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Optimization of gearshift MAP based on DP for vehicles with automated transmission

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Dear editor,

The gearshift system is the key part of an automatic transmission vehicle that optimizes power and economy. An accurate and reasonable shift schedule has a significant theoretical and practical meaning for improving both dynamic and economic performances because it defines the control parameters used for the gearshift decision making and shift timing [1–3]. One gearshift strategy is to establish an optimal control problem to improve the overall performance. In the face of complex road conditions and individual driving requirements, many researchers adopt the method of building an intention recognition model to correct the shift schedule in real time [4, 5]. However, the optimal problem cannot be approximated as a continuous one because the gear ratio is discrete, thereby making it a nonlinear problem, which is challenging to solve. Thus, the nonlinear optimization is often time consuming and not suitable for online implementation to a certain extent [6, 7].

The other strategy is based on a static shift map, which determines the gear position and shift timing using the current speed and acceleration pedal. A gearshift map is traditionally based on know-how, experience of the calibration engineers, and tunings in a heuristic manner. This method has been widely adopted as a standard solution for shifting gears online in practical automotive engineering because it is relatively robust, and takes less computational effort. Traditional methods for calibrating a gearshift map can be found in [8, 9]. However, they only select either the optimal dynamic gearshift schedule or the optimal economic gearshift schedule and, hence, would not be able to fully provide the comprehensive performance of vehicles.

Driven by the above mentioned ultimate goal, this study proposes a designing approach of calibrating a gearshift map by combining the optimal-control-based method and the traditional experience-based method. Under multiple driving cycles, the engine fuel consumption is the objective function; the gear shifting sequence is the control input; and the current gear position is the state variable. The global optimal solution and the corresponding shift schedule can be obtained by dynamic programming (DP). Based on the optimal results, the acceleration pedal positions, speed values, and corresponding gears can be obtained using a vehicle simulation model built in AMESim. Finally, the primary shift lines can also be derived. We then consider a dynamic performance to tune the parameters in the primary shift lines for a comprehensive performance. The simulation results show that the designed gearshift map is better than the traditional fuel economy dominated gearshift schedule both in energy efficiency and

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power performance.

Objective function based on DP. The objective of the gearshift optimization is to schedule the gearshift to minimize fuel consumption. This is formulated as a DP problem in

$$J_k^*(x(k)) = \min_{u(k)} Q_t(k) \ + J_{k+1}^*(x(k+1)), \quad (1)$$

where J_k^* represents the optimal cost at the time step k; Q_t is the fuel rate; $x(k)$ denotes the state variables; and Δt is the time interval. The derivation process of the dynamic programming algorithm and the optimal sequence of the gear ratio are derived in three kinds of driving cycle.

Building model. After obtaining the optimal overall gearshift schedules in new European driving cycle (NEDC), urban dynamometer driving schedule (UDDS), and 10-15, we used the resulting optimal gearshift schedules to derive the relationship of the accelerator pedal position, vehicle speed, and gear position to control the transmission in the commercial software AMESim. In the AMESim simulation environment, the aerodynamic and brake characteristics in the car body module, effect of gearshift and engine losses, transmission gear efficiency, primary shaft inertia, and powered axle efficiency in the transmission module were considered in different parts of the established simulation modeling. A gearshift logic control model was built in MATLAB/Stateflow. This model implemented the logic used to choose the target gear according to the established gearshift schedule.

Making shift schedule based on DP. We can extract the gear position data, throttle opening, and vehicle speed in each of the driving cycles by running the simulation model. The optimal gear operational points are plotted on the standard transmission shift map in Figure 1(a). Finally, the maximum overlapping region of the gear operational points of the three drive cycles was found through the gearshift map, and the optimal gear shifting schedule was drawn. We can derive the initial downshift and upshift lines from the initial map obtained by covering the maximum overlap region. Several gearshift maps were obtained to improve the fuel economy of the gearshift lines by displacing the gearshift curves into several units. The corresponding fuel consumption was then obtained. The final optimal gearshift map was obtained by comparing these fuel consumption values. The results showed that the final downshift and upshift lines were determined by the displacement units of -5 and 0, respectively.

Traditional methods of making the shift schedule. The traditional power- and economy-based shift schedules were designed to evaluate the fuel economy of the optimized gearshift schedule. The power-based shift schedule was designed by taking the velocity point at the same accelerations between the adjacent gears under the same throttle opening. Its simplified form is presented as follows:

$$T_e(i_{g,n}, v, \alpha) i_{g,n} = T_e(i_{g,n+1}, v, \alpha) i_{g,n+1}, \quad (2)$$

where v is the speed; T_e is the engine output torque; i_g is the gear ratio; and α is the certain throttle opening. $T_e(\cdot)$ can be expressed in a form of a steady-state engine map, and is a function of the engine speed and the accelerator pedal position. According to the experimental data of the engine torque, speed, and partial parameters of the vehicle, the velocity and the acceleration curves of the adjacent gears can be obtained, as well as the intersection point, which is then chosen as the up-shift point. These points can generate the overall gearshift lines. Note that the up-shift schedule curves can be fitted by cubic spline interpolation, while the down-shift schedule curves can be obtained by moving the upshift lines left reasonably. Accordingly, the power-based shift schedule was drawn.

The basic principle of the economic shift schedule was to make the engine work in the high-efficiency area. The gearshift point in the economy-based strategy was determined by the timing that the fuel rate using the adjacent gears was the same under the same throttle opening α and vehicle speed. That is,

$$\begin{aligned} &Q_t(T_e(i_{g,n}, v, \alpha), \omega(v, i_{g,n})) \\ &\quad = Q_t(T_e(i_{g,n+1}, v, \alpha), \omega(v, i_{g,n+1})), \end{aligned} \quad (3)$$

where Q_t is the fuel rate, and ω is the engine speed. Similar with the method of the power-based shift strategy, we can obtain the economy-based gearshift map using different vehicle speeds, throttle pedal opening, and other parameters.

Performance evaluation and improvement. Several comparison simulations were conducted using the designed three control maps to observe the fuel economy of the proposed method. By running the simulation and obtaining the data of the engine operation points, the throttle opening and the fuel consumption were found under the three driving cycles. The results showed that the engine operation points arising from the DP- and economy-based gearshift strategies were mostly located on the higher efficient zone of the engine compared with the power-based gearshift schedule.

Meanwhile, the results of the throttle opening in different driving cycles used the power-and DP-based controller. Figure 1(b) illustrated that although the DP-based gearshift map can reduce

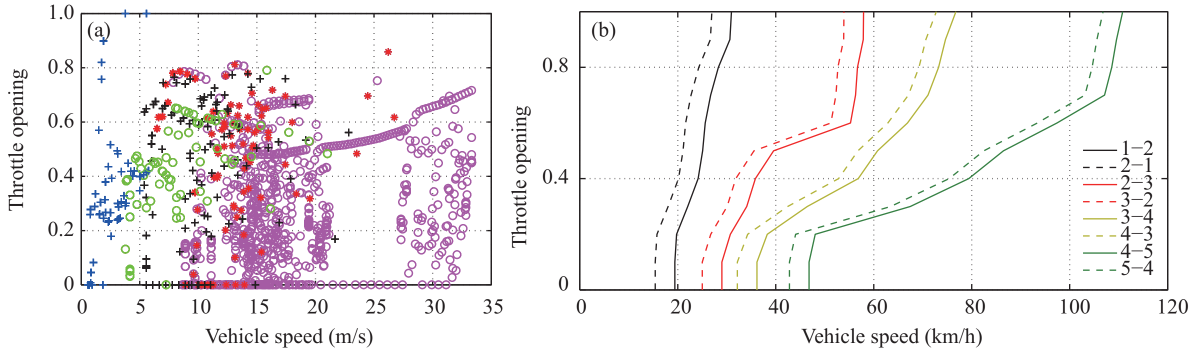

Figure 1 (Color online) (a) Gear operational points of the three driving cycles and (b) the optimized DP-based gearshift schedule map.

fuel consumption, the average throttle opening was higher, indicating a performance loss of drivability. In this study, we added a parameter to reduce the influence of the dynamic performance of the DP-based map and adjust the DP-based gearshift lines. These upshift and downshift lines tended to move right with the increase of the throttle opening. From the throttle opening results after the adjustment, the dynamic performance then improved.

Conclusion. In this study, an optimal gear shifting schedule for a conventional gasoline vehicle equipped with a five-speed automated manual transmission under multiple driving cycles was found using DP. An adjustment approach was added to reduce the influence of the proposed method on the dynamic performance and provide the optimized gearshift map with a good fuel economy without sacrificing power. The gear shifting schedule derived from the DP algorithm obtained a better fuel consumption economy of over 5% compared with the traditional gear shifting schedules.

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