_i \int (i_t - i) dt + K_d \frac{d(i_t - i)}{dt} \tag{11}$$

where t is time; K_p、K_i、K_d are the proportional control parameter, the integral control parameter and the differential control parameter in the PID controller respectively. After simulation tests, the proper control parameters are given as: $K_p = 25$, $K_i = 0.11$ and $K_d = 0.02$. According to Eq. (11) and the three control parameters, PID control model of CVT transmission ratio established in MATLAB/Simulink is shown in Fig. 6.

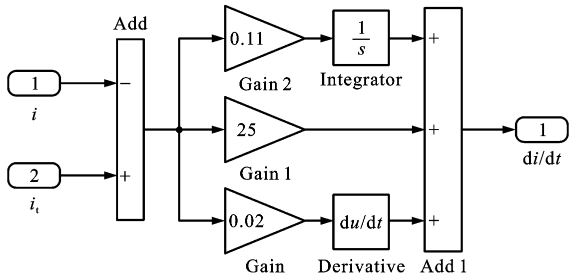

Fig. 6 PID controller of CVT transmission ratio

3.4 Whole vehicle model

The resisting torque of vehicle during climbing slope is

$$T_w = Gfr_d + Gjr_d + \frac{C_d A v^2 r_d}{21.15} + \delta m r_d \frac{dv}{dt} + \frac{I_f i_0^2 i \eta v}{r_d} \frac{di}{dt} \tag{12}$$

where G is vehicle gravity (N); m is vehicle quality (kg); f is the rolling resistance coefficient, C_d is the aerodynamic resistance coefficient of vehicle; A

is vehicle windward acreage (m^2); δ is the rotating quality conversion coefficient of vehicle; I_f is the sum of engine rotational inertia and flywheel rotational inertia($kg \cdot m^2$).

According to Eqs. (9)-(12), whole vehicle model established in MATLAB/Simulink is shown in Fig. 7. Nissan 1.6 L TIIDA CVT vehicle is taken as an example, and the simulation parameters are shown in Tab. 2.

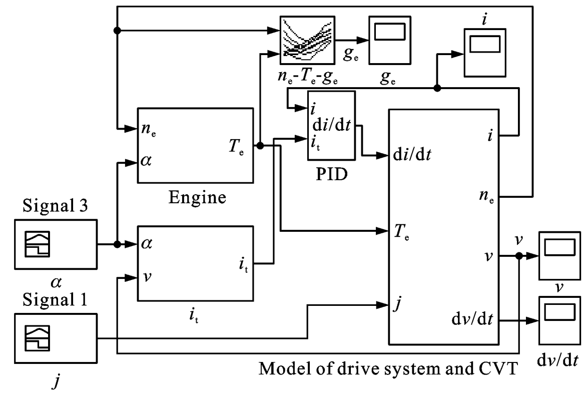

Fig. 7 Vehicle simulation model

Tab. 2 Vehicle simulation parameters

m/kg	1 300
i_0	5.2
r_d/m	0.325
η	0.9
i	0.42-3.30
C_d	0.3
A/m^2	1.99
δ	1.2
f	0.15
I_f/(kg · m^2)	0.2
K_a/(N · m · rad^{-1})	10 000
C_a/[N · m · (rad · s^{-1})$^{-1}$]	150

4 Simulation analysis of control strategy

4.1 Simulation of optimal dynamic and economical control strategy

The simulation time is 100 s, in which the front 18 s is the period of start-up and acceleration. Since the 18th s, the gradient j rapidly increases from 0 to 6%, which is shown in Fig. 8. After the 21th s, the throttle opening α changes from 35% to 80%, and keeps at 80%, which is shown in Fig. 9. The whole climbing period is from the 18th s to the 78th s.

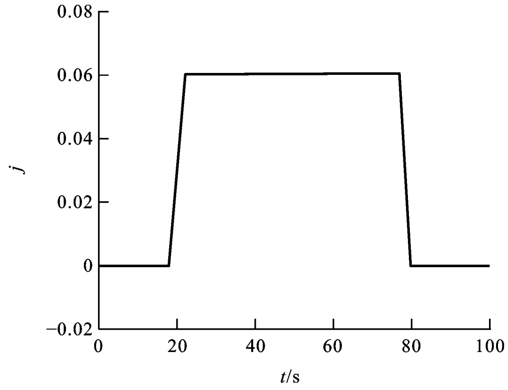

Fig. 8 Signal j

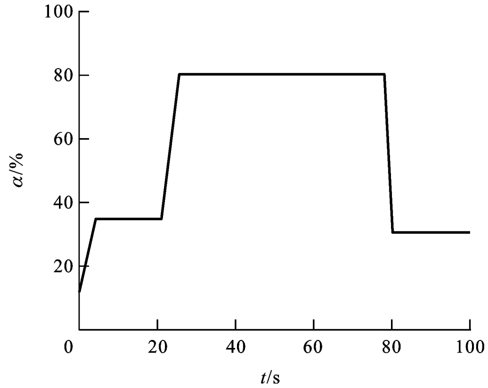

Fig. 9 Signal α

The simulation result is shown in Fig. 10. In Fig. 10(a), when the optimal dynamic control strategy (curve S) is adopted, vehicle acceleration curve has saltatorial inflection points and the rangeability is large, which shows that the ride comfort of vehicle is poor. However, the change time of acceleration from negative to positive is short, which shows that vehicle have better power performance under climbing condition. In Fig. 10(b), When the optimal dynamic control strategy is adopted, fuel consumption increases by more than 20%. In Fig. 10(c), when the optimal dynamic control strategy is adopted, the transmission ratio is larger than the optimal economy transmission ratio, and has apparent saltatorial inflection points, which will result in higher demand on the hydraulic actuating mechanism of CVT. Furthermore, the saltatorial inflection points of transmission ratio curve will have some influences on the service life of CVT. When the optimal economy control strategy(curve E)

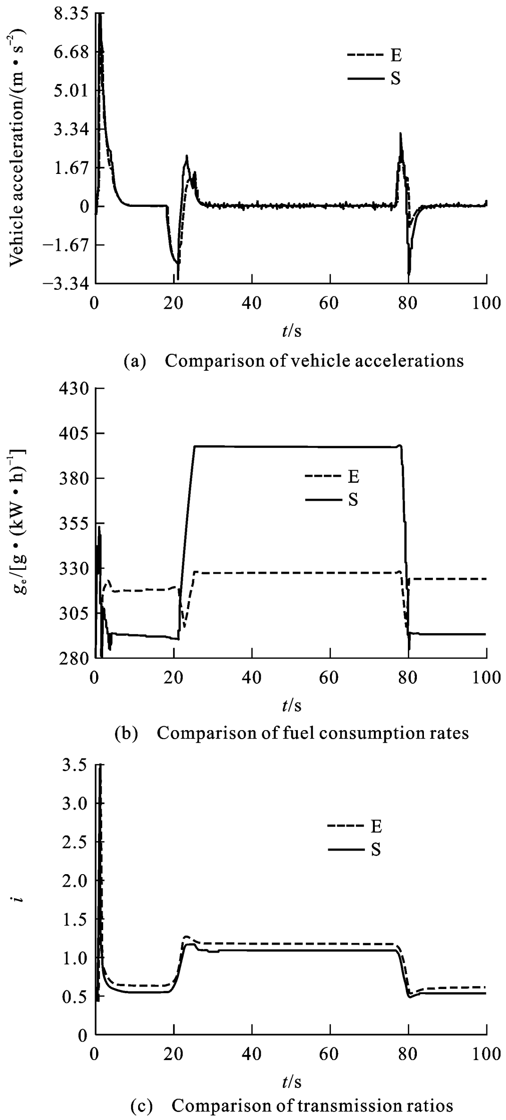

Fig. 10 Simulation result comparison of control strategies

is adopted, the acceleration change of vehicle is smooth and the rangeability is very small, but vehicle has poor power performance under climbing condition, and its back-up power is not enough, only it is obviously better than the optimal dynamic control strategy in fuel economy aspect. So the above analysis shows that it is necessary to find out the more ideal control strategy under climbing condition.

4.2 Determine optimal control strategy

Different drivers have different dynamic demands on the sections with the same gradient, which shows the throttle opening α treaded by the drivers are different. So, in order to find the optimal control strategy on long uphill section, it is necessary to do simulation tests at different α and different j, so as to find more ideal working point (n_{em}, T_{em}, i_{tm}), and to conduct it as the control strategy of CVT transmission ratio, thus the climbing ability, fuel economy and ride comfort of vehicle can be satisfied[13-14]. Taking Fig. 8 and Fig. 9 as input signals, simulation tests are carried out by the method in 2.3 section, and the simulation results are shown in Fig. 11 during climbing slope.

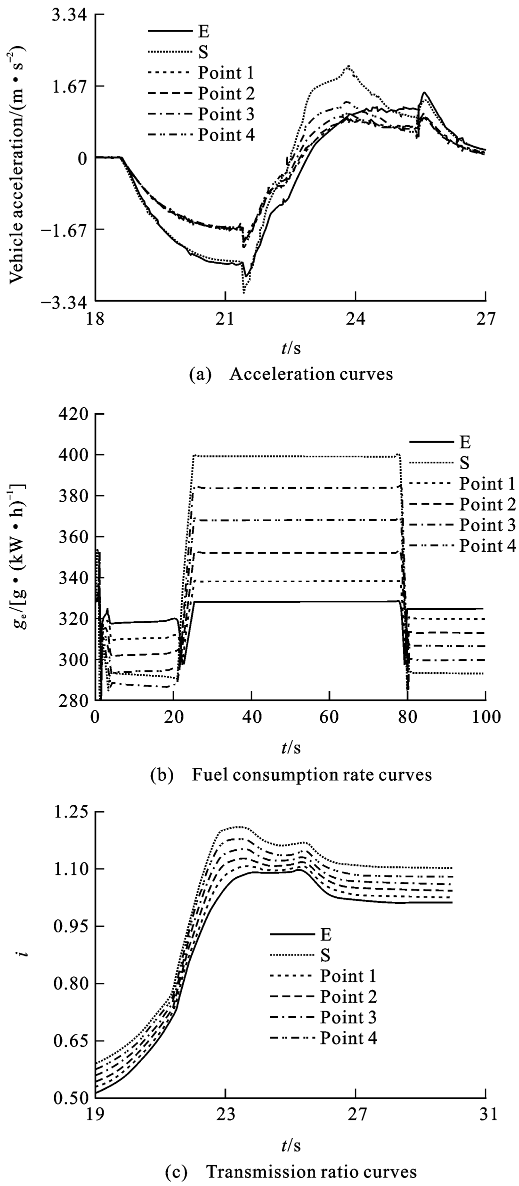

Fig. 11 Comparison of simulation results

In Fig. 11(a), the curve at simulation point 4 is smoother and has no obvious inflection points compared to the optimal dynamic control strategy, so the power performance and ride comfort of acceleration response can be ensured when vehicle is climbing slope. Moreover, the acceleration time decreases by 1.2 s compared to the optimal economical control strategy.

In Fig. 11(b), the fuel consumption rate at simulation point 4 is 366.4 g·$(\mathrm{kW}\cdot\mathrm{h})^{-1}$ and decreases by 7.9% compared to 399.0 g·$(\mathrm{kW}\cdot\mathrm{h})^{-1}$ of the optimal dynamic control strategy at uniform speed.

In Fig. 11(c), the transmission ratio is stabilized at 1.14 at uniform speed, simulation point 4 can be selected as the optimal control strategy of CVT transmission ratio under the working condition, thus the power performance, fuel economy and ride comfort of vehicle can be balanced during climbing slope. So the optimal control strategy of transmission ratio can be expressed as $j=0.06$, $\alpha=80\%$, $i=1.14$.

With the above method, simulation tests are carried out at different points selected from the boundary of $4\%\leqslant j\leqslant 10\%$ and $40\%\leqslant\alpha\leqslant 100\%$, the optimal control strategies of transmission ratio at different j and α are obtained, and the transmission ratio precise values are shown in Tab. 3. With the cubic spline interpolation method, the optimal control MAP of transmission ratio is obtained and shown in Fig. 12 when vehicle runs on long uphill section. The MAP can be used to control CVT transmission ratio on long uphill section, and can be embeded beforehand in the control unit of CVT, so as to be called.

Tab. 3 CVT transmission ratios of optimal control strategies

α/%	j						
	0.04	0.05	0.06	0.07	0.08	0.09	0.10
40	1.17	1.26	1.32	1.52	1.78	2.13	2.54
50	1.16	1.17	1.25	1.38	1.61	1.88	2.14
60	1.15	1.16	1.18	1.31	1.49	1.72	1.94
70	1.14	1.14	1.17	1.27	1.38	1.59	1.79
80	1.14	1.14	1.14	1.22	1.33	1.48	1.68
90	1.11	1.15	1.15	1.18	1.25	1.37	1.54
100	1.01	1.11	1.14	1.16	1.22	1.29	1.44

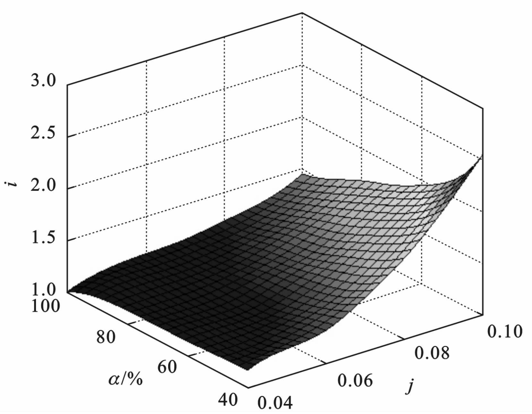

Fig. 12 MAP of transmission ratio

5 Conclusions

In this paper, whole vehicle simulation model in Simulink is set up by using engine test bench experiment data, vehicle transmission system model and vehicle parameters. Simulation result indicates that when power performance or economy control strategy is only thought, the intercoordination among the timeliness of dynamic response, ride comfort and fuel economy is not achieved during climbing slope. The best calculation method of transmission ratio control strategy is proposed based on optimal matching the factors under long uphill condition. The MAP of optimal CVT transmission ratio control strategy under long uphill condition is obtained by simulation at different α and j. The control strategy proposed in this paper can be used to accurately determine the MAP of CVT transmission ratio control strategy, and to optimize the power performance, fuel economy and ride comfort of vehicle under long uphill condition.

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