Double-Mode Vehicular Electronic Throttle for Driver Assistance Systems

Dezhao ZHANG, Jianqiang WANG, Shengbo LI, Lei ZHANG, Keqiang LI

Abstract—**Normally used electronic assistant throttle actuators for R&D of vehicle longitudinal driver assistance systems, such as ACC, may conflict with car's primary throttle system and have inconvenience in switch between ACC control and driver operating. In order to overcome the disadvantages abovementioned, this paper addresses the design, control and experiments of a Double-Mode Electronic Throttle (DMET) which can be operated by ACC and driver synchronously. First, based on the existing electronic throttle system the structure of the DMET is designed. Then, focusing on the time delay of the DMET, a gain-adaptive Smith predictor based on a identified transfer function is set to get better system dynamic performance. Furthermore, in order to achieve seamless switch between ACC control mode and driver operating mode, a dead zone restriction is introduced to the controller. Finally, the system performance in tracking ACC desired throttle angle and switching between two operating modes is confirmed by series of experiments.**

Key words—**Driver assistance system; ACC; Throttle control; Gain-adaptive Smith predictor**

I. Introduction

As one part of driver assistance systems, Adaptive Cruise Control (ACC) system, targeting the improvement of traffic flow, driving safety and workload relief for the driver, has attracted great attention of automotive manufactures and research institutions around the world. In order to realize inter-vehicular distance control and cruise control, ACC must be able to regulate engine torque and brake pressure automatically [1]. To satisfy the requirement of automatic engine torque regulation, the key issue is to develop an electronic throttle control device which can adjust the throttle angle driver-independently.

Generally, there are two methods to attain the abovementioned purpose. One is based on the car's primary electronic throttle system. The automotive manufactures achieve the goal by modifying the program of engine ECU. But the changed control logic of engine may disturb the normal engine operating conditions, demanding great workload to improve it. Moreover, it is not applicable for most of the automotive research institutions because the program of the engine ECU is unopened to them. The other is to add a motor actuator to the throttle valve. The throttle angle can be automatically adjusted by the added motor. But the supplementary always conflicts with the primary actuator device and the switch between the two actuators is always untoward. In addition, the fixing of the supplementary is also a difficulty.

In this study, the design, control and experiments of a Double-Mode Electronic Throttle (DMET) were implemented. The DMET system which can be operated by ACC and driver synchronously was first designed based on the gasoline car's primary electronic throttle. Its working modes can be switched according to different control requirements. Then, in order to eliminate the influence of time delay of the system, the transfer function of the controlled plant was identified and then a gain-adaptive Smith predictor based PID controller was designed. To achieve seamless switch between ACC control mode and driver operating mode, a dead zone restriction was recommended to the PID controller. Finally, series of experiments using a test vehicle were implemented to validate the performance of the proposed DMET system.

II. Design of DMET structure Review Stage

Fig.1 shows a primary electronic throttle system of a general gasoline engine. It consists of an acceleration pedal position sensor, an engine ECU and a throttle actuator body. When a driver manipulates the acceleration pedal, the pedal position sensor converts the acceleration position into an analog voltage signal and then transmits it to the engine ECU which can figure out the desired throttle angle according to acceleration pedal position and current engine operating state. Then the engine ECU drives the throttle actuator to track the desired throttle angle by a closed-loop control [2] [3].

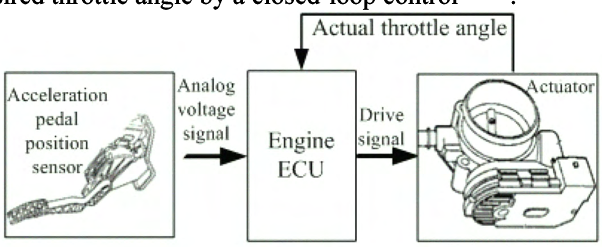

Fig.1. Schematic diagram of electronic throttle system

Here, based on the primary electronic throttle system, the

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designed DMET system is shown in Fig.2. Compared with the primary electronic throttle system, the DMET controller is the unique additional hardware. The acceleration pedal position sensor is connected to the DMET controller rather than the engine ECU. And the output terminal of the DMET controller links to the engine ECU. Besides, in order to carry out a closed-loop control, the actual throttle angle must be accessible for the DMET controller.

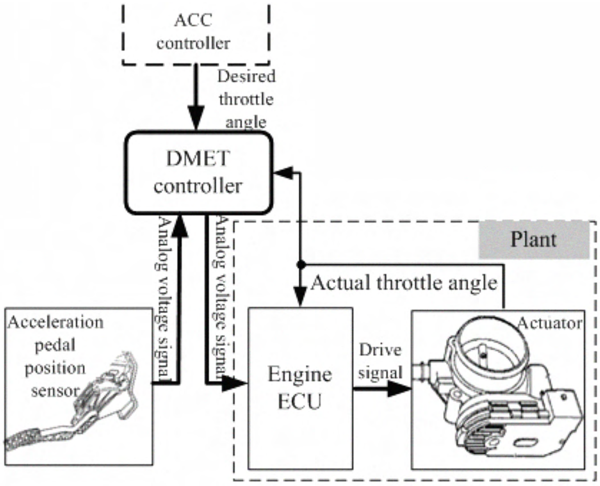


Fig.2. Schematic diagram of DMET system

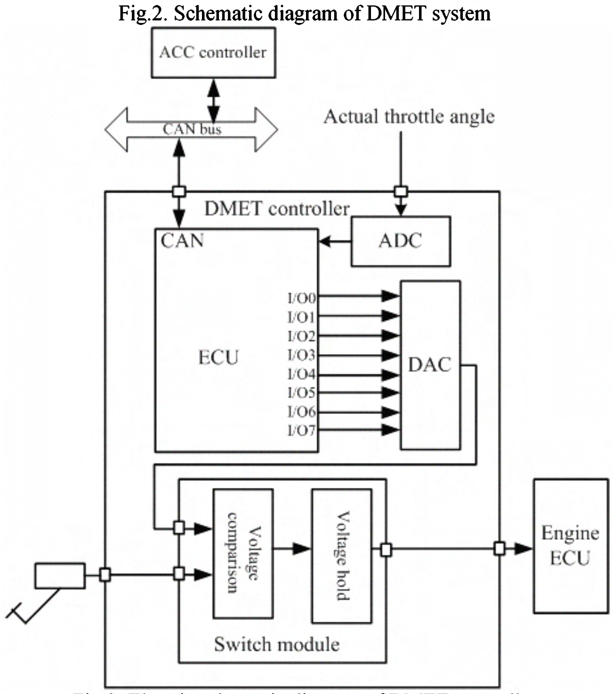


Fig.3. Electric schematic diagram of DMET controller

Fig.3 shows the electric schematic diagram of DMET controller. The DMET controller gets the throttle angle demand from the ACC controller via a CAN bus and gets the actual throttle angle signal from the throttle angle sensor via an AD conversion module. And then the control variable will be figured out by the DMET controller with suitable control-software. A DA conversion module is set to convert the control variable into an analog voltage signal which is equivalent to the output of the acceleration pedal position sensor. Mark the former as U_1 and the latter as U_2. Then U_1 and U_2 are in proportion to the desired throttle angle of ACC system and driver respectively.

DMET controller achieves seamless switch of throttle angle demands between ACC controller and driver via a switch module. The switch module compares U_1 and U_2 via a voltage comparison module and output the bigger one. That is to say, the greater one of the two voltage values determines the resulting throttle angle:

$$U_{out}=\max(U_1,U_2) \qquad (1)$$

To prevent the output from the influence of follow-up circuit load, DMET controller utilizes operational amplifiers to hold the output. Thereafter, the analog voltage is outputted to the engine ECU, driving the throttle actuator to track the demands of ACC system or driver.

Based on the DMET controller, the DMET system can switch between ACC control mode and driver operating mode according to different control requirements. For example, during adaptive cruise control actuation the driver can take over accelerating action at any time via acceleration pedal intervention to override the throttle angle value set by ACC. The DMET can recognize the driver's speeding purpose by comparing U_1 and U_2 and then control the throttle to obey the driver. This can also happen vice versa, that means that if the driver releases the acceleration pedal, the DMET can control the throttle in response to the ACC's demand at once. Consequently, the DMET system can not only satisfy the requirement of ACC system but also can recognize the purpose of driver and assure driver's priority.

III. CONTROL ALGORITHM OF DMET SYSTEM

It can be seen from Fig.2 that the controlled plant of DMET controller is essentially a closed-loop system which consists of an engine ECU and a throttle actuator. Tests show that the plant has a large time delay which result in a biggish tracking hysteresis of the whole DMET system.

The Smith predictor is a popular and very effective long dead-time compensator because it can take the time delay outside the control loop in the transfer function relating the control output to set point [5]. Hence, a Smith predictor based PID controller is designed here to get better system dynamic performance [8].

Because the design of Smith predictor depends upon an accurate mathematical model, the transfer function of the plant is identified first. Typical Smith predictor is so sensitive to the accuracy of predictor model that it is hardly used in practical engineering, so a modified gain-adaptive Smith predictor structure is employed to design the DMET controller. Furthermore, in order to achieve seamless switch between driver operating mode and ACC control mode, a dead zone is introduced to the PID algorithm.

A. Transfer function identification

Because step test needs little equipment and can even be performed manually, a step test based identification method is used here to identify the transfer function of the plant. Fig.4 shows the step response of the controlled plant, from which we can see it has characteristics of typical first-order plus dead-time model. Hence, we assume that the transfer function of the plant is as Eq. (2).

$$G(s)=\frac{K}{Ts+1}e^{-\tau s} \quad (2)$$

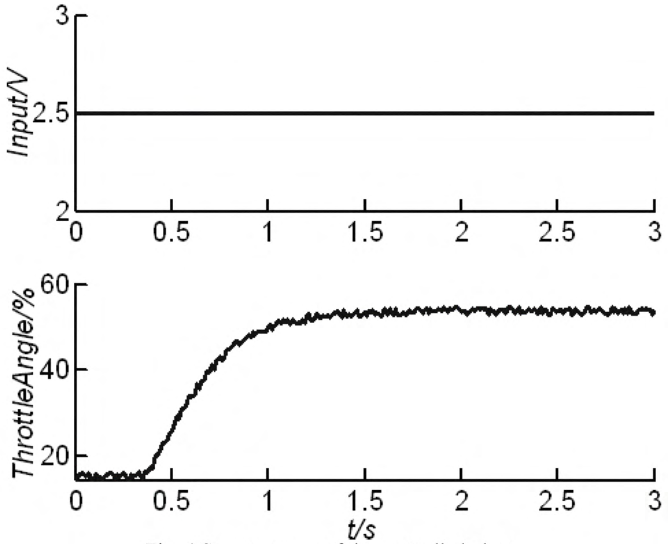


Fig. 4 Step response of the controlled plant

Refer to [7], when the measurement noise is a white noise, the estimation of the first-order plus dead-time model parameters can be obtained using the least-squares method as

$$\theta=\left(\Psi^T\Psi\right)^{-1}\Psi^T\Gamma \quad (3)$$

where $\theta=[K,\tau K,T]^T$,

$$\Psi=\begin{bmatrix} hmT_s & -h & -y[mT_s] \\ h(m+1)T_s & -h & -y[(m+1)T_s] \\ \vdots & \vdots & \vdots \\ h(m+n)T_s & -h & -y[(m+n)T_s] \end{bmatrix},$$

$$\Gamma=\begin{bmatrix} A[mT_s] \\ A[(m+1)T_s] \\ \vdots \\ A[(m+n)T_s] \end{bmatrix},$$

$$A(t)=\int_0^t y(l)dl,\ t\geq\tau.$$

Ts is the sampling interval and here T_s=0.01s. h is the input amplitude and here h=2.5V. y is the output of the plant. We get m=39 by

$$y[mT_s]\geq 15\%+2B_n$$

where 15% is standby throttle angle, B_n is the noise band and here B_n=1%.

We get n= 87 by

$$y[(m+n)T_s]\leq 95\%\times\max(y)$$

Utilizing equation (3) and the step test result, θ can be obtained as

$$\theta=[K,\tau K,T]^T=[21.4744,5.5136,0.3289]^T$$

It means that K=21.4744, τ =0.2568, T=0.3289. Then the transfer function of the plant is

$$G(s)=\frac{21.4744}{0.3289s+1}e^{-0.2568s} \quad (4)$$

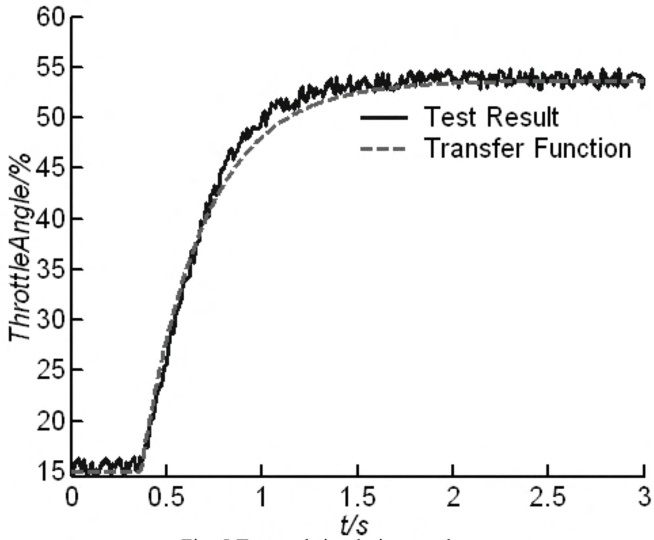


Fig. 5 Test and simulation results

A simulation with the same step input is made using Eq. (4) and the result is compared with the actual test, shown in Fig. 5. From the comparison we can see that the identified transfer function has high accuracy and it can be applied as a reference model for the Smith predictor design.

B. Gain-adaptive Smith predictor design

Smith predictor can eliminate the time delay from the characteristics equation of the closed loop system. However, when there is difference between the plant and its identified model, Smith predictor will be of poor robust performance [8]. The transfer function (Eq. 4) identified in last section is just an approximation of the plant and besides it doesn't take care of the disturbance. Hence, if the Smith predictor is designed based on Eq. (4) exactly, the system will not be of good dynamic performance.

The gain of the DMET plant is sensitive to disturbance, especially to the change of engine working state. So, a modified gain-adaptive Smith predictor is applied to control the DMET system [9] [10]. The gain of the predictor model can be auto- tuned on-line according to the control error. The structure of the controller is shown in Fig. 6.

In Fig. 6, PID controller is the main controller. α_{des} and α_{act} are respectively desired throttle angle and actual throttle angle. $\Delta\alpha$ is the error between actual throttle angle and the output of the Smith predictor. $F(s)$ is a low-pass filter. $K_m(t)$ and τ_m are the gain and the time delay of the predictor model respectively. Refer to Eq. (4),

$$\tau_m=0.2568$$

$$G_{m0}(s)=\frac{1}{0.3289s+1}$$

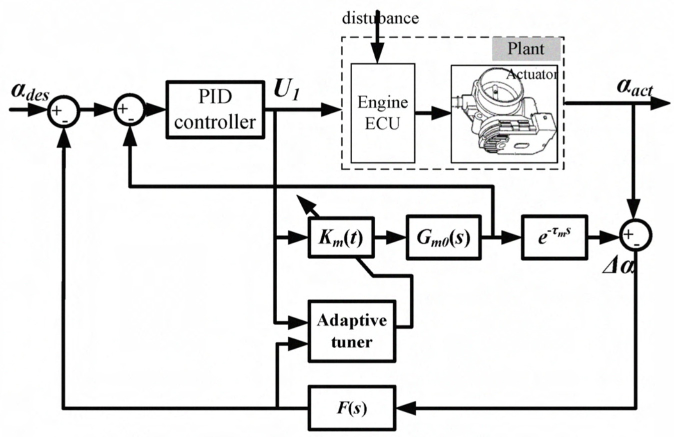


Fig. 6 Structure of gain-adaptive Smith predictor based controller

The adaptive tuner is set for tuning the K_m .It has been proved in [10] that if the plant is asymptotically stable, the general format of the gain adaptive tuning law can be as Eq. (5).

$$\dot{K}_m(t) = \eta U_1 \Delta\alpha \tag{5}$$

where η is a constant.

Then the gain of the predictor model can be obtained as

$$K_m(t) = K_m(0) + \int_0^t (\eta U_1 \Delta\alpha) dt \tag{6}$$

where $K_m(0)$ is the initial value. From Eq. (4), it can be got that $K_m(0)$=21.4744.

From Eq. (6) we can see that the gain will be continuously tuned until $\Delta\alpha$=0, which means that the plant and the Smith predictor have the same output and the predictor model has got accurate enough for the Smith predictor.

C. *Dead zone restricted PID controller*

If the driver takes over accelerating action during adaptive cruise control actuation, the DMET system will switch from ACC control mode to driver operating mode and the actual throttle angle will be greater than the ACC set value, which results in continuous decrease of the integral term of the PID controller. After some time if driver releases the pedal, the DMET will switch to ACC control mode again. However, the integral term has diminished so much that the throttle angle will instantly go down to a very small value and then rise to the ACC desired value gradually, which leads to acceleration impact and bad riding performance.

To avoid the abovementioned instant up and down of the throttle angle, a modified PID controller which is restricted by a dead zone has been designed [4]. Before calculating the tracking error of the throttle angle, the control variable U_1 of the DMET controller and the output U_2 of the acceleration pedal position sensor will be compared.

If U_2 is bigger than U_1, it means that the driver desire greater throttle angle than the ACC system and then the PID controller goes into the dead zone in which the tracking error is always set to zero. The control law is shown as Eq. (7).

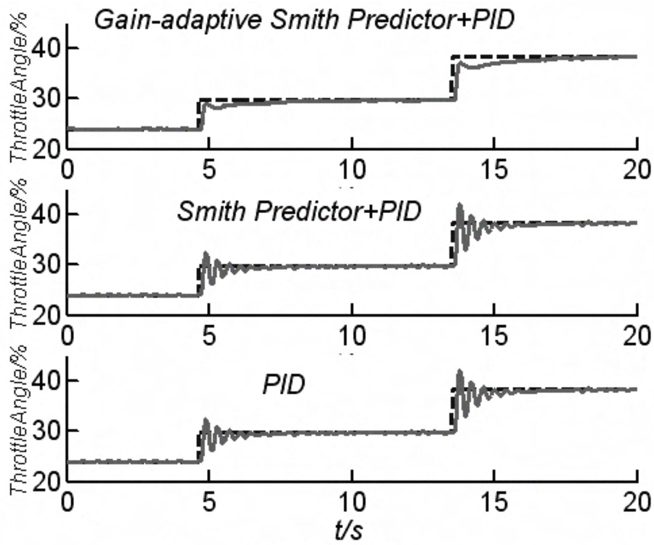
$$e_{in}(k) = \begin{cases} 0 & U_1 \le U_2 \\ e(k) & U_1 > U_2 \end{cases} \tag{7}$$

Where, $e(k)$ is the tracking error of the throttle angle. $e_{in}(k)$ is the input of PID controller.

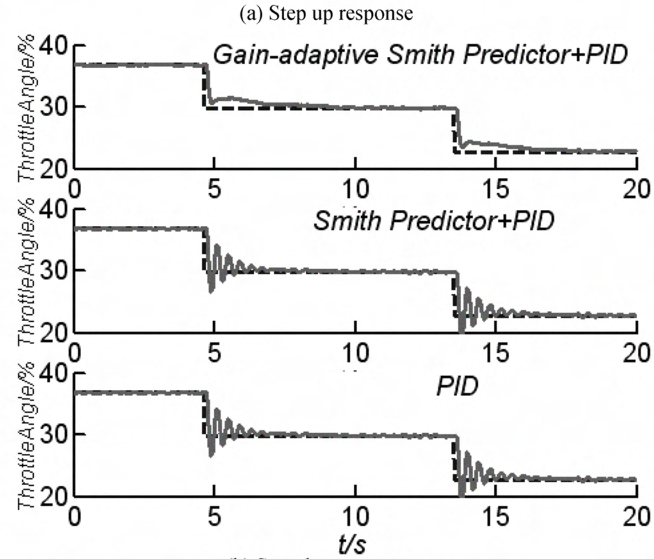
Using Eq. (7), although the actual throttle angle is greater than the ACC set value in driver operating mode, the integral term of the PID controller will not change because the input is zero. It can availably avoid the impact of throttle angle.

IV. EXPERIMENTS AND RESULTS

In order to validate the response performance of the DMET system, the plant is controlled by three strategies, which are gain-adaptive Smith predictor based PID control, Smith predictor based PID control and PID control. All the three controllers have the same PID parameters. Step signals are used as input in the test. The test results are shown in Fig.7.



(a) Step up response

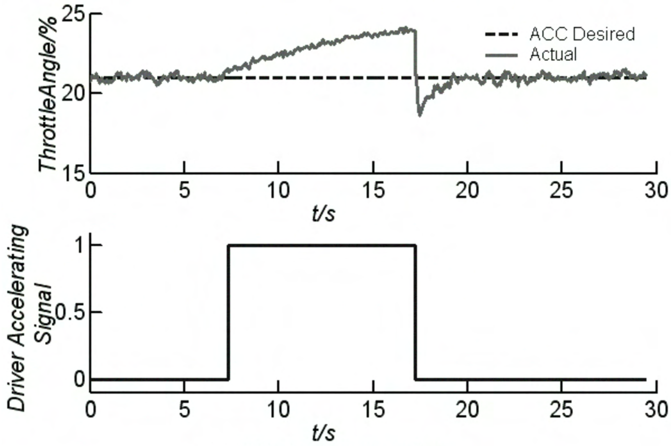


(b) Step down response

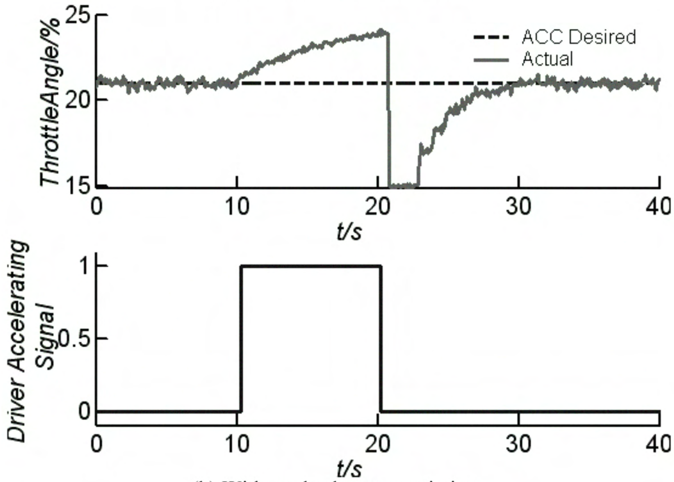
Fig.7 DMET step input response

From the test results we can draw the impressions that when the input steps up or down, all the controllers can eliminate the tracking error quickly. However, only the gain-adaptive Smith predictor based PID algorithm can realize stable transitions while the other two bring on fluctuations to the system which go against the driving comfort. The results validate that the gain-adaptive Smith predictor based PID controller is contrastively competent to improve the dynamic performance of the DMET system.

Furthermore, in order to verify the switch performance of DMET system between two operating modes, two more tests are also done. In the tests, the driver pushes down the acceleration pedal to a certain angle during ACC actuation, followed a several-second maintaining and then releases it. A typical PID controller and a dead-zone restricted PID controller are respectively used as the main controller in the tests.



(a) With dead-zone restriction



(b) Without dead-zone restriction

Fig.8 Switch performance of DMET

It can be made out from Fig.8 that when the driver wants to overtake a car, the acceleration pedal is stepped down and the DMET system switches to driver operating mode rapidly and controls the throttle angle in compliance with the driver's desire. For the time being, the actual throttle angle is greater than the ACC set value. The integral term of the PID controller with dead-zone restriction doesn't change while the one without dead-zone restriction decrease a lot. After the driver releases the pedal, the PID controller with dead-zone restriction can make the actual throttle angle catch up the ACC set value soon while the other one results in throttle angle instantly going down to a very small value and then rising to the ACC desired value gradually. The car controlled by former controller can get better riding performance.

V. Conclusions

A Double-Mode Electronic Throttle (DMET) system which can be operated by ACC and driver synchronously has been proposed based on the existing electronic throttle system. In order to compensate the time delay of the system, a gain-adaptive Smith predictor based on a identified transfer function is introduced to the DMET controller. Furthermore, aiming at seamless switch between ACC control mode and driving operating mode, a dead zone restriction is also brought in. Series of experiments confirm the following.

(1) Owing to the switch module of the DMET controller, the system can not only respond to the ACC command but also obey the driver's purpose. Both driver's and ACC's requirement for adjusting throttle angle can be satisfied by the DMET system.

(2) Due to the gain-adaptive Smith predictor, the DMET system is independent from the influence of the time delay and has good dynamic performances.

(3)Due to the dead zone restricted PID control algorithm, the switch between driver operating mode and ACC control mode can be achieved seamlessly.

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