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A dynamic weight multi-objective model predictive controller for adaptive cruise control system

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ABSTRACT
Adaptive cruise control (ACC) is recognized as an effective method to improve vehicle safety and reduce driver workload. This paper proposes a whole hierarchical multi-level state ACC system. According to the function of ACC system, the three-level state ACC system is designed and the conversion mechanism between different states is put forward. As for the complex car-following mode, considering the variable headway safety distance and the road adhesion coefficient, the expected safety distance model is established, using the distance error and the speed error as fuzzy input, based on the fuzzy control algorithm, the following mode is obtained; considering vehicle safety, tracking capability and ride comfort, the control objectives are formulated into the model predictive control algorithm. A dynamic weight strategy is proposed to solve time-varying multi-objective control problems, where the weight can be adjusted with respect to different following conditions. The simulation results demonstrate that the car following performance of ACC with the proposed dynamic weighted MPC can provide better performance than that using constant weight MPC, and the multi-level state ACC system can display the control mode more intuitively.

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KEYWORDS
Adaptive cruise control; multi-level state; the following mode; model predictive control; dynamic weight

1. Introduction

The adaptive cruise control (ACC) system is one of the vehicle ADAS technologies and is an important part of the advanced driver assistance system. It uses distance sensors to obtain the longitudinal distance between the vehicle and the preceding vehicle, and automatically adjusts the throttle opening or braking pressure according to the longitudinal distance, making the vehicle increase the longitudinal speed or maintain a safe distance. Adaptive cruise control is recognized as an effective way to improve vehicle safety and reduce driver workload, and is therefore widely used in many vehicles [1].

As for the adaptive cruise modes, many scholars have done a lot of researches, Fancher et al. [4] studied the related vehicle state, and then divided the state of ACC system into car-following mode and constant speed cruise mode, which is also the most commonly used mode of ACC system. Pei et al. [5] divided ACC system into constant speed cruise, steady state following, approaching the preceding vehicle, strong acceleration and deceleration control modes. Leng et al. [6] designed a multi-mode adaptive cruise hierarchical controller, including cruise control, approaching the preceding vehicle, steady-state following, collision avoidance following. Zhang et al. [9] added two states of overtaking and close to the preceding vehicle based on the existing states of constant speed cruise and car-following, making the ACC system more specific and accurate. In the car-following mode, the vehicle can automatically adjust the vehicle speed and acceleration to maintain a safe distance from the preceding vehicle. Moreover, because the environment is complicated, when the preceding vehicle suddenly start or stop, vehicles from another lane cut into the lane, etc., the ACC vehicle must be controlled to suit for the motion of the preceding vehicle. Haroon et al. [2] proposed a cruise control strategy to alleviate traffic congestion under the stop-go scenario. Cai et al. [3] proposed an adaptive cruise control strategy which was optimized based on side car merging behaviour. Mosharafian et al. [25] designed a mode that allows switching between warning, danger and lane-change, as well as adjusting the steering angle to perform lane change manoeuvres when required, for efficient and safe autonomous driving. A complete ACC system should include functions such as start, start and stop, cruise control, car-following, cut-in/off, etc. However, few investigations have been found in the open literature with respect to the whole hierarchical ACC system.

Due to the variable motion of the preceding vehicle, the following behaviour is relatively complicated, which is the focus of ACC research at present. Yan [10] divided the following conditions into steady-state following

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and transient-state following according to the expected acceleration amplitude, and defined the transition area by the distribution of characteristic parameters of the car-following behaviour of the tested driving group. Seungwuk et al. [7] divided the following modes into three modes: safety, warning, and danger, and proposed different control strategies depending on different driving situations. Zhang et al. [11] comprehensively coordinated the driver's expected response, car following safety and other control objectives, and adopted fuzzy inference and acceleration-weighted average strategies to achieve the best matching of operating modes and smooth transition. Huang et al. [12] proposed a car-following controller based on explicit model predictive control theory, and used explicit polyhedron piecewise affine system to calculate the expected acceleration. Changwoo et al. [13] established a car-following controller based on linear quadratic algorithm, and considered acceleration and acceleration change rate as performance indicators. Mahtout et al. [8] proposed a multi-objective ACC control method in order to cope with different system operating conditions in the following scenario. Zhao et al. [14] proposed a multi-objective adaptive cruise control method for vehicles based on explicit model predictive control. Chu et al. [24] established a car-following style learning algorithm on the basis of reinforcement learning. Since the model predictive control algorithm can simultaneously coordinate multiple objectives and multiple constraints, and restore accurate control strategies in a short time, therefore, it is very suitable for solving the control problem of ACC.

Although many studies have greatly improved the performance of ACC systems, most of the current ACC systems use a set of parameters with fixed values. For example, Darbha [15] used fixed headway method as the ACC system vehicle distance control method to improve the stability of some road traffic flow, without taking into account the preceding vehicle information. In many complex environments, the fixed headway method will also make the vehicle less flexible and stable [16]. Cheng et al. [19] took constant time headway and the preceding vehicle speed as the tracking target, and the minimum and maximum values of acceleration and rate of change of acceleration were used as constraints. These ACC systems with fixed parameter values can represent the average preference of most person, which could not meet the different goals of different following states. Naus et al. [17] used explicit model predictive control to parameterize the key characteristics of the ACC system for different cruise control modes. Gao B et al. [20] proposed a personalized adaptive ACC system based on driving style recognition and model predictive control to meet different driving styles while ensuring car-following, comfort and fuel-economy performances. Andreas et al. [18] designed an energy-saving ACC method based on model predictive control and dynamic programming. However, some control objectives (driving safety, tracking stability, ride comfort, etc.) still need to be considered.

It can be seen from the above that the mentioned studies mostly focus on solving the non-smooth switching between different modes, coordinating and optimizing indicators such as car following, safety and comfort. However, when the vehicle drives under different working conditions, the focus of ACC should be different, such as the safety when the preceding vehicle is decelerating, and the following performance when the preceding vehicle is accelerating. Based on these studies, the tracking capability, vehicle safety is difficult to achieve an extremely appropriate state at the same time. So how to make ACC systems meet different preferences needs further study.

Therefore, this paper focuses on the design of an overall hierarchical multi-level state ACC system, the conversion machine among different states is put forward. As for complicated car-following modes, a dynamic weighted MPC algorithm is proposed considering vehicle safety, tracking capability and ride comfort simultaneously. The overall control framework of adaptive cruise designed in this paper is shown in Figure 1, which mainly contains two modules: the multi-level state machine decision module and the car-following control module. According to the input information of the vehicle and the preceding vehicle, the expected safety distance between the ACC vehicle and the preceding vehicle is obtained. Through the multi-level state machine decision module, the ACC state is obtained according to vehicle state, driving distance and driver operation information. If the vehicle is in the car-following mode, the specific following mode is determined by fuzzy control algorithm, then the dynamic weighted multi-objective model predictive controller is used to obtain the expected acceleration and then control the throttle opening or braking pressure through the inverse longitudinal dynamics model to achieve expected adaptive cruise control.

The main contributions of this article are as follows:

(1) According to the function of ACC system, comprehensively consideration of the interaction among driver, vehicle, external environment, the three-level unified ACC framework system is constructed by adopting the concepts of layering and modularization, and the conversion mechanism among different modes is established. This work can enable the system to clearly describe the working mode in the application.
(2) The expected safety distance is modelled based on variable headway time distance and road adhesion coefficient, and the distance error and speed error are used as fuzzy inputs to obtain the following

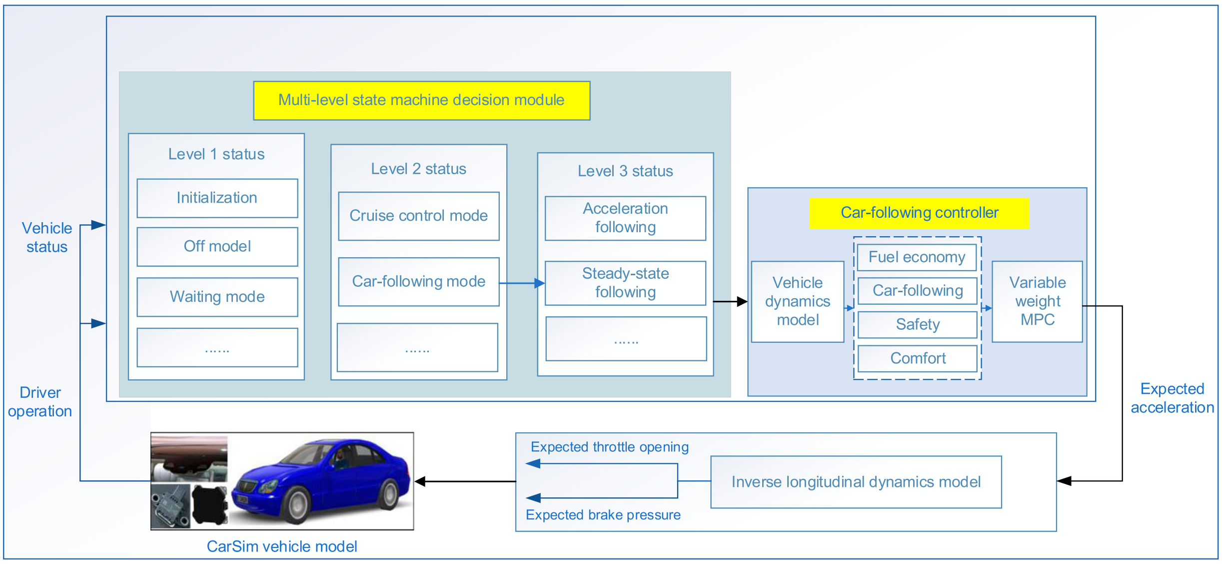


Figure 1. Control structure diagram of ACC.

mode by fuzzy control algorithm. In order to balance the performance weights of the ACC system under different following states, the control objective is formulated as a model predictive control algorithm, taking into account tracking capability and ride comfort. A dynamic weight strategy is proposed to solve time-varying multi-objective control problems. Based on Matlab/Simulink and CarSim, the above ACC control strategy is verified.

2. Multi-level state machine decision module

The multi-level state machine decision module is shown in Figure 2. The ACC mode is comprehensively defined in three levels using the method of hierarchical division. Among them, the first-level state, the second-level state, and the third-level state are layers of inclusion and subordination. The first-level state > the second-level state > the third-level state.

2.1. *First-level state*

The purpose of the first-level state is to establish the logical relationship between driver behaviour and ACC, and to define the overall operating state of ACC. It mainly includes ACC initialization mode, off mode, failure mode, activation mode, waiting activation mode, suspended mode. The switching mechanism is shown in Figure 3.

After the vehicle starts, the ACC system automatically enters the initialization mode. When the driver turns on the ACC, the system enters the waiting for activation mode, according to the driver's operation and the driving status of the vehicle, judges whether the

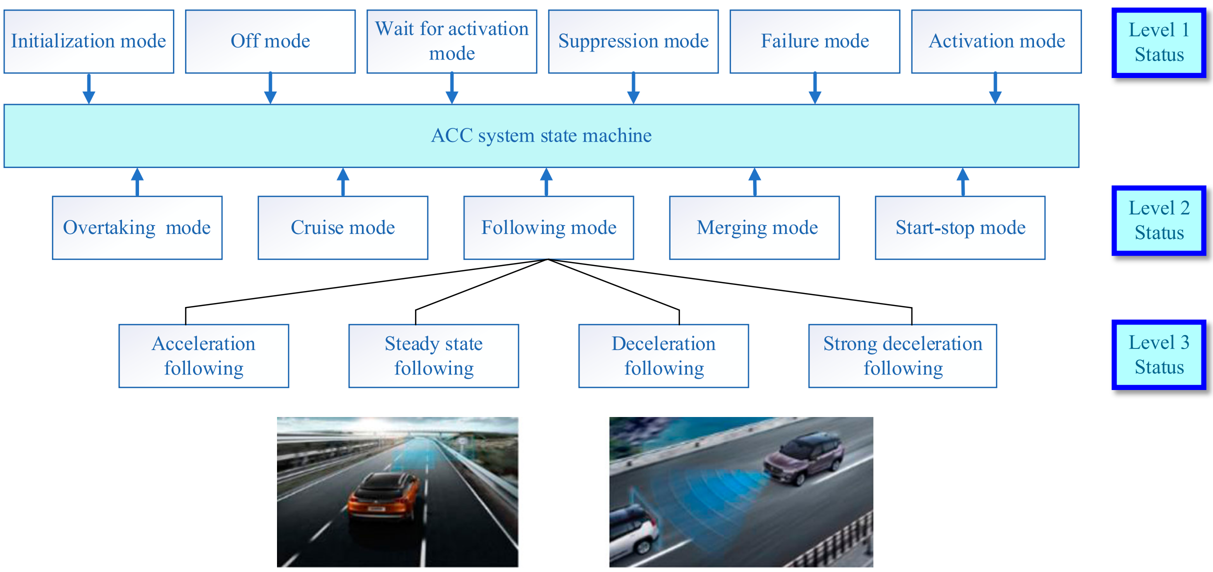


Figure 2. Schematic diagram of multi-level state machine.

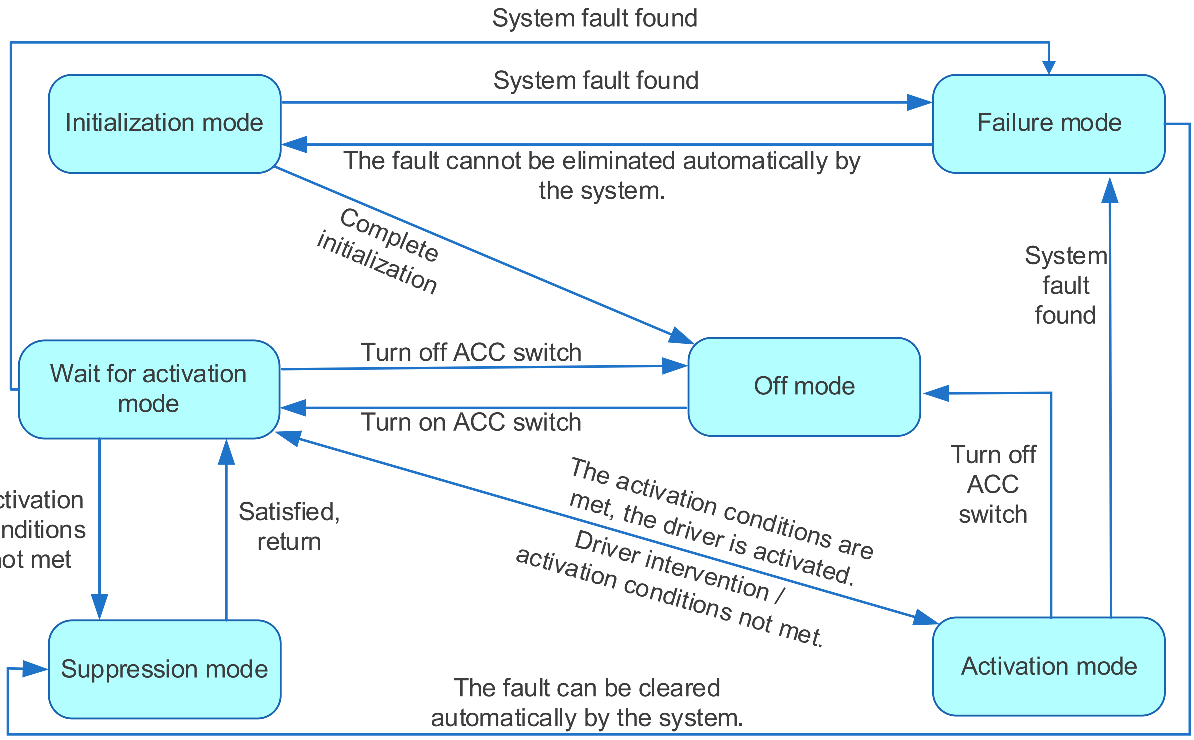


Figure 3. First level state design and its switching mechanism.

activation conditions are met. If the system fails or the driver turns off the ACC, the system enters the failure mode and the off mode respectively from the activation mode, while if the activation condition is not met due to the driver's operation such as applying the brake, the system enters the waiting activation mode.

2.2. Second-level state

The secondary state is the further state after the ACC system enters the active mode. When the ACC is in normal operation, through the analysis of driver behaviour, driving state, etc., The state mainly includes overtaking mode, cruise mode, following mode, start-stop mode, cut-in(merge) mode. After the ACC system starts to work normally, it first judges whether the vehicle is in the parking phase according to the vehicle speed, and if it is, it enters the start-stop mode; it judges to enter the overtaking mode according to whether the driver steps on the accelerator; then judges it is a constant speed based on the result of the sensor detecting the preceding vehicle cruise or car-following mode. The switching mechanism between secondary states is shown in Figure 4.

(1) Start-stop mode: It is used in congested urban traffic conditions, to realize the functions of following the preceding vehicle to stop and start automatically when the vehicle is driving and following the vehicle at low speed. For example, when the vehicle speed is less than 1 km/h, it enters the start-stop mode, and if the parking time is less than three seconds, it automatically enters the follow-up mode, if it is greater than 3s, it judges whether to start based on the driver's operation.

(2) Overtaking mode: When the driver steps on the accelerator pedal, the ACC system judges the driver's pedal strength, determines whether it is stepped by mistake, and then enters the transcendental mode. If the driver continues to accelerate the accelerator for more than 10s, the ACC system will exit the work by itself, otherwise it will exit the overtaking mode and continue to work normally.

(3) Merging mode: Predict whether the vehicle in the side lane will cut into the lane and whether the preceding vehicle of the lane has the behaviour of cutting out of the lane, when it indicates that there is a tendency to change lanes to the own lane, it is judged that the next car should change into the own lane and enter the parallel mode of the side car.

(4) Cruise mode: Control the speed of the vehicle to reach the driver's designated speed within a suitable time and maintain a constant speed.

(5) Following mode: By controlling the speed of the vehicle, the vehicle can reasonably follow the preceding vehicle to drive stably with a certain distance and the same speed.

2.3. Third-level state

The third-level state is the classification of the mode when the vehicle is in the following mode, due to the traditional single control mode and switching mechanism cannot meet the driver's expectations and requirements for the ACC system, and in order to ensure

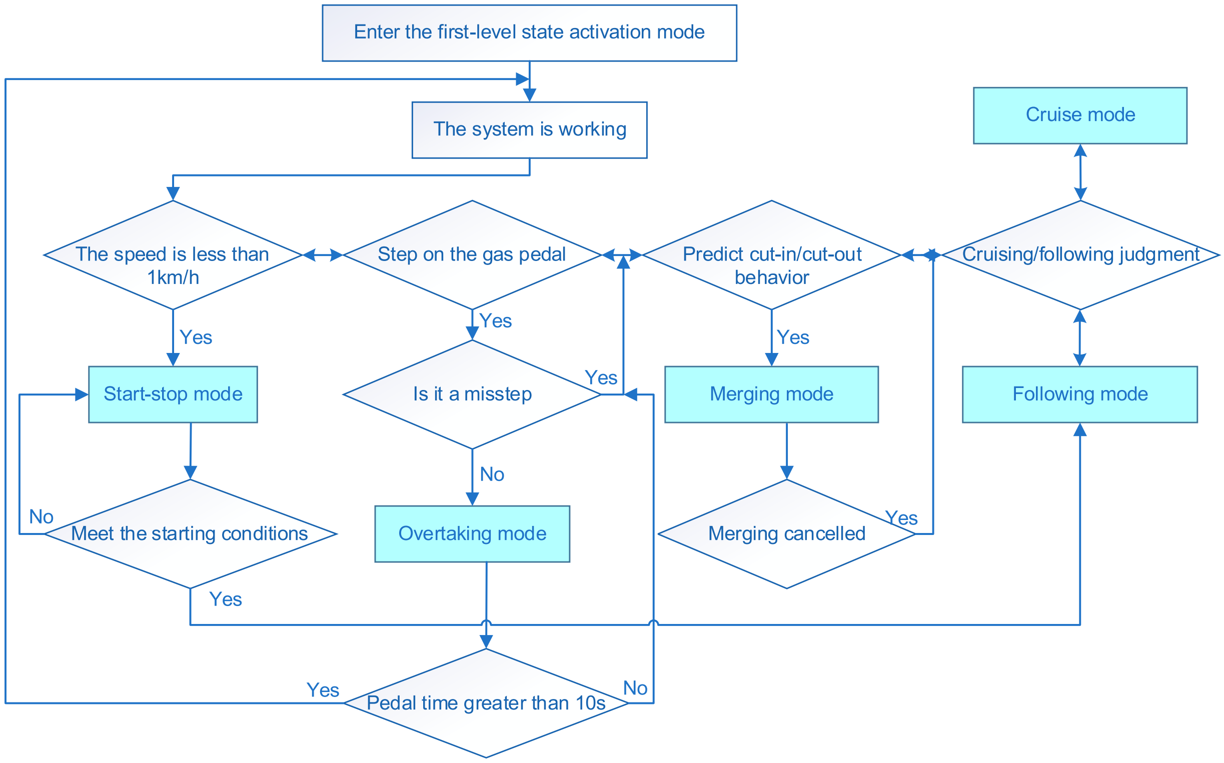


Figure 4. Secondary state design and its switching mechanism.

the safety and other performance of the ACC system in the complex driving environment performance. This paper adopts four following modes: acceleration following, deceleration following, steady-state following and strong deceleration following. The four following modes can well reflect the driver's behaviour when driving, avoid the confusion of switching and the abrupt change of acceleration caused by multi-mode. The detail content will be introduced in next section.

3. Adaptive cruise control for following vehicles

3.1. The longitudinal kinematic model

The longitudinal kinematic model of the ACC system is shown in Figure 5. d_{act} is the actual vehicle distance between the two vehicles, d_{des} is the expected vehicle distance between the two vehicles, d_r is the error between the actual vehicle distance and the expected vehicle distance, d_x, v_x is the position and the speed of the ACC vehicle, d_f, v_f is the position and the speed of the preceding vehicle. Based on the dynamic relationship between vehicles, the following relationship can be obtained [21]:

$$\begin{cases} d_{act}(k) = d_f(k) - d_x(k) \\ d_r = d_{act}(k) - d_{des}(k) \\ v_r = v_f(k) - v_x(k) \end{cases} \tag{1}$$

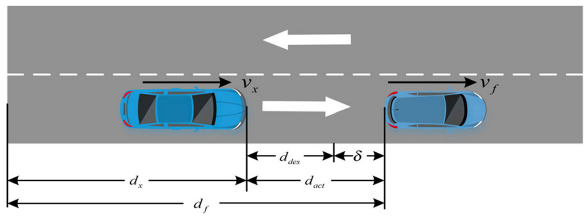


Figure 5. Longitudinal kinematics diagram of ACC system.

According to the moving state of the preceding vehicle, the ACC vehicle can automatically adjust velocity to maintain the expected distance from the preceding vehicle ($d_r \to 0$, $v_r \to 0$).

3.1.1. The expected safety distance model

The vehicle distance between the two vehicles is important, long distance will decrease the traffic efficiency and lead to frequent preceding vehicle's cut-in from adjacent lanes, short distance will make driver feel uncomfortable, even cause collisions, because the expected safety distance can improve traffic efficiency on the basis of ensuring safety. Based on the constant headway safety distance model, considering the speed of the ACC vehicle, the relative speed of the two vehicles, the acceleration of the preceding vehicle and the road adhesion coefficient, the variable headway safety distance model is established:

$$d_{des} = thv_x + d_0 \tag{2}$$

where, th represents the headway, which is calculated as follows:

$$th = \begin{cases} th_{\max} & th_0 - K_r v_r - K_f a_f \geq th_{\max} \\ th_0 - K_r v_r - K_f a_f & th_{\min} < th_0 - K_r v_r - K_f a_f < th_{\max} \\ th_{\min} & th_0 - K_r v_r - K_f a_f \leq th_{\min} \end{cases} \quad (3)$$

where, th_0 represents the initial setting headway, $v_r = v_x - v_f$ represents the relative speed, K_r represents the relative speed coefficient, a_f, K_f represent the acceleration and acceleration coefficient of the preceding vehicle. d_0 is the minimum relative distance, which is related to speed and road adhesion coefficient.

The calculation formula is as follows:

$$d_0 = \min\left(\frac{2v_x}{K_x(\mu + \mathrm{b})}, 2\right) \quad (4)$$

where, μ represents the road adhesion coefficient, K_x represents the ACC vehicle speed coefficient (set the value is 22.5), and the constant coefficient b is 0.3 [22], 2 is the minimum distance when the vehicle stops.

3.2. Switching mechanism design of car-following mode

We classify the following process into four following modes: acceleration, deceleration, steady state, and strong deceleration. The four following modes can well reflect the driver's behaviour when driving, avoid the confusion of switching and the abrupt change of acceleration caused by multi-mode. How to achieve smooth switching is the primary problem to be solved. In view of the subjectivity and uncertainty of driving intention, fuzzy reasoning can better simulate human thinking in dealing with empirical model decision-making problems. Fuzzy control algorithm is adopted to design the switching mechanism of car following mode.

The speed error v_r and the distance error d_r are taken as the input variable. The model factor S_{factor} is proposed as the output variable. The fuzzy sets, the rule matrix of the fuzzy controller and the three-dimensional map surface are shown in Figure 4.

According to the expert experience, driver's driving habits and rational analysis, the following fuzzy control rules are established. These fuzzy rules are easily comprehended. For example, if the speed error is NL and the distance error is NL, this rule implies that if the ACC vehicle is fast approaching the preceding vehicle and the two vehicles are very close, it is a dangerous situation which is desirable to decelerate the ACC vehicle quickly to avoid car collision. So the output state safety factor S_{factor} is L (strong deceleration following mode). Moreover, the rule matrix is symmetric with respect to the diagonal entries (Figures 6 and 7).

3.3. Design of multi-objective control algorithm based on variable weight MPC

The following controller uses a model predictive control algorithm to calculate the expected acceleration of the vehicle, and then uses an inverse longitudinal dynamics model to derive the throttle opening or braking pressure to control the vehicle acceleration, deceleration to realize the adaptive cruise function. The frame is shown in the Figure 8. Due to the different requirements in different modes, this paper discusses the tracking controller in detail.

3.3.1. Design of MPC control

Based on the longitudinal kinematics between the following vehicle and the preceding vehicle of the ACC system in Figure 5, the lower-level controller is considered as a first-order lag etc., the following equations can be obtained:

$$\begin{cases} d_{act}(k+1) = d_{act}(k) + v_r(k)T_s \\ +\frac{1}{2}a_f(k)T_s^2 - \frac{1}{2}a_x(k)T_s^2 \\ v_r(k+1) = v_r(k) + a_f(k)T_s - a_x(k)T_s \\ v_x(k+1) = v_x(k) + a_x(k)T_s \\ a_x(k+1) = \left(1 - \frac{T_s}{\tau}\right) v_x(k)a_x(k) + \frac{T_s}{\tau}u(k) \\ j(k+1) = -\frac{1}{\tau}a_x(k) + \frac{1}{\tau}u(k) \end{cases} \quad (5)$$

where $a_x(k)$ is the vehicle's acceleration at moment k, $j(k)$ is the rate of change of the vehicle's acceleration at moment k, $a_f(k)$ is the acceleration of the preceding vehicle, T_s is the discrete sampling period, τ is the time constant of the lower controller, $u(k)$ is the expected acceleration output from the upper controller at time.

The car-following model is a continuous-time system, but in real-time control applications, the car-following model is usually applied to the discrete time domain, then it is converted into the discrete-time domain, the actual distance, the vehicle speed, the relative vehicle speed, the vehicle acceleration and the rate of change of acceleration are selected as the following controller state variables:

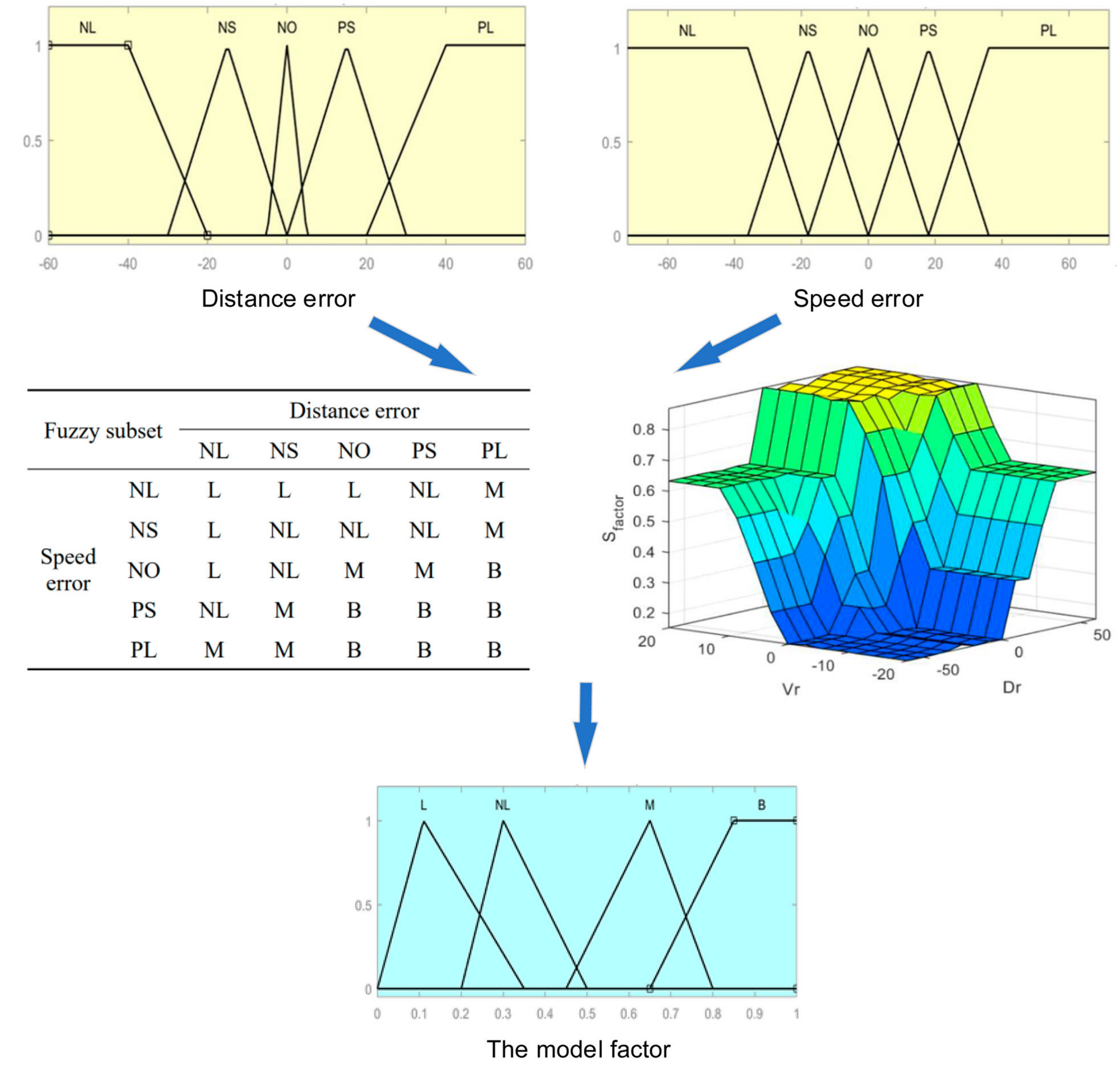
$$x(k) = [d_{act}(k)\ v_x(k)\ v_r(k)\ a_x(k)\ j(k)]^T \quad (6)$$

With the preceding vehicle acceleration as the system disturbance and the expected acceleration as the control output, the longitudinal kinematic equation of state is expressed as:

$$x(k+1) = Ax(k) + Bu(k) + Gw(k) \quad (7)$$

where:

$$A = \begin{bmatrix} 1 & 0 & T_s & -\frac{1}{2}T_s^2 & 0 \\ 0 & 1 & 0 & T_s & 0 \\ 0 & 0 & 1 & -T_s & 0 \\ 0 & 0 & 0 & 1-\frac{T_s}{\tau} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau} & 0 \end{bmatrix}, \ \mathrm{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{T_s}{\tau} \\ \frac{1}{\tau} \end{bmatrix},$$



Fuzzy subset		Distance error				
		NL	NS	NO	PS	PL
Speed error	NL	L	L	L	NL	M
	NS	L	NL	NL	NL	M
	NO	L	NL	M	M	B
	PS	NL	M	B	B	B
	PL	M	M	B	B	B

Figure 6. The Fuzzy sets and rule matrix for the fuzzy controller.

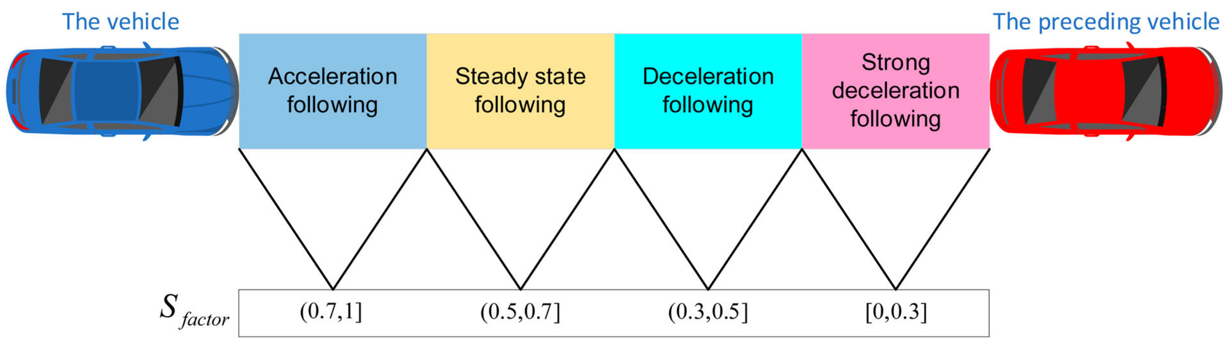


Figure 7. The relationship between the mode factor and following mode.

$$G = \begin{bmatrix} \frac{1}{2}T_s^2 \\ 0 \\ T_s \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

In order to fully ensure the performance of the upper-level controller of the ACC system to meet the expectations of the driver, the design of the controller needs to meet the requirements of driving safety, ride comfort, and followability, and transform the control requirements into corresponding system

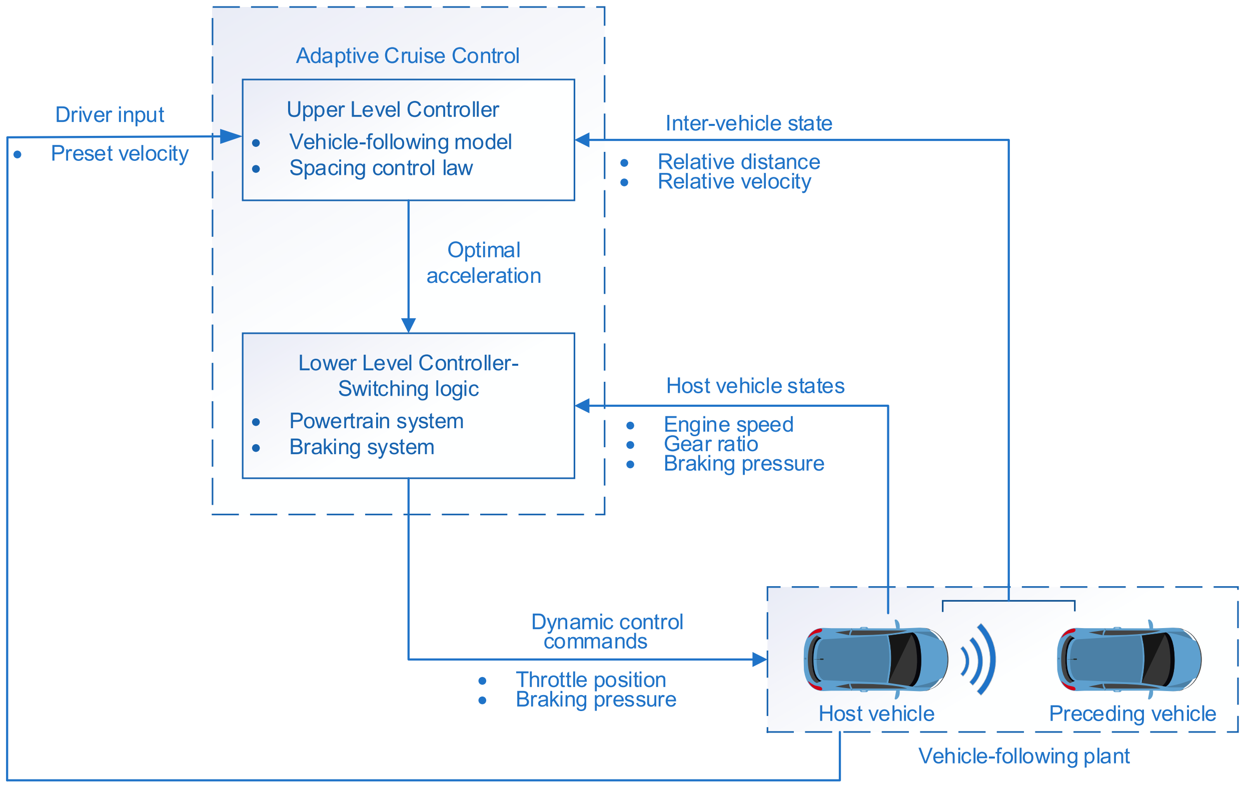


Figure 8. Hierarchical control structure of the proposed ACC system.

constraints, and performance indicators. The ACC system is dynamically coordinated and optimized, and then a comprehensive performance indicator function is obtained.

(1) Car-following performance index: It is evaluated by relative vehicle speed and relative distance error. When the vehicle enters a steady state, the index approaches 0:

$$Objective\ 1 : \begin{Bmatrix} d_r \to 0 \\ v_r \to 0 \end{Bmatrix} \tag{9}$$

(2) Driving safety index: To ensure driving safety, the actual distance between the two vehicles is restricted:

$$Objective\ 2 : d_{act} > d_0 \tag{10}$$

(3) Ride comfort index: the acceleration and rate of change of acceleration of ACC vehicle should be as small as possible within the range allowed:

$$Objective\ 3 : \begin{Bmatrix} \min |a_x(k)| \\ \min |j_x(k)| \end{Bmatrix} \tag{11}$$

In addition, considering the speed limitation information of the road and the maximum travel speed, maximum acceleration capability and maximum braking performance of the vehicle itself, speed and acceleration are also required to be constrained.

$$Objective\ 4 : \begin{Bmatrix} v_{x\,\min} \le v(k) \le v_{x\,\max} \\ a_{x\,\min} \le a(k) \le a_{x\,\min} \\ j_{\min} \le j(k) \le j_{\max} \end{Bmatrix} \tag{12}$$

To sum up, select the distance error, relative speed, acceleration, acceleration change rate to form the optimization performance index vector, the expression is as follows:

$$y(k) = Cx(k) - Z \tag{13}$$

Among them,

$$\begin{cases} y(k) = [\delta(k)\ \mathrm{v}_r(\mathrm{k})\ \mathrm{a}_x(\mathrm{k})\ \mathrm{j(k)}]^T \\ C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},\ Z = \begin{bmatrix} d_{des}(k) \\ 0 \\ 0 \\ 0 \end{bmatrix} \end{cases} \tag{14}$$

3.3.2. Design of model prediction algorithm

The discrete MPC prediction equation can be obtained from the above optimized performance indicator vector equation and the longitudinal kinematic equation of state in standard form as:

$$\begin{cases} \hat{X}_p(k+p\,|k) = \bar{A}x(k) + \bar{B}Ux(k+m) \\ +\bar{G}W(k+p) + \bar{H}e_x(k) \\ \hat{Y}_p(k+p\,|k) = \bar{C}x(k) + \bar{D}U(k+m) \\ +\bar{E}W(k+p) + \bar{F}e_x(k) - \bar{Z} \end{cases} \tag{15}$$

where:

$$\begin{cases} \hat{X}_p(k+p|k) = \begin{bmatrix} \hat{x}_p(k+1|k) \\ \hat{x}_p(k+2|k) \\ \vdots \\ \hat{x}_p(k+p|k) \end{bmatrix}, \\ \hat{Y}_p(k+p|k) = \begin{bmatrix} \hat{y}_p(k+1|k) \\ \hat{y}_p(k+2|k) \\ \vdots \\ \hat{y}_p(k+p|k) \end{bmatrix} \\ U(k+m|k) = \begin{bmatrix} u(k) \\ u(k+1) \\ \vdots \\ u(k+c-1) \end{bmatrix}, \\ W(k+p) = \begin{bmatrix} w(k) \\ w(k+1) \\ \vdots \\ w(k+p-1) \end{bmatrix} \\ e_x(k) = x(k) - x(k-1) \end{cases} \quad (16)$$

where p is the prediction matrix; c is the control time domain; $\hat{x}_p(k+1|k), \hat{x}_p(k+2|k), \ldots, \hat{x}_p(k+p|k)$ is the predicted value of the state variable for p consecutive times obtained based on the iteration of the prediction model at time k; $\hat{y}_p(k+1|k)$, $\hat{y}_p(k+2|k), \ldots$, $\hat{y}_p(k+p|k)$ is the predicted value of the output variable for p consecutive times obtained based on the iteration of the prediction model at time k; $u(k)$ is the system output, which is the desired acceleration; $W(k+p)$ is the matrix of systematic error coefficients at time p; and e_x is the error between the actual detected state vector and the predicted.

The multiple performance indicators are expressed in weighted form as the following function:

$$\begin{aligned} J = \sum_{i=1}^{p} [\hat{y}_p(k+i\,|k) - y_r(k+i)]^T \\ \times Q[\hat{y}_p(k+i\,|k) - y_r(k+i)] \\ \times + \sum_{i=0}^{m-1} u(k+i)^T R u(k+i) \end{aligned} \quad (17)$$

3.3.3. Real-time dynamic weight fuzzy adjustment strategy

According to different car-following modes, the different system constraint groups and weight coefficient values in the MPC controller are shown in Table 1.

Table 1. Indicator constraint group in different modes.

Follow mode/range	v_x	$a_x(k)$	$j(k)$	$u(k)$
Accelerated following mode	(0,120)	(0,2)	(−4,4)	(0,2)
Steady state following mode	(0,120)	(−1,1)	(−2,2)	(−1,1)
Decelerated following mode	(0,120)	(−2,0)	(−3,3)	(−2,0)
Strong deceleration following mode	(0,120)	(−4,0)	(−5,5)	(−4,0)

MPC with constant weights hardly obtains satisfactory control performance for different complex situations in ACC systems. Therefore, a real-time dynamic weight adjustment strategy is proposed to cope with the problem [23]. In the formula 17, Q and R are the weighting coefficients of output and control, represents the weight of car following safety, and R represents the weight of ride comfort.

During the process of car following, the safety is more important than comfort, this paper sets the weighting factor R to be 1, while the weighting factor Q is self-adjusting when the mode changes, for example, in the acceleration mode (the distance between the two vehicles is large), the ACC vehicle is safe, more attention should be paid to ride comfort, so the weighting coefficient R > Q; while in the deceleration mode (the inter-vehicle distance is negative), the safety of the vehicle is more important than the ride comfort, so the weighting coefficient R < Q. By adjusting the weighting Q coefficients, the values of the expected acceleration and speed can be controlled. The member function of weighting coefficient Q is shown in Figure 9.

Likewise, the solution algorithm for the weighted coefficient Q also uses fuzzy control algorithm, the fuzzy control algorithm is consistent with the vehicle-following mode solution algorithm, The distance error d_r and the speed error v_r are taken as the input variable. Which is the same as the vehicle-following mode, the output becomes the dynamic weighted coefficient Q, the membership functions of Q is triangular. It is set to four levels: L (low), NL (lower), M (medium), and B (big), and its domain range is [0,3]. According to the expert experience, driver's driving habits and rational analysis, the following fuzzy control rules are established, the detail fuzzy rules experience table is shown in Table 2, the rule matrix is symmetric with respect to the diagonal entries.

These fuzzy rules are easily comprehended. For example, if the speed error is NL and the distance error is NL, then the output coefficient Q is B. This rule implies that if the ACC vehicle is rapidly approaching the preceding vehicle and the two vehicles are very close, the safety of the ACC vehicle is most important, so the weighting coefficient Q is big. If the speed error is

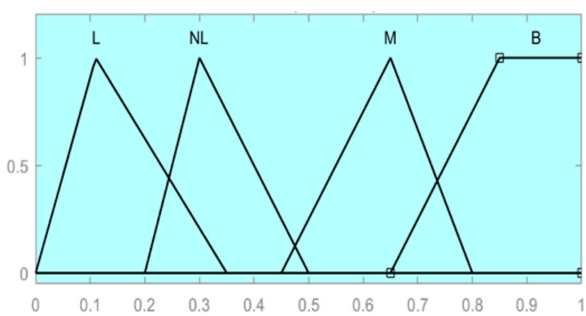


Figure 9. Membership function of weighting coefficient Q.

Table 2. Fuzzy control rules table of security weight.

	Distance error				
Speed error	NL	NS	NO	PS	PL
NL	B	B	B	M	NL
NS	B	B	M	NL	NL
NO	B	M	NL	NL	L
PS	M	NL	L	L	L
PL	NL	NL	L	L	L

NS, and the distance error is PL, then the output coefficient Q is NL. This rule implies that if the ACC vehicle is approaching the preceding vehicle and the distance of vehicles is long, the ACC vehicle has no danger, so the ride comfort of the ACC vehicle is more important than safety, so the weighting coefficient Q is NL.

4. Simulation and verification

4.1. Car following verification

To verify the feasibility and effectiveness of the ACC strategy established, a set of general scenarios are shown in Table 3. By changing the driving conditions of the preceding car, analyzing the performance of the car following and the mode change of ACC. Assuming that the ACC mode is already active (the first level state is active, indicating that the ACC system is in working mode). The simulation process is 100s, and the initial speed of the preceding vehicle is 40 km/h. Three ACC controllers are simulated and compared, one is the proposed MPC with real-time weighted strategy, which is state dependent, one is MPC with constant weights, the other is the fuzzy algorithm. Three ACC controllers were implemented using Matlab/Simulink and CarSim. The B-class hatchback fuel vehicle is selected, with an engine power of 125 kW, matched with a continuously variable transmission and a torque converter. The vehicle speed, acceleration, distance error, weight parameter Q, ACC modes are analyzed, and the simulation results are shown in Figures 10–13.

4.1.1. The performance of car following

The car following simulation of ACC system is 100s, which is divided into 6 working conditions. It can be

Table 3. Changes in preceding vehicle movement.

Working condition	Stage	The change of the preceding vehicle
1	0 s–10 s	Travels at an initial speed of 40 km/h
2	10 s–30 s	Accelerates to 60 km/h at an acceleration of 2 m/s^2
3	30 s–40 s	Decelerates to 50 km/h at a deceleration of 1 m/s^2
4	40 s–55 s	Accelerates to 70 km/h at an acceleration of 1.5 m/s^2
5	55 s–75 s	Decelerates to 40 km/h at a deceleration of 1.5 m/s^2
6	75 s–100 s	Decelerates to 0 km/h at a deceleration of 3.5 m/s^2

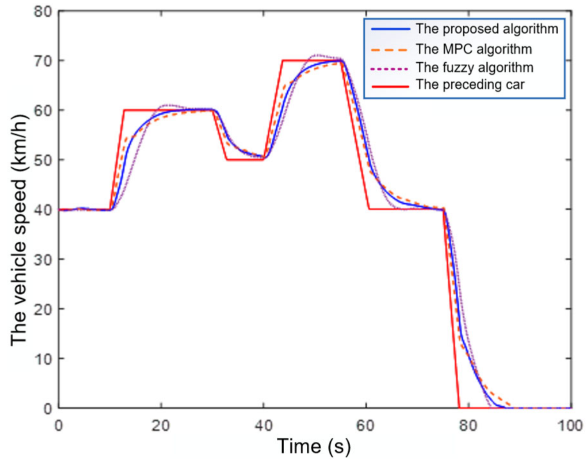


Figure 10. The curve of vehicle speed with different algorithm.

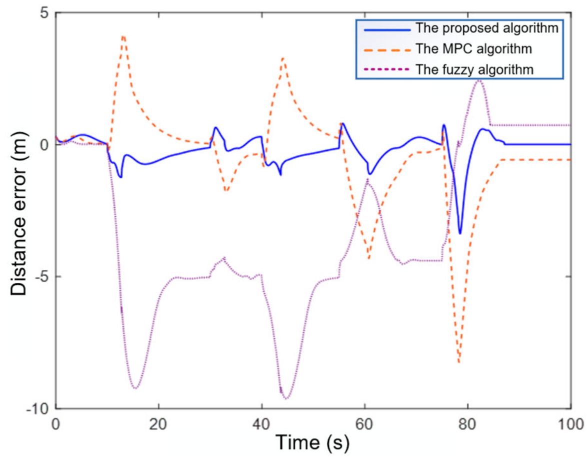


Figure 11. Comparison of the distance error curve under car following conditions.

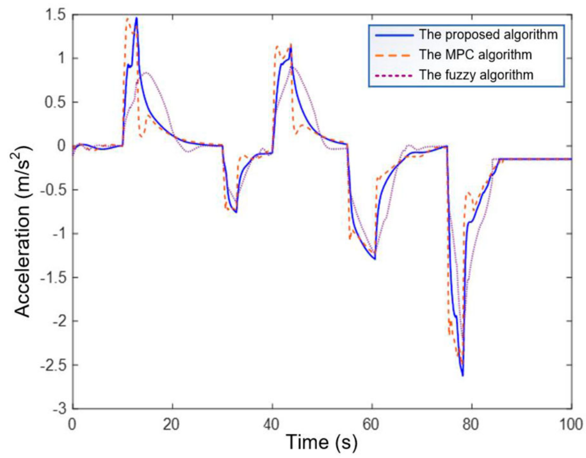


Figure 12. Comparison of the expected acceleration curve under car following conditions.

obtained from Figure 10 that when the preceding vehicle accelerates and decelerates, the ACC vehicle also accelerates and decelerates accordingly. Due to the different speeds between the two vehicles, the distance deviation is changing. From Figure 11 and Table 4, the

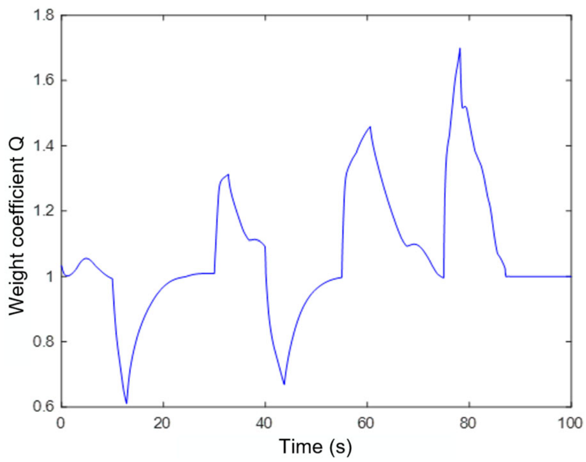


Figure 13. The change of dynamic weight Q.

peak value of the distance error generated by the proposed algorithm is about −3.31 m, while the peak values of the other two algorithms are about −8.26 m and −9.24 m, respectively. The change of vehicle acceleration under the three algorithms is shown in Figure 12 and Table 4. As can be seen from Figure 10, although the velocity following ability of the proposed algorithm is slightly better than that of the MPC algorithm, the effects are not significantly different. For example, under the first two working conditions, the time of the speed convergence of the algorithm in this paper to the steady speed of the preceding vehicle is shorter than that of the MPC algorithm, and the distance error is smaller. Although the acceleration of the fuzzy control algorithm changes more slowly under the first two conditions, the distance error is too large and the speed convergence is slow under the steady-state following mode, which has too poor following performance.

In addition, the average acceleration rate of change of the proposed algorithm is also smaller than the other two algorithms. According to the performance index analysis, the proposed algorithm improves the comfort. In the following deceleration process, the maximum deceleration of the proposed algorithm is larger than that of the MPC algorithm, and the deceleration change is smoother. The tracking error is much smaller than the other two algorithms, so the tracking performance of the proposed algorithm is better.

4.1.2. *The change of car following mode*

(Figure 14) The Q value and the working mode of ACC system will change with the distance error and relative vehicle speed, and the specific changes are shown in Table 5. It can be seen that the distance between the two vehicles increases when the vehicle accelerates, and the safety is high at this time. The following performance of the vehicle should be considered, so the Q value decreases, and the car-following mode is accelerated mode. As shown in Figures 11 and 12, when the preceding vehicle acceleration is 2 and 1.5 m/s^2, respectively, the corresponding Q values are 0.6 and 0.7. The greater the preceding vehicle acceleration, the smaller the Q value. On the basis of ensuring the safety, the comfort performance of the vehicle should be improved.

When the preceding vehicle is decelerated, the distance between the two vehicles is reduced, and it is

Table 4. Peak value comparison in different stages.

		Condition				
		Working condition change				
Algorithm		1–2	2–3	3–4	4–5	5–6
Distance error	The proposed	−1.27	0.68	−1.15	0.78	−3.31
	The MPC	4.11	−1.76	3.27	−4.31	−8.26
	The fuzzy	−9.24	−4.81	−9.63	−5.12	2.43
Acceleration	The proposed	1.49	−0.78	1.11	−1.30	−2.64
	The MPC	1.49	−0.73	1.12	−1.23	−2.46
	The fuzzy	0.84	−0.65	0.90	−1.23	−2.22

Table 5. The value of dynamic weight Q and following modes.

	Working condition change				
The preceding vehicle	1–2	2–3	3–4	4–5	5–6
	Accelerate	Decelerate	Accelerate	Decelerate	Decelerate
Q	0.60	1.31	0.67	1.6	1.7
Mode	1	3	1	3	3 and 4

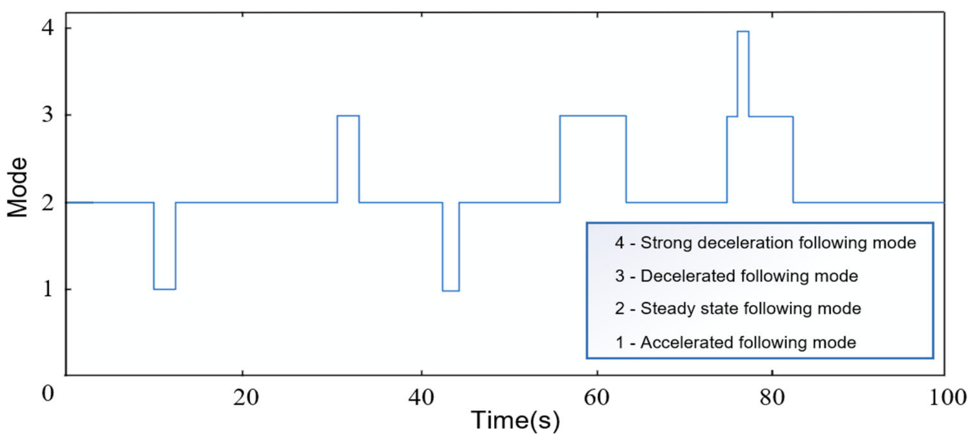


Figure 14. The change of the following mode.

easy to collide at this time. Therefore, the safety is in the first place, so the Q value increases. The car following mode is decelerated mode. When the preceding vehicle deceleration is 1, 1.5 and 3.5 m/s^2, the corresponding Q values are 1.3, 1.5 and 1.68. Because when the acceleration is 3.5 m/s^2, in order to ensure the vehicle safety, the following mode changes to strong deceleration mode. When the distance and speed of the two vehicles increase, the following mode changes from strong deceleration to deceleration.

It can be seen from the above figures and tables when the preceding vehicle accelerates, the acceleration change rate of the proposed algorithm is lower than that of the ordinary MPC, which means that the ride comfort of the algorithm in this paper is much better than that of ordinary MPC. When the preceding vehicle decelerates, the maximum deceleration of the proposed algorithm is greater than that of ordinary MPC, the deceleration change is smoother, and the distance error during deceleration is smaller. When following the vehicle in the steady state mode, the following error and speed convergence in this paper are also better than that of ordinary MPC, that is, the following performance of this algorithm is better than that of ordinary MPC. Although the change of acceleration and deceleration and the speed following effect of fuzzy control are not much different from those of the proposed algorithm, the overall distance error of fuzzy control is much greater than that of the proposed algorithm. Therefore, the car following performance, comfort and safety of the proposed algorithm are better than those of the other two algorithms.

4.2. Two level ACC mode changes

In order to better observe the changes of adaptive cruise mode at different levels, the following scenarios are designed on the basis of the above car-following modes. The scenarios and tables are shown in Figure 15 and Table 6, and then through simulation analysis, the corresponding mode changes are shown in Figure 16.

As the primary state of the vehicle is assumed to be the activation phase, the ACC system is in the working state. According to the simulation setup conditions, the ACC mode of the vehicle changes as shown in Figure 16, the mode of ACC can be seen intuitively.

(1) As can be seen from the secondary state, the vehicle is always in following mode when there is a car in front of this lane, except for the stop and start phases. During the stop and start phase, the secondary state changes to start-stop mode. When the preceding vehicle leaves the lane, the mode of

Table 6. Specific changes of the preceding vehicle.

Working condition	Stage	The preceding vehicle specific changes
1	0–10 s	Travels at an initial speed of 40 km/h
	10–30 s	Accelerates to 60 km/h at an acceleration of 2 m/s^2
	30–45 s	Accelerates to 80 km/h at an acceleration of 1.5 m/s^2
2	45–65 s	Decelerates to 40 km/h at a deceleration of 1.5 m/s^2
	65–85 s	Decelerates to a stop at a deceleration of 3.5 m/s^2
3	85–110 s	Accelerates to 54 km/h at an acceleration of 1.5 m/s^2
	110 s	The preceding vehicle cuts out of the lane

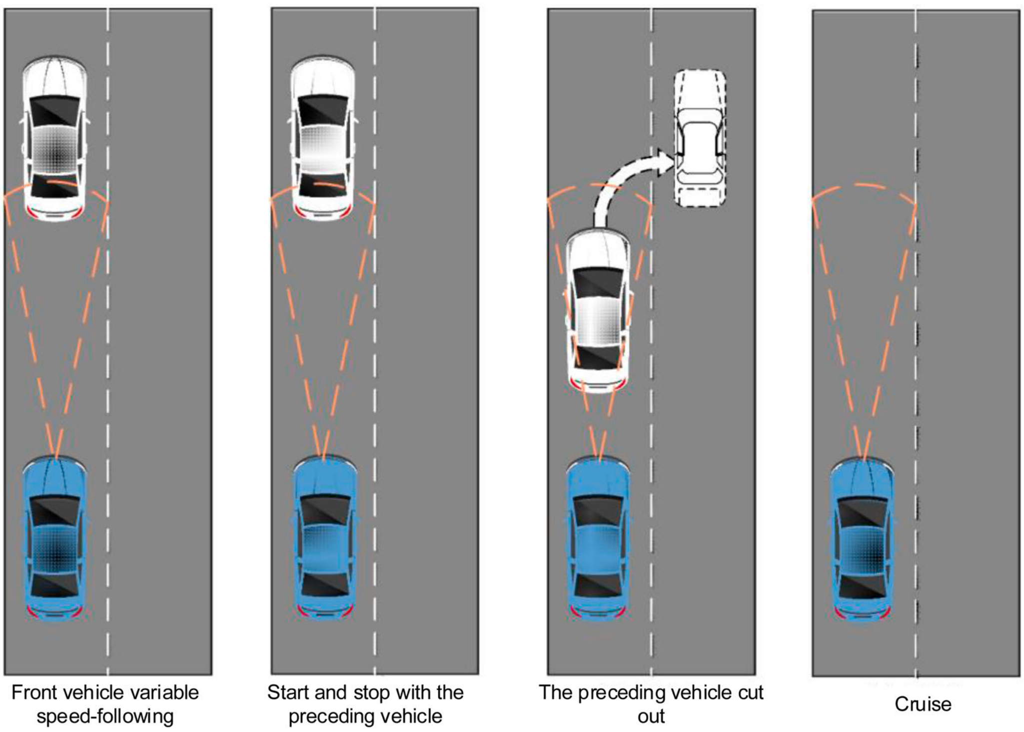


Figure 15. Typical driving simulation scenario of ACC system.

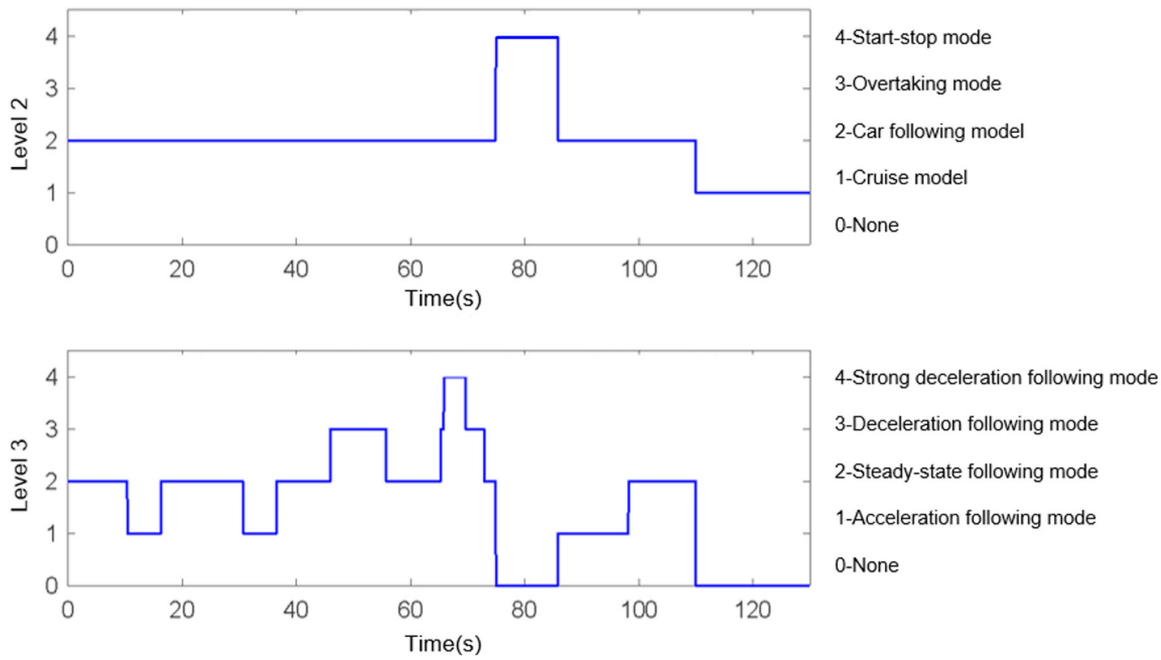


Figure 16. Mode simulation diagram of multi-level state machine.

vehicle changes from the following mode to the constant speed cruise mode.

(2) It can be clearly seen from the three-level state that when the preceding vehicle is driving stably, the vehicle is in the steady-state following mode. When the preceding vehicle is accelerating or decelerating, the car is in the accelerating or decelerating following mode. When the preceding vehicle stops, starts, or leaves the lane, and there is no three-level state.

5. Conclusion

Adaptive cruise control is recognized as an effective method to improve vehicle safety and reduce driver workload, in order to improve its performance and application, according to the interaction among driver, vehicle, external environment, the three-level ACC framework system is constructed and the conversion mechanism among different modes is established. In this paper, the expected safety distance is modelled based on variable headway time distance and road adhesion coefficient, and the distance error and speed error are used as fuzzy inputs to obtain the following mode by fuzzy control algorithm. In order to balance the performance weight of ACC system under different following conditions, the control target is set as model predictive control algorithm, and tracking ability and ride comfort are considered. A dynamic weight strategy is proposed to solve time-varying multi-objective control problems. The above ACC control strategy is verified by experiments under complex operating conditions. Comparing with normal following MPC algorithms, the results show that the proposed algorithm can reasonably weigh the performance indicators, improve the ride comfort performance under acceleration conditions and the safety performance under deceleration conditions, optimize the driver's experience while meeting most people's driving habits.

The ACC system control algorithm studied in this paper is limited to the longitudinal control level of the intelligent vehicle. In some complex working conditions involving steering, the influence of lateral control on the ACC system needs to be further analyzed.

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References

[1] Wu GQ, Zhang LX, Liu ZY, et al. Research status and development trend of vehicle adaptive cruise control systems. J Tongji Univ Sci Technol. 2017;45(4):544–553. DOI:10.11908/j.issn.0253-374x.2017.04.012

[2] Haroon Z, Khan B, Farid U. Switching control paradigms for adaptive cruise control system with stop-and-go scenario. Arab J Sci Eng. 2019;44(3):2103–2113. DOI:10.1007/s13369-018-3346-4

[3] Cai YF, Lv ZJ, Sun XQ, et al. Adaptive cruise control method based on parallel behavior recognition. Automot Eng. 2021;43(07):1077–1108. DOI:10.19562/j.chinasae.qcgc.2021.07.015

[4] Fancher P, Bareket Z. Evaluating Headway Control Using Range Versus Range-Rate Relationships. Vehicle

System Dynamics. 2007;23(1):575–596. DOI:10.1080/00423119408969076
[5] Pei XF, Liu ZD, Ma GC. Multi-mode switching control of vehicle adaptive cruise system. Chin J Mech Eng. 2012;48(10):96–102. DOI:10.3901/JME.2012.10.096
[6] Leng Y, Zhao SE. Adaptive cruise control with multimode strategy of intelligent vehicle. J Chongq Univ Technol. 2020;34(9):73–81. DOI:10.3969/j.issn.1674-8425(z).2020.09.008
[7] Seungwuk M, Ilki M, Kyongsu Y. Design, tuning, and evaluation of a full-range adaptive cruise control system with collision avoidance. Contr Eng Pract. 2009;17:442–455. DOI:10.1016/j.conengprac.2008.09.006
[8] Mahtout I, Navas F, Gonzalez D, et al. Youla–Kucera based multi-objective car following controller. Contr Eng Pract. 2021;115:104908. DOI:10.1016/j.conengprac.2021.104908
[9] Zhang DZ, Wang JQ, Liu JX, et al. Switching strategy for adaptive cruise control modes for continuous acceleration. J Tsing Univ. 2010;50(08):1277–1281. DOI:10.16511/j.cnki.qhdxxb.2010.08.015
[10] Yan W. (2016). Study on adaptive cruise control algorithms imitating car-following behaviors of drivers (Ph.D. Thesis). Jilin University, People's Republic of China.
[11] Zhang JH, Li Q, Chen DP. Multi-objective adaptive cruise control with multi-mode strategy. J Univ Electron Sci Technol China. 2018;47(03):368–375. DOI:10.3969/j.issn.1001-0548.2018.03.008
[12] Huang J, Wei W, Zhou DB. Research on mode switching strategy of adaptive cruise system based on personalized distance strategy. Automot Eng. 2020;42(10):1302–1311. DOI:10.19562/j.chinasae.qcgc.2020.10.002
[13] Changwoo P, Namju J, Hyeongcheol L. A study of adaptive cruise control system to improve fuel efficiency. Proc World Congr New Technol. 2015;202(1-6):15–19. DOI:10.11159/ijepr.2017.002
[14] Zhao SE, Leng Y, Shao YM. Explicit model predictive control of multi-objective adaptive cruise of vehicle. J Traffic Transp Eng. 2020;20(3):206–216. DOI:10.19818/j.cnki.1671-1637.2020.03.019
[15] Swaroop D, Rajagopal KR. Intelligent cruise control systems and traffic flow stability. Transp Res Part C. 1999;7(6):329–352. DOI:10.1016/S0968-090X(99)00024-8
[16] Marzbanrad J, Karimian N. Space control law design in adaptive cruise control vehicles using model predictive control. Proc Inst Mech Eng Part D J Autom Eng. 2011;225(D7):870–884. DOI:10.1177/0954407011400819
[17] Naus GJL, Ploeg J, Van de Molengraft MJG, et al. Design and implementation of parameterized adaptive cruise control: An explicit model predictive control approach. Contr Eng Pract. 2010;18:882–892. DOI:10.1016/j.conengprac.2010.03.012
[18] Andreas W, Daniel G, Li XH. Energy-optimal adaptive cruise control combining model predictive control and dynamic programming. Contr Eng Pract. 2018;72:125–137. DOI:10.1016/j.conengprac.2017.12.001
[19] Cheng S, Li L, Mei M, et al. Multiple-objective adaptive cruise control system integrated with DYC. IEEE Trans Veh Technol. 2019;68(5):4550–4559. DOI:10.1109/TVT.2019.2905858
[20] Gao ZH, Yan W, Hu HY, et al. Human-centered headway control for adaptive cruise-controlled vehicles. Adv Mech Eng. 2015;7(11):1–13. DOI:10.1177/1687814015615042
[21] Payman S, Andrzej O. Nonlinear model predictive control approach in design of adaptive cruise control with automated switching to cruise control. Contr Eng Pract. 2014;26:160–177. DOI:10.1016/j.conengprac.2014.01.016
[22] Yang SQ. (2019). Research on adaptive cruise control system of electric vehicle based on fuzzy control (Master Thesis). Changan University, People's Republic of China.
[23] Xu L, Xie N, Wang JC. A variable weight adaptive cruise control strategy based on lane change recognition of leading vehicle. Automatika. 2022;63(3):555–571. DOI:10.1080/00051144.2022.2055913
[24] Chu HQ, Guo LL, Yan YJ, et al. Self-learning optimal cruise control based on individual car-following style. IEEE Trans Intell Transp Syst. 2021;22(10):6622–6633. DOI:10.1109/TITS.2020.2981493
[25] Mosharafian S, Velni JM. Cooperative adaptive cruise control in a mixed-autonomy traffic system: a hybrid stochastic predictive approach incorporating lane change. IEEE Trans Veh Technol. 2023;72(1):136–148. DOI:10.1109/TVT.2022.3202084