A Control Strategy of ACC System Considering Fuel Consumption

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Aiming at heavy-duty vehicle, a fuel optimal ACC system controller using consolidated action of throttle and gear is designed in this paper. Based on the investigation of fuel consumption characteristics in lower layer system with inverse model, a combined throttle and gear control algorithm is proposed to realize engine operational points track optimal fuel economic curve, thus minimizing fuel consumption rate. Computer simulation with a nonlinear heavy-duty vehicle model is carried out and its results show that the proposed control system can improve the fuel economy of ACC vehicle without sacrificing its tracking performance.

1. INTRODUCTION

In the research field of driver assistance system, adaptive cruise control system (ACC) has been widely investigated due to its potentials for reducing the workload of drivers, enhancing the safety and convenience, and increasing the traffic capacity of existing highways. Currently, most of the ACC products applicable for vehicles aim at tracking the preceding vehicle precisely, however, with increasing customer requirements for energy conservation, the optimization problem of fuel consumption begin to draw the researchers’ attention in the design of future ACC control strategies.

By surveying the effects of ITS on energy conservation, Sadayuki Tsugaw has pointed out that besides road capacity the vehicle platoon has a function to improve vehicle’s fuel economy due to maintain smoothing traffic and reduce the following vehicle’s aerodynamic drag [1]. On the basis of this concept, a modified PID type following controller was designed and computer simulation in acceleration condition demonstrated that the last vehicle’s fuel consumption could be saved by 9% in an eight heavy truck string [2]. In order to improve fuel economy in ACC system, Johan Jonsson et al proposed a Stop and Go control method based on Dynamic Programming theory, in which fuel consumption was optimized by choosing a cost function of vehicle states[3]. Because the control strategies above only depend on throttle control, which implies that fuel consumption of vehicle is directly relevant to the acceleration level, the tracking performance is somewhat sacrificed inevitably at the moment fuel economy becomes better. To deal with this problem, a cruise controller using gain scheduling method is designed to regulate engine speed while the optimal gear ratio for fuel economy is given simultaneously [4]. Additionally, based on the similar strategy, cruise control system for motor vehicles with CVT was developed and its improvement on fuel economy is proved by computer simulation [5]. In the two systems above, consolidated engine and transmission control method presents its potential to improve fuel economy. But, its application is only limited to cruise control system by now.

In order to reduce the fuel consumption while maintaining good tracking performance for ACC system, a fuel optimal controller is designed in the paper using consolidated action of throttle and gear. Aiming at the characteristics of heavy-duty vehicle’s driveline, an inverse longitudinal model based lower layer system is developed, followed by the investigation of its fuel consumption characteristics. Combined throttle and gear control algorithm is proposed to realize engine operational points track optimal fuel economic curve as close as possible on the premise of maintaining desired engine output. And computer simulation in acceleration scenarios is carried out to validate the tracking and fuel-saving performance of the proposed ACC control system finally.

2. Construction of inverse longitudinal model

The fundamental of ACC system is that according to information such as inter-vehicle distance, relative speed and vehicular velocity measured by sensors mounted on the following vehicle, an engine and brake feedback control law is employed to keep the following vehicle tracking the preceding one based on a specific headway policy. Currently, two-layer control strategy has been used widely to implement the ACC controller, in which the upper layer outputs desired acceleration and the lower layer system realizes the acceleration tracking [6]. Because this paper gives emphasis...
on acceleration case, two ACC controllers only relevant to engine control is designed. One is based on inverse longitudinal model and the other is based on consolidated action of throttle and gear. For the purpose of concision, they are called controller A and controller B, respectively.

Figure 1 shows a conceptual schematic diagram of a heavy duty vehicle’s powertrain system. It consists of such assemblies as diesel engine, clutch, automatic transmission, final gear and wheel. A full order nonlinear longitudinal vehicle model has been constructed before and will be used for computer simulation in section 5.

![Fig. 1 Conceptual Schematic diagram of powertrain](image)

In order to simplify the inverse longitudinal vehicle model, it is assumed that (1) The engine dynamics due to intake and combustion delay is neglected; (2) The engagement and disengagement of clutch are finished instantaneously, as well as the gear switching of automatic transmission; (3) Vehicle runs on dry asphalt road straightly and the driven torques acting on left and right shafts equal approximately; (4) There is no slip between tyre and road. Figure 2 shows the block diagram of the inverse model.

![Fig. 2 Inverse longitudinal vehicle model](image)

According to the desired acceleration command \( a_{des} \) given by upper layer system, the desired traction force acting on driven wheel \( F_{edes} \) is computed from the following equation:

\[
F_{edes} = F_a + F_R + \delta ma_{des}
\]

\[
= \frac{1}{2} C_{d} \rho A \nu_j^2 + mgf + \delta ma_{des},
\]

where \( F_a \) denotes aerodynamic drag, \( F_R \) denotes rolling resistance, \( \nu_j \) is the following vehicle velocity, \( m \) is vehicle mass, \( \delta \) is mass factor and \( C_{d} \rho A \) are aerodynamic coefficient, gravity constant and friction coefficient, respectively. Considering the inverse model of wheel, transmission and final gear, the desired engine torque \( T_{edes} \) is derived from:

\[
T_{edes} = \frac{F_{edes} r}{i_g \cdot i_h \cdot \eta_T},
\]

where \( r \) is effective radius of wheel, \( i_g \) and \( i_h \) denote ratio of transmission and final gear, \( \eta_T \) denotes powertrain efficiency. And the desired throttle angle, \( a_{thdes} \), for the given engine torque \( T_{edes} \) and engine speed \( \omega_e \) can be calculated from inverse engine map described by equation(3) and the inverse longitudinal vehicle model is obtained ultimately.

\[
a_{thdes} = Map^{-1}(T_{edes}, \omega_e).
\]

In theory the output of lower layer system identifies the input completely, however, due to parametric uncertainties and unmodeled dynamics of actual vehicle plants, they are somewhat inconsistent and a first order system is used to model this disagreement:

\[
a_f = \frac{K}{T_S + 1} a_{des},
\]

where \( K, T \) denote the estimated parameters. Considering the dynamic characteristics of lower layer system, a state space model for following and preceding vehicle can be written as equation (5) by employing the constant-time headway policy.

\[
\begin{bmatrix}
\Delta d \\
\Delta v \\
\Delta a_f \\
\dot{a}_f
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & -\tau_h & 0 \\
0 & 0 & -1 & 0 \\
0 & 0 & -1/T_i & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta d \\
\Delta v \\
\Delta a_f \\
\dot{a}_f
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
0 \\
1/T_i
\end{bmatrix} a_{des} + \begin{bmatrix}
0 \\
0 \\
0 \\
K/T_i
\end{bmatrix} a_f,
\]

where \( \tau_h \) is headway time, \( \Delta d \) is the error between actual distance and desired headway, \( \Delta v \) is the relative speed and \( \dot{a}_f \), \( a_f \) denote acceleration of preceding and following vehicles, respectively. By using linear quadratic optimal control theory, the state feedback law

\[
a_{des} = Kx,
\]

is chosen to minimize the cost function:

\[
J = \int_0^\infty \left( x^T Q x + R \cdot a_{des}^2 \right) dt,
\]

where \( x \) represents the system states, \( Q \) and \( R \) are weighting matrices which give a tradeoff between tracking performance and ride comfort.

3. Fuel economy analysis of Controller A

Before analyzing the fuel consumption characteristics of ACC vehicle with controller A, let’s review the fundamental design process of a powertrain. In a product vehicle, fuel economy and power performance is two of the most concerned issues. To compromise between them, the reasonable matching of engine and drive line, in particular engine and transmission, is necessary. Due to the following reasons: (1) power requirements in such conditions as upgrade and overtake; (2) the unknown acceleration level in an actual traffic flow, the finished powertrain usually have the potential to provide redundant traction force, which results in low engine load and consequently increase the fuel consumption. This can be illustrated by figure 3, in which star line represents engine operational points of ACC vehicle with controller A and dotted line represents optimal fuel economic curve. The fact that the former keeps away from the latter indicates that the fuel consumption rate is not optimal in ACC vehicle with controller A and it is possible to
reduce fuel consumption by regulating engine operational points skillfully.

It happens that there is not overtake situation in an ACC system and the desired acceleration is also known due to the existence of upper layer system. This indicates that the required engine output can be determined in advance and redundant power which results in low engine load is no more necessary in an ACC-activated vehicle. For a given engine power, the optimal fuel economic curve has minimum fuel consumption rate. If we can regulate engine to operate around it, fuel economy of ACC vehicle is possible to be improved. Moreover, vehicle’s tracking performance is still maintained because the desired acceleration required by upper layer system is guaranteed.

However, pure throttle control doesn’t suffice for the need due to the influence of the fixed shift schedule of automatic transmission. Therefore, apart from the throttle actuator, the real-time adjustment of gear ratio is also necessary so as to develop a fuel-saving lower layer control system. Because the desired acceleration given by upper layer system reflects the requirement for ACC vehicle arising from road traffic and the control of throttle angle and gear ratio, even a specific shift schedule for ACC-activated layer system reflects the requirement for ACC vehicle arising from road traffic and the control of throttle angle and gear ratio. As a case in points, a lower layer system above can be regarded as the matching between powertrain and traffic flow. As a case in points, a lower layer system based on consolidated action of throttle and gear is developed in the following section.

4. Combined throttle and gear control algorithm design

![Fig. 4 Combined throttle and gear control algorithm](image)

The basic principle of combined throttle and gear control algorithm is to make the engine operational point track optimal fuel economic curve as close as possible while maintaining desired engine power. Figure 4 shows its schematic diagram, which consists of three parts: desired power calculator, optimal engine states calculator and assistant gear-switch compensator. The first part is used to calculate the desired engine power according to control command given by upper layer system. The second part is to compute desired throttle angle and desired engine speed according to optimal fuel economic curve. The last part is to reduce the error of desired and actual gear ratio by adjusting the gear-shift of automatic transmission.

According to vehicle current states and desired acceleration command given by upper layer controller, the desired engine power \( P_{edes} \) can be calculated by the following equation:

\[
P_{edes} = \frac{1}{\eta_f} \left( mgfv_f + \frac{1}{2} C_D \rho A v_f^3 + \delta mv_f a_{des} \right)
\]  

(8)

Using formula \( P_e = \omega_e T_e \), the mathematical description of optimal fuel economic curve in terms of engine output and engine speed can be derived from figure 3:

\[
P_e = f(\omega_e)
\]  

(9)

In optimal engine states calculator, the desired engine speed \( \omega_{edes} \) can be calculated from \( P_{edes} \) through inverse function of equation (9) and subsequently the desired throttle angle \( \alpha_{des} \) can be computed by engine MAP according to obtained \( \omega_{edes} \).

In the heavy-duty vehicle, two-variable shift schedule of AT depends on vehicle speed and throttle angle, in which the former has a stronger effect of the switching of gear. In order to keep engine operating on the desired operational points, the actual engine speed and throttle angle should be adjusted to approach the desired value \( \omega_{edes} \) and \( \alpha_{des} \) as close as possible. To track \( \omega_{edes} \), an assistant gear-switch compensator is designed to retune gear switching on the basis of original economic mode shift schedule. Figure 5 shows its block diagram. The desired gear ratio \( i_{ges} \) is derived from actual vehicle velocity and desired engine speed and its difference with the actual gear ratio \( i_g \) is fed back to a PID controller. The output of PID controller is employed to compensate actual vehicle velocity, giving virtual signal \( v_f' \) to automatic transmission.

![Fig. 5 Assistant gear-switch compensator](image)

Theoretically, engine speed would approach the desired engine speed if the actual gear ratio equals the desired value. Considering the input on the throttle, engine will work close to optimal fuel economic curve, thus generating minimum fuel consumption rate. Moreover, due to equation (8), desired acceleration given by upper layer controller is guaranteed, which implies tracking performance is not sacrificed.

Similarly to controller A, the upper layer controller can be designed by linear quadratic optimal control theory and consequently controller B is achieved.
5. Simulation results

In the foregoing sections, the ACC controller A is designed based on inverse vehicle model and controller B is based on consolidated action of throttle and gear, which is intended to be more fuel-saving. In order to validate the performance of those controllers, a series of computer simulations in acceleration scenarios are carried out based on a full order nonlinear longitudinal heavy-duty vehicle model. Additionally, due to two types of shift schedule fixed with heavy-duty vehicle, controller A is simulated under economic mode and dynamic mode, respectively.

Considering four typical acceleration scenarios, acceleration profiles of preceding vehicle are selected to be sinusoidal signal with parameters as Table 1. Figure 6(a) shows the preceding vehicular velocity profile.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Frequency (rad/s)</th>
<th>Amplitude (m/s²)</th>
<th>Bias (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>II</td>
<td>0.6</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>III</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>IV</td>
<td>0.3</td>
<td>0.5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

The preceding and following vehicle have the same initial speed 1m/s, and initial distance is set as 9 m. To compare the performance of those controllers, parameters of upper layer controller are selected to be identical, that is $K = [-2.2, -2.3, 4.3]$.

Figure 6(b)(c)(d) shows the tracking errors of acceleration, velocity and distance, which are defined as the difference between preceding and following acceleration, the difference between preceding and following velocity, the difference between actual and desired inter-vehicle distance, respectively. A-E Mode denotes controller A under economic mode and A-D Mode denotes controller A under dynamic mode. From $t=0s$ to $t=15s$, ACC controllers regulate the states of following vehicle to eliminate the initial clearance error. From $t=15s$ to $t=45s$, the following vehicle is under steady following scenario, however, acceleration error and velocity error vary in bounded ranges rather than convergence to zero due to variational preceding vehicle. From $t=45s$ to $t= 60s$, for the limited maximum velocity of the following heavy-duty vehicle is smaller than the preceding one, the absolute value of distance error increases inevitably as the velocity error between two vehicles augments. The simulation results in period $[0s, 45s]$ show that the velocity and distance errors are basically the same, which indicates that the tracking performance of controller B is not reduced compared with controller A.

Figure 7(a) shows gear ratio under controller A and B in scenario III. Simulation results show that actual gear ratio under controller B tracks desired value more precisely than controller A, which indicates engine is in higher fuel-saving operating area. Additionally, as shown in figure 7(b), engine operational points under controller B are closest to optimal fuel economic curve. Controller A with economic mode and dynamic mode takes the second and third place. This is consistent with the foregoing analysis.

Figure 8 shows bar graph of fuel consumption at the end time of four acceleration scenarios. Simulation results show that controller B has better fuel economy than controller A, even though under economic mode. In order to quantify the
performance of fuel economy, a relative fuel-saving degree (RFD) is defined as

\[ RFD = \frac{L_A - L_B}{L_A} \times 100\% \]  

where \( L_A \) denotes fuel consumption of following vehicle with controller A, \( L_B \) denotes that of following vehicle with controller B. By simple calculation, we know that fuel consumption of controller B is reduced by 4.94% in average compared with controller A under economic mode, by 12.6% compared with controller A under dynamic mode.

From those simulation results, it is conclude that the ACC controller based consolidated action of throttle and gear can improve fuel economy of following vehicle while the tracking performance is basically not influenced.

6. CONCLUSION

Aiming at the fuel economy problem, a fuel optimal controller using consolidated action of throttle and gear is implemented for ACC system in this paper after investigating fuel consumption characteristics of inverse model based lower layer system. Theoretical analysis and computer simulation indicate that:

(1) Due to the consideration of redundant acceleration performance in shift schedule of automatic transmission, engine load in lower layer system with pure throttle control usually is low and fuel consumption rate has the potential to be decreased further;

(2) The proposed lower layer system based on consolidated action of throttle and gear can minimize fuel consumption rate by making engine operational points track optimal fuel economic curve. In nature, this method can be regarded as reasonable matching between traffic flow and powertrain.

(3) ACC system based on consolidated action of throttle and gear can improve fuel economy of ACC vehicle while maintaining the same tracking performance as that with inverse longitudinal model.

REFERENCES