Research on Economic and Dynamic Gear Shift Strategy for Vehicle Transmission

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***Abstract*-Shiftstrategy is a crucial technique for vehicletransmission,it has very significantimpact on the dynamic and economic performance of a driving vehicle. According to vehicle acceleration characteristics and fuel consumption characteristics, a research is performed for the vehicles'power performance and economic shift law; and, an overallshiftstrategy is proposed to meet the demand of vehicles.**

Keywords- Vehicle Transmission; Shift Strategy; Optimal Dynamic Shift law; Optimal Economic Shift law

During the development of vehicles, the vehicle power transmission system always plays an important role. The drivability and economyof a vehicle does not only depend on the engine, but also on the vehicle transmission, especially the matching betweenvehicletransmission and engine. In order to significantly improve thevehiclepower performance and fuel economy.It is necessary to investigatethe shift strategy and power and economic characteristics of the vehicle transmission.

Shift strategy refers to the change rule about the gear-shift which is determined by thevehicle running status and the associated control parameters. Shift strategy is the core issue that needs to be solved for the transmission development, and its performance directly determines the vehicle power performance, fuel economy and passenger comfort.Shift strategy and its characteristics lay the theoretical foundation for the research of automatic shifting transmission, the main content is about how and when to perform gear shift [1].

The common shift strategy include three kinds [2]: one is the shift rule of power or economy, one is the gear path decision for curved road and the slope road, and another one is the locking rule of hydraulic torque converter for vehicle driven by hydro mechanical drive. This paper focuses on shift strategy considering fuel economy and vehicle power performance.

I. INTRODUCTION TO SHIFT STRATEGY DEVELOPMENT

Shift strategy considering fuel economy or vehicle power performance is obtained by optimizing the predetermined parameters, which prioritize the fuel economy or vehicle power performance, whereby the transmission gear is switched, and the optimal fuel economy or vehicle power performance is achieved for a driving vehicle.

Based ondifferent control variables used, the shift strategy can be classified as(1)Single- parameter shift strategy, (2) Double-parameter shift strategyand (3)Three-parameter shift strategy.

1) Single- parameter shift strategy

In general, the vehicle speed is regarded as the control variable, as shown in Fig. 1, if the speed increases up tov_2, the transmission is in second gear; if the speed goes down tov_1, the transmission would be placed in first gear. However, for a speed ranging fromv_1 to v_2, it could be eitherin first gear orsecond gear, suchshift strategy makes it difficult to achieve the fuel economy and vehicle power performance, and is unable to indicate the operator's intention, therefore, it is rarely adopted in practice.

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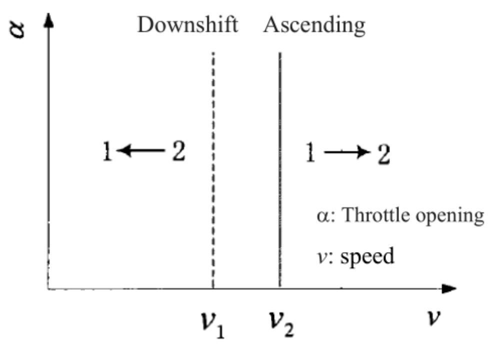


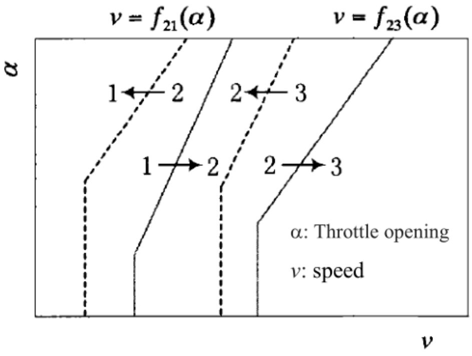
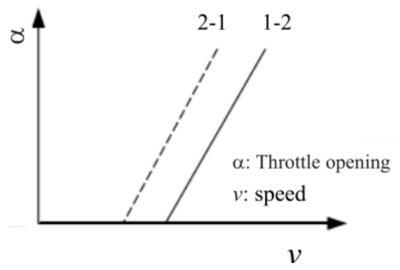


Fig.1 Single- parameter shift strategy

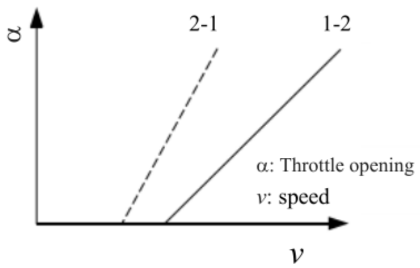
Fig.2 Double- parameter shift strategy

2) Double- parameter shift strategy

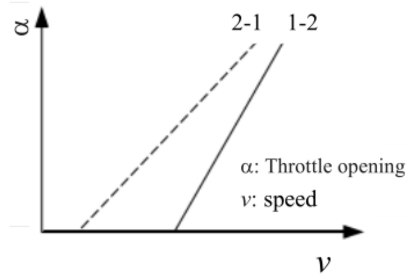
At present, the generally used shift strategy employs vehicle speed and throttle signalsas shift control parameters. As shown in Fig.2, the introduction of throttle signals allows for the indication of the operator's intention. Based onthe speed difference of gearing change, which varies with respect to the throttle opening, the shift delaycan be classified asequal delay type, convergent type, divergent type and combinatorial type.As shown in Fig.3(a), the equal delay shift strategy is the one that the speed difference of gearing changedoesnot change with respect to the throttle opening.As shown in Fig.3 (b),the divergentshift strategy is a schedule that the shift delay is divergent, which increases as the throttle opening decreases. As shown in Fig.3 (c), the convergentshift strategyrefers to the one that the shift delay is convergent, which decreases as the throttle opening increases. As shown in Fig.3 (d), the combinatorialshift strategy is the one that the optimal shift strategy is determined by the different throttle opening position, this shift strategy has been widely used in practical settings. Fig. 4 depicts a combinatorial shift strategy, which is employed by a fourgear automatic transmission, the solid line represents the upshifting curve, thedash line denotes the downshifting curve.



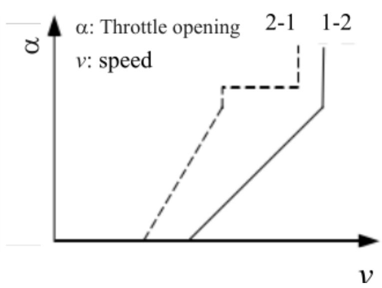
(a)equal delay type



(b)convergent type



(c)divergent type



(d)combinatorial type

Fig.3 Types of double- parameter shift strategy

3) Three- parameter shift strategy

Double-parameter shift strategy is based on the steady state of the vehicle, and the optimal shift point is determined by the optimal fuel economy or vehicle power performance.During the gear-shifting process, the vehicle is in a non-steadystate, where

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double-parameter shift strategy shows poor adaptability. The additive consideration of the vehicle acceleration would transform the double-parameter shift strategy into the three-parameter shift strategy: vehicle speed, throttle index(The opening angle of the engine throttle to change the intake of the engine) and vehicle acceleration, which can be used to determine gearshift timing in an automatic transmission system. This shift strategy can significantly improvevehiclepowerperformance, fuel economy and shifting quality, but it is difficult to achieve the realtime control, and the cost is high, which hinders its general application.

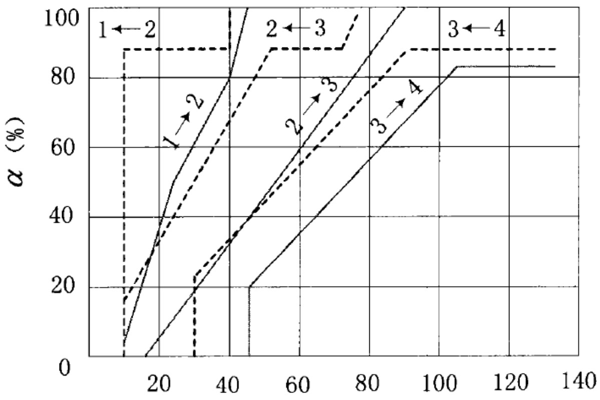
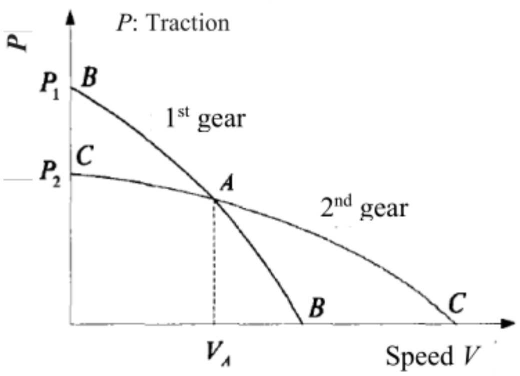


Fig.4 Combinatorial type of double- parameter shift strategy

II. PRINCIPLE OF DYNAMIC AND ECONOMIC SHIFT LAWS

Dynamic or economic shift strategy is based on the optimal vehicle driving dynamics or fuel economy optimization of the parameters that affect the shift to determine the gear changes with these parameters, so that the vehicle to obtain the best dynamic or Fuel economy. The best dynamic shift law is that the vehicle shifts at the intersection of the two acceleration curves under the same accelerator opening degree. The principle is shown in FIG. 5, thereby obtaining good shift comfort and reducing shift shock. The best economic shift law is that its objective function is that at a certain accelerator opening, the total fuel consumption should be minimized when the vehicle accelerates from a standing start to a certain set speed in situ, and its principle is shown in FIG. 6.



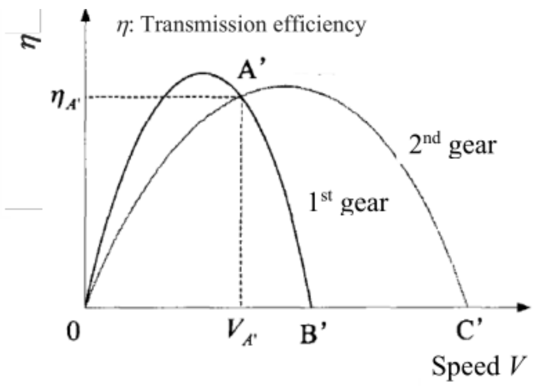


Fig.5 Gearshift for optimal vehicle Fig.6 Gearshift for optimal Power performancefuel economy

1) Dynamic shift law

If the transmission is in Nth gear, the acceleration of the vehicle isgiven by[3]:

$$\frac{dv_n}{dt} = \frac{g}{\delta_n G_\alpha}\left(F_{t(n)} - F_{\psi+\omega}\right) \tag{1}$$

where G_a is the weight of the vehicle, $\delta_n$is the conversion coefficient,$F_{t(n)}$is the traction when the transmission is in Nth gear,$F_{\psi+\omega}$is the sum of resistances of airs and road surfaces.

Note that the transmission acceleration is the same under different speeds, and it has:

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$$\frac{dv_n}{dt}=\frac{dv_{n+1}}{dt} \tag{2}$$

$$\frac{F_{t(n)}-F_{\psi+\omega}}{\delta_n}=\frac{F_{t(n+1)}-F_{\psi+\omega}}{\delta_{n+1}} \tag{3}$$

If the throttle is fixed, the vehicle engine torque $T_e$only depends on the rotational speedn_e.[4]

$$T_e=f(n_e) \tag{4}$$

And

$$F_{t(n)}=\frac{T_e i_o i_{g(n)}\eta_{PT}}{r_r} \tag{5}$$

where$i_0$is the transmission reduction ratio,$i_{g(n)}$is the transmission ratio in Nth gear, $r_r$is the rolling radius of the vehicle wheel, $\eta_{PT}$is the transmission gear efficiency of shafting.

Substitute Eqs.(4)and(5) into Eq.(3), the optimal vehicle speed $v_n$can be obtained. In general, the engine torqueT_e and the resistance$F_{\psi+\omega}$ can be approximated by a quadratic polynomial of v. It is worth noting that, if the obtained vehicle speed $v_n$in Nth gear is higher than the engine maximum speed, then, the gear shifting vehicle speed is the vehicle speed corresponding to themaximumengine speed. According to the experimental data, the optimal dynamic shift law is depicted in Fig.7.

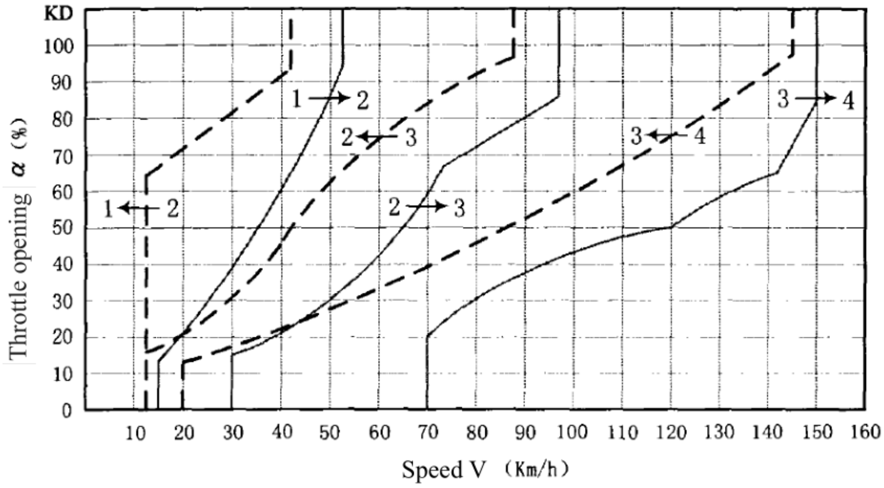

Fig.7 Gear shift law for optimal vehicle power performance

2) Economic shift law

The lowest L/100km scoreis taken as index to evaluate theeconomic shift law. During vehicle's accelerating process, its economic shift law aims to achieve the minimum fuel consumptionQ, when a vehicle is accelerated from rest to a certain speed [5].

$$Q=\int_0^t Q_T dt \tag{6}$$

whereQ_T is engine hourly fuel consumption

According to Eq.(1), it has:

$$dt=\frac{\delta_n G_\alpha dv}{g(F_{t(n)}-F_{\psi+\omega})} \tag{7}$$

Substitute the above equation into Eq.(6), hawse get:

$$Q=\int_0^v \frac{Q_T\delta_n G_\alpha}{g(F_{t(n)}-F_{\psi+\omega})}dv \tag{8}$$

If the throttle opening is constant, Q_T depends on the rotation speed n_e, and:

$$Q_T=f(n_e) \tag{9}$$

By finding the extreme value of Eq.(9), the minimum fuel consumption is obtained:

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$$\frac{dQ}{dv} = 0 \tag{10}$$

For two neighboring gears of the transmission, the following condition should be satisfied:

$$\frac{d}{dv}\left[\int_{v_{n-1}}^{v_n} \frac{Q_{T(n)}\delta_n G_\alpha}{g(F_{t(n)} - F_{\psi+\omega})} dv + \int_{v_n}^{v_{n+1}} \frac{Q_{T(n+1)}\delta_{n+1} G_\alpha}{g(F_{t(n+1)} - F_{\psi+\omega})} dv\right]$$

$$= \frac{d}{dv}\left[\int_{v_{n-1}}^{v_n} \frac{Q_{T(n)}\delta_n G_\alpha}{g(F_{t(n)} - F_{\psi+\omega})} dv - \int_{v_{n+1}}^{v_n} \frac{Q_{T(n+1)}\delta_{n+1} G_\alpha}{g(F_{t(n+1)} - F_{\psi+\omega})} dv\right] \tag{11}$$

$=0$

and

$$Q_{T(n)}\delta_n\left(F_{t(n+1)} - F_{\psi+\omega}\right) = Q_{T(n+1)}\delta_{n+1}\left(F_{t(n)} - F_{\psi+\omega}\right) \tag{12}$$

With the above equation and Eq.(10), the optimal vehicle speed $v_n$can be obtained. In general, the enginetorqueT_e and the engine fuel consumption characteristicsQ_T can be approximated by a quadratic polynomial of v, which has a satisfactory accuracy.

The fuel consumption ratio curves of two neighboring gears in transmissiondo not necessarily intersect, in this case,by connectingthe shift points at different accelerators,a curve can be obtained, which serves an alternative of the optimal economic shift law.

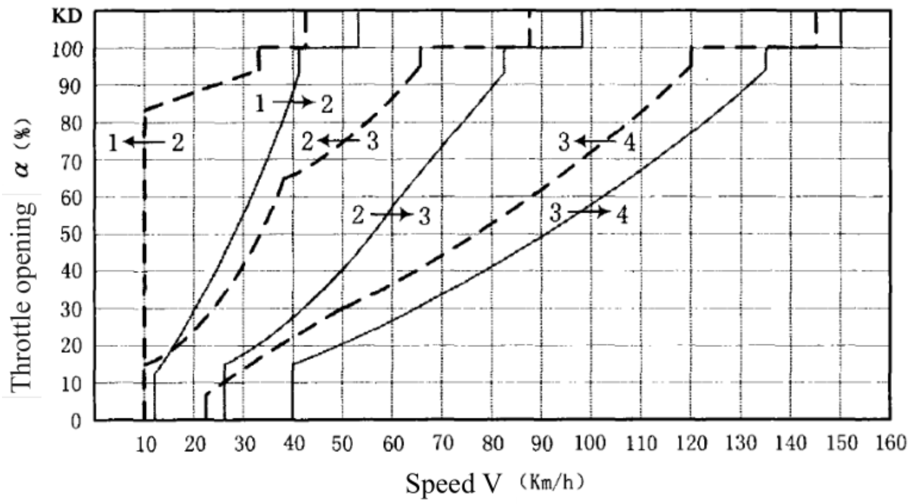

Fig.8 Optimal gearshift lawfor fuel economy

III. RELATIONSHIP BETWEEN DYNAMIC SHIFT LAW AND ECONOMIC SHIFT LAW

As shown in Fig.5 and Fig.6, either the optimal dynamic shift law or the optimal economic shift law is employed, as long as anoptimal shift point can be correctly identified, and the gear shift is performed, a significant improvement in terms of shiftquality can be achieved. If the optimal shift points of the two shift laws are the same, i.e. $V_A \neq V_A^{/}$, both the optimal dynamic shift and the optimal economic shift can be achieved.However, due to the penetration of hydraulic torque converter, this goal is almost unachievablefor the hydraulic transmission in practical settings. The penetration of the torque converter refers to the increase of the engine load when the rotating speed of the torque converter decreases as the load increases. Since the connection between the engine and the pump wheel of the torque converter is rigid, the performance of the engine is affected by the performance of the torque converter. Therefore, the two shift points cannot coincide, that is, $V_A \neq V_A^{/}$。

Thus, it is difficult to guarantee the optimal dynamic shift law and optimal economic shift law at the same time, a choice has to be made according to the practical settings. Although the shift critical points of the two shift laws may not be the same, but their difference would not be large, that’s to say, the vehicle speed for the optimal dynamic shift law is close to that of the optimal economic shift, hence, it is possible to ensure the control objectives.

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As shown in Fig.5 and Fig.6, if the optimal dynamic shift law in Fig.5 is employed as the basic shift strategy, then, the optimal economic shift law should be adopted as the additional shift strategy. In general, the fluid torque converteroverlaps slightly, and is continuous in the high-efficiency area of each gear in transmission. The high-efficiency area can be set in advance, which is generally above 70%, therefore, when performing the optimal dynamic shifting, as long as the driver can shift gear in time such that the working point of the fluid torque converter is around the peak of the efficiency curve, the vehicle transmission system can operate at the high-efficiency area.

IV. CONCLUSION

This paper classifies the vehicle gear shifting strategy, the emphasis is put on the principle of the dynamic and economic shift law. According to the vehicle acceleration characteristics and fuel consumption characteristics, a discussion is performed for the dynamic, economic, and some suggestions are given about the overall gear shift law.

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