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Model Predictive Enhanced Adaptive Cruise Control for Multiple Driving Situations

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Abstract— **This paper presents an Enhanced Adaptive Cruise Control (EACC) framework that can work in different modes according to the forward targets. The EACC system, which was proposed in this paper, is based on a unified model and can achieve speed tracking, stop & go and autonomous emergency braking (AEB). Notably, speed tracking does not require a real preceding vehicle, a virtual vehicle can be set in front of the EACC vehicle. The mathematical method of setting the virtual preceding vehicle and the switching logic between the different working modes of the EACC system were given. Employing a constraints softening method to avoid computing infeasibility, an optimal control law is numerically calculated using the CVXGEN solver. Finally, real vehicle tests show that the EACC framework provides significant benefits in terms of speed-tracking capability, safety and comfort requirements while satisfying driver desired car following characteristics for different driving situations.**

I. INTRODUCTION

Intelligent Vehicles(IV), as an important part of intelligent transportation system (ITS), are attracting more attention than ever before. Adaptive cruise control has been commercialized by automotive manufacturers and it has the potential to improve vehicle safety and reduce drivers' workload. In the past period of time, the research on ACC was mainly focused on maintaining a certain desired distance from the preceding vehicle or traveling at a certain desired speed. In recent years, the studies of ACC become more pluralistic. There are many studies on multi-objective collaborative control optimization question of ACC system. [1] pointed out that the smoothing feature of ACC vehicles could improve fuel efficiency of mixed traffic flow, including that of the ACC vehicle itself. Their research further disclosed that the effect was more obvious under conditions of large acceleration. [2]-[4] proposed an optimal control algorithm and take fuel consumption as an optimization goal. With the development of intelligent transportation, [5] proposed a cooperative adaptive cruise control (CACC) deriving from conventional ACC. The CACC system adds wireless communication means such as dedicated short range communication technology to the traditional ACC system, and it can realize vehicle-vehicle and vehicle-road communication in a specific area and broadcasting information in real time.

However, the above research on ACC still focuses on the optimization and perfection of single function. A review of current literatures shows that current ACC systems focus entirely on a onefold driving scene, such as tracking a desired spacing from a preceding vehicle or tracking a desired speed, and considers many objectives. There are three problems of current MPC based ACC system:

1) A model used for car-following cannot achieve speed-tracking without a preceding vehicle;

2)when the preceding vehicle have an emergency brake, inter-vehicular distance shortens quickly and collisions happen more easily.

3) ACC vehicle cannot autonomously adapt to different driving scenes;

The EACC system proposed in this paper can realize conventional ACC, speed tracking and autonomous emergency braking (AEB). EACC does not simply combine three driver assistant systems, but is based on a unified model and algorithm framework. With the development of autonomous vehicles, especially the deep research on the control of autonomous vehicle, it is very important to make unified framwork design for the longitudinal control of autonomous vehicles. The main advantages of EACC include two aspects: one is that it can be applied to a variety of driving scenes while meeting the driving requirements for different driving situations, and the vehicle longitudinal control can be more intelligent. Two, the efficiency of system calculation is higher. For autonomous vehicles, the computer needs to calculate and process a large number of data, including environmental perception data, positioning data and vehicle driving data, etc. The execution of code to follow the bad nesting and loops is more complex. The unified framework design of the longitudinal control algorithm will reduce the complexity of the code and improve the efficiency of operation.

This paper is organized as follows. In Section II, it established a three-state car-following model. Then it analysed control objectives, I/O constraints and working modes conversion for different driving situations. Real vehicle tests were carried out to test the performance in different scenes in Section III. Finally it made some supplementary instructions and drawn some conclusions in the Section IV.

II. PROBLEM FORMULATION

As in many other longitudinal vehicle control applications, we utilized a hierarchical controller consisting of an upper level planner and a lower level controller. The upper-level planner computes the acceleration commands a_{des}, which are sent to the lower-level controller. The lower-level controller then uses the throttle and braking commands to track the spacing-control laws or achieve the speed-tracking, as

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is shown in Fig.1. This project deals with use of model predictive control (MPC) for designing of the upper-level planner. First of all, we need to establish a model of car-following based on longitudinal kinematics of the EACC vehicle and the preceding vehicle. All the driving situations mentioned in this paper are based on this model. The speed of the preceding vehicle detected by the vehicle-mounted radar is used to switch different working modes to deal with different driving scenes. For each working mode, the model established is changeless, but the cost function, constraints or weighting coefficients may be different. It is noteworthy that when the system is working in the speed-tracking mode, it is necessary to set a virtual preceding vehicle. In addition, the speed of the virtual preceding vehicle and initial distance between EACC vehicle and virtual preceding vehicle must be assigned.

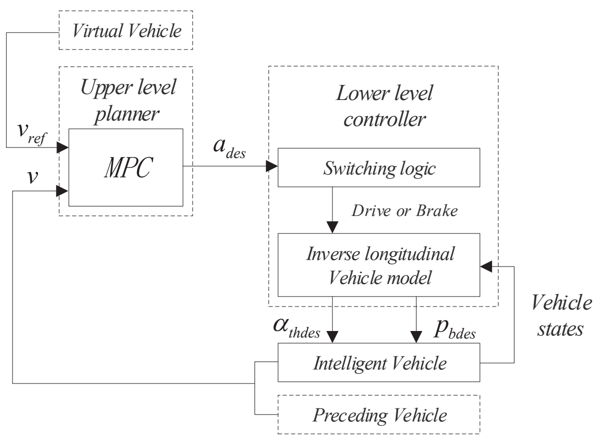

Fig. 1. The architecture of the Enhanced ACC System

A. Modelling of Car-following System

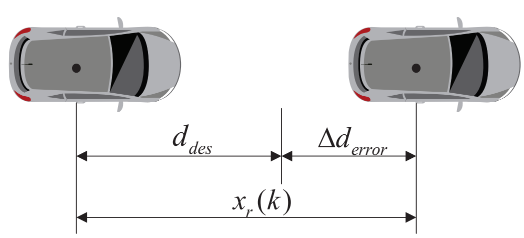

Fig. 2. Longitudinal kinematics of car-following

The longitudinal kinematics between the EACC vehicle and the preceding vehicle is shown in Fig.2. It is used to describe the positions relationship between two vehicles in the same direction. Considering the fact that an MPC algorithm is usually designed and implemented in the discrete-time domain, the car-following system can be described as

$$\begin{cases} x_r(k+1) = x_r(k) + v_r(k)T_s + \frac{1}{2}(a_{al}(k) - a_h(k)){T_s}^2 \\ v_r(k+1) = v_r(k) + (a_{al}(k) - a_h(k))T_s \\ v_h(k+1) = v_h(k) + a_h(k)T_s \end{cases} \tag{1}$$

where x_r, v_r are the distance and relative speed between EACC vehicle and preceding vehicle. a_h, a_{al} are the acceleration of EACC vehicle and preceding vehicle respectively. v_h is the speed of EACC vehicle. T_s is the sampling time of the system. Due to the short sampling time, the preceding vehicle can be seen as uniform motion, $a_{al} = 0$. This discretized formulations can be written in a concise mode as

$$\xi(k+1) = \boldsymbol{A}\xi(k) + \boldsymbol{B}u(k) \tag{2}$$

$$\xi(k) = [x_r(k) \quad v_r(k) \quad v_h(k)]^T$$

$$u(k) = a_h(k)$$

$$\boldsymbol{A} = \begin{bmatrix} 1 & T_s & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boldsymbol{B} = [-\frac{1}{2}{T_s}^2 \quad -T_s \quad T_s]^T$$

where $\xi \in R^3$ is the a vector of the system states. k represent the kth sampling point. $u \in R^1$ represents the control input. $\boldsymbol{A}$,$\boldsymbol{B}$ are system matrices.

B. Cost Function Design and I/O Constraints

When there is preceding vehicle in front of the EACC vehicle, the ultimate goal of the ACC system is to make the actual distance between two vehicles close to the desired distance calculated by the spacing static strategy. In other words, that is, two vehicles are in a relatively static state. It can be described as

$$x_r(k) \rightarrow d_{des} \qquad v_r(k) \rightarrow 0$$

where d_{des} is the desired distance between EACC vehicle and preceding vehicle. There are several spacing strategies such as fixed spacing strategy and constant time headway strategy. The fixed spacing strategy is chosen in this paper.

When there is no preceding vehicle, the EACC vehicle is expected to track a reference speed profile or drive at a reference speed which is usually the road speed limit v_{max}. Besides, the system input $u(k)$ is expected to be close to a reference acceleration $a_{ref}(k)$ which is provided by the linear follow-car driver model proposed in [2].

$$u(k) \rightarrow a_{ref}(k)$$

$$a_{ref}(k) = k_V v_r(k) + k_D \Delta d_{error} \tag{3}$$

where k_V, k_D are coefficients of the driver model. Δd_{error} is the difference between $x_r(k)$ and d_{des}. Based on the above discussions, the cost function is put forward as following formulation

$$J_1 = \sum_{k=0}^{N_p-1} [\rho(u(k) - a_{ref}(k)) + \alpha(u(k+1) - u(k)) + \|\xi(k) - \xi_{ref}\|_Q] \tag{4}$$

$$\xi_{ref} = [d_{des} \quad 0 \quad v_{max}]^T$$

where N_p is the length of predictive horizon, $k+1$ denotes the predicted value at time $k+1$ based on the information at time k. ρ is the confidence factor of the driver model. When the driver model is confident about its predictions, ρ is large and deviations from the reference accelerations are strongly penalized. $u(k+1)-u(k)$ is the control increment and α is the parameter penalizing the jerk. $\boldsymbol{Q}$ is a weighting matrix, $\boldsymbol{Q} = diag(q_1, q_2, q_3)$. The relative importance of different terms in the cost function can be calibrated by adjusting corresponding coefficient.

For the safety and ride comfort requirements, paper [15] provides a criterion:

1) the vehicle acceleration/deceleration is constrained;

2) the absolute value of jerk should be as small as possible.

Here, we restrict both the acceleration and jerk to improve driver's longitudinal ride comfort. We use the following equalities as constraints,

$$u_{\min} \leqslant u_k \leqslant u_{\max} \tag{5}$$

$$|u_{k+1} - u_k| \leqslant \Delta u_{\max} \tag{6}$$

$$H\xi(k) \leqslant \boldsymbol{G} \tag{7}$$

$$\boldsymbol{H} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1 \end{bmatrix}$$

$$\boldsymbol{G} = [-d_{\text{safe}} \quad v_{\max} \quad 0]^{\mathrm{T}}$$

where $u_{\min} = a_{\min}$ is the lower boundary of u, $u_{\max} = a_{\max}$ is the upper boundary of u. $\Delta u_{\max} = j_{\max}$ is the upper boundary of Δu. d_{safe} is the minimum distance allowed to the preceding vehicle. $v_{\max}$ is the maximum speed allowed.

A key issue with this optimization algorithm is the computing infeasibility. One of the representative causes is that the tracking errors exceed the boundaries of hard constraints because of rapid acceleration/deceleration of the preceding vehicle. In this situation, the problem may have no optimal solution since the hard constraints are never satisfied. So we employ a constraints softening method by introducing a slack variable $\varepsilon(k) \in \mathrm{R}^3$. It is used to relax part of the hard constraints, expand the upper and lower bounds of the constraints and ensure that the predictive optimization problem is solvable. Then the I/O constraints (7) are transformed into softened constraints with a slack variable.

$$\boldsymbol{H}\xi(k) \leqslant \boldsymbol{G} + \varepsilon(k) \tag{8}$$

$$\varepsilon(k) \leqslant \begin{bmatrix} \varepsilon_{\mathrm{d}}^{\max} \\ \varepsilon_{\mathrm{v}}^{\max} \\ 0 \end{bmatrix} \tag{9}$$

However, $\varepsilon(k)$ can increase the deviation with the ideal state to some extent. Therefore we can make it a cost function with an additional quadratic term of a slack variable

$$J_2 = \sum_{k=0}^{N_p-1} \|\varepsilon(k)\|_{\boldsymbol{R}} \tag{10}$$

where $\boldsymbol{R}$ is a weighting matrix, $\boldsymbol{R} = diag(r_1, r_2, r_3)$. Therefore, we have a predictive optimization problem modified by constraint softening method

$$\text{Minimize} \quad J = J_1 + J_2 \tag{11}$$

Subject to :

$$a.\ Car-following\ model\ (2)$$
$$b.\ I/O\ constraints\ (5),(6),(8)$$
$$c.\ Softening\ constraint\ (9)$$

C. Modes Conversion for Multiple Driving Situations

Current ACC systems focus entirely on a single driving situation and it cannot autonomously adapt to different driving scenes. The conventional ACC system only works when there is a preceding vehicle, with which ACC vehicles can maintain a desired spacing. Generally speaking, the mentioned objectives such as speed tracking capability,comfort requirements and safety usually conflict with each other. There should be different main performance indexes in different driving situations. To solve this problem, we developed the EACC framework, which is proposed in this paper, and it can adapt to different driving situations by switching different working modes. Thus it is applicable to the following three most common driving situations and it has corresponding working mode of each driving situation. 1) There is a preceding vehicle, system's working mode is stop & go or conventional ACC. 2) There is no preceding vehicle, system's working mode is speed-tracking mode. 3) If the spacing rate $\dot{x}_r$ is small enough, system's working mode is AEB mode. For these three working modes, the minimization of (11) can guarantee convergent spacing errors and speed tracking errors. But different working modes require different configurations.The conversion of the system's working modes in these driving situations is shown in Alg.1.

Algorithm 1 Conversion of the System's Working Mode

Input: Speed information of the preceding vehicle v_p.
Output: EACC System working mode.

```
function MODE CONVERSION(v_p, ẋ_r)
    Obtain the speed of preceding vehicle v_p and calculate spacing rate ẋ_r;
    if v_p = None then
        Mode ← Speed Tracking
    else
        Mode ← Stop&Go or Conventional ACC
    end if
    if ẋ_r < -5 m/s^2 then
        Mode ← AEB
    end if
    return Mode
end function
```

The EACC system's working modes for each driving situation need different parameter configurations including weight coefficients and the initial value of model variables. For the case of no preceding vehicle, it is a good choice to

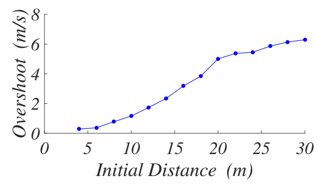

Fig. 3. $v_{\mathrm{ref}} = 3\mathrm{m/s}$

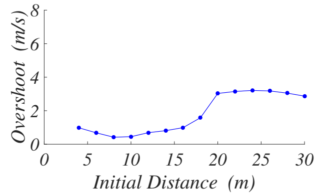

Fig. 4. $v_{\mathrm{ref}} = 6\mathrm{m/s}$

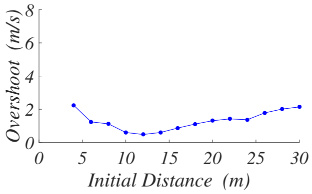

Fig. 5. $v_{\mathrm{ref}} = 9\mathrm{m/s}$

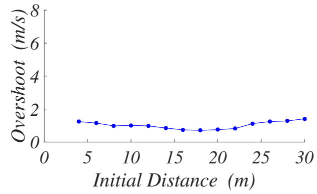

Fig. 6. $v_{\mathrm{ref}} = 12\mathrm{m/s}$

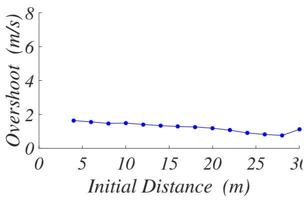

Fig. 7. $v_{\mathrm{ref}} = 15\mathrm{m/s}$

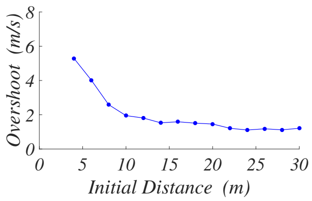

Fig. 8. $v_{\mathrm{ref}} = 18\mathrm{m/s}$

suppose that there is a virtual preceding vehicle in front of the EACC vehicle as the tracking target. Thus EACC vehicle can track a reference speed which is the speed of virtual vehicle. Simulation tests show that the configuration of initial distance between EACC vehicle and virtual preceding vehicle is a key issue. It has an important influence on the performance of reference speed tracking.

As is shown in Fig.3-Fig.8 where the horizontal axis is the initial distance from EACC vehicle to virtual preceding vehicle and the vertical axis is maximum overshoot to the reference speed, there is an optimal initial distance for different reference speed to reach the minimum overshoot. Take Fig.3 for example, when reference speed $v_{\mathrm{ref}} = 3\mathrm{m/s}$, if the initial distance is chosen to be 4m, the overshoot to the reference speed will be the smallest. We fitted the relationship between optimal initial distance $x_{\mathrm{r}}(0)$ and reference speed v_{ref} and it is described as (12).

$$x_{\mathrm{r}}(0) = 1.47 v_{\mathrm{ref}} + 2.5 \tag{12}$$

III. PERFORMANCE

In this section, the performance of the proposed framework will be illustrated in real vehicle tests. Since it is a optimization problem, the optimal control sequence $U^* \mid_{0 \ldots N_{\mathrm{p}}-1}$ can be obtained. The optimal control input U_{opt} is the first term of U^*. U_{opt} is can also be called desired acceleration a_{des}. The lower level controller calculates pedal position α_{thdes} and brake pressure p_{bdes} to generate a actual acceleration a_{f} to ensure that the desired acceleration a_{des} is tracked by the actual acceleration while the upper level planner determines the desired longitudinal acceleration according to inter-vehicle states and vehicle states. In this paper, a first order system is applied to model the lower level controller.

$$a_{\mathrm{f}} = \frac{K}{\tau s + 1} a_{\mathrm{des}} \tag{13}$$

where $K = 1.0$ is the system gain, τ is the time constant, $\tau = 0.2$ and 0.5 for the simulation vehicle and the real vehicle respectively. The EACC framework was run on a IPC using Intel Core i7 with which EACC vehicle is equipped. We run the algorithm in C++, which is a kind of efficient language. In the EACC framework, optimization problem for each iteration was solved using the CVXGEN solver. In consideration of real-time requirement, $N_{\mathrm{p}} = 20$. Test results show that run time of this framework is about 5ms. The running cycle of the function module is 20ms. We designed two scenarios for the real vehicle tests.

A. Scenario 1: Preceding Vehicle Exists

There is a preceding vehicle in this test. In the process of the preceding vehicle's free driving, the EACC vehicle can autonomously switch the working modes to meet the requirements under different driving situations. For better illustration, the preceding vehicle gradually accelerates and then rapidly decelerates to stop (red curve in Fig.9). The EACC vehicle needs to autonomously start and maintain a desired distance with it. When the preceding vehicle rapidly decelerated, the EACC vehicle can achieve emergency braking and stop outside the safe distance.

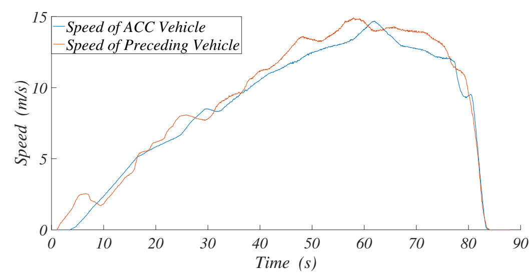

Fig. 9. Speed of ACC vehicle and preceding vehicle

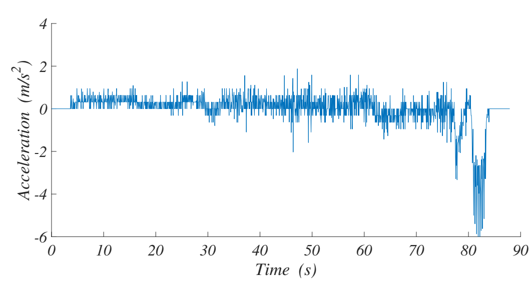

Fig. 10. Acceleration of ACC vehicle

As is shown in Fig.9-Fig.11, EACC vehicle get started autonomously after preceding vehicle's moving at 4s. The EACC vehicle can follow the preceding vehicle with a stable spacing during preceding vehicle's free driving. From 0s to 80s, the EACC vehicle was working on conventional ACC mode and corresponding parameters for this working

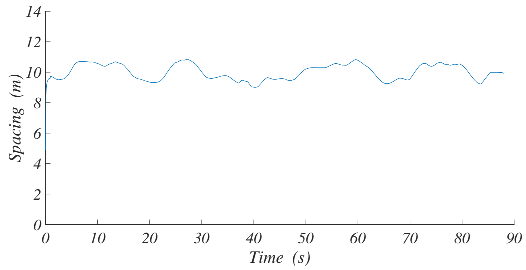

Fig. 11. Spacing of ACC vehicle and preceding vehicle

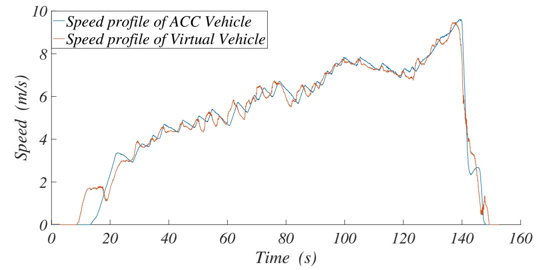

Fig. 12. Speed of EACC vehicle and virtual preceding vehicle

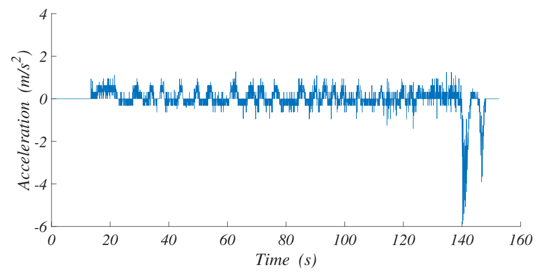

Fig. 13. The acceleration of EACC vehicle

mode are shown in TABLE. I. In this mode, spacing control and comfort requirement are the main indexes. Therefore, $a_{\min}$ is set to be -3.6m/s^2. It is shown that the spacing between EACC vehicle and preceding vehicle is kept at about 10m, while satisfaction of acceleration constraints for EACC vehicle can be guaranteed and it meets comfort requirements in this configurations. At 80s, EACC vehicle converts to work on AEB mode as a result of preceding vehicle's emergency braking. In this mode, safety is the only index. Corresponding parameters for this working mode are shown as TABLE. II. Finally, the EACC vehicle stopped with the spacing of 9m at 84s.

TABLE I
PARAMETER FOR CONVENTIONAL ACC MODE

Para.	q_1	q_2	q_3	r_1	r_2	r_3	ρ	α
Value	30	30	10	30	30	30	30	30
Para.	$v_{\max}$	d_{des}	d_{safe}	$a_{\min}$	$a_{\max}$	$\Delta u_{\max}$	-	-
Value	20	10	5	-3.6	2.5	1.5	-	-

TABLE II
PARAMETER FOR AEB MODE

Para.	q_1	q_2	q_3	r_1	r_2	r_3	ρ	α
Value	40	20	10	30	30	30	30	30
Para.	$v_{\max}$	d_{des}	d_{safe}	$a_{\min}$	$a_{\max}$	$\Delta u_{\max}$	-	-
Value	20	10	5	-6	2.5	1.5	-	-

B. Scenario 2: Preceding Vehicle Does Not Exist

There is no preceding vehicle in this test. The EACC vehicle should drive to track a certain reference speed profile which is uniform motion in practical applications. The EACC vehicle needs to track the reference speed with fast response and small overshoot.

For this scenario, system's working mode is speed tracking mode. We mainly focused on the speed tracking performance of EACC vehicle. It is necessary to do some parameter adjustment, as is shown in TABLE. III. To test the performance more persuasively, the referrence speed profile was acquired by manual driving(red curve in Fig.12). First, supposing a virtual preceding vehicle is set somewhere in front of the EACC vehicle. Then the reference speed profile is assigned to the virtual vehicle. Note that the initial distance from virtual preceding vehicle to EACC vehicle is calculated by (12) at the beginning of each running cycle. As is shown in Fig.12, Fig.13, from 20s to 138s, system's working mode is speed tracking mode. The EACC vehicle has a good performance of reference speed tracking and the speed tracking precision can be kept within 1km/h. When virtual vehicle rapidly decelerated from 138s to 145s, the ACC vehicle converts to work on AEB mode and generates a large deceleration reaching the $a_{\min}$ to track the reference speed profile.

TABLE III
PARAMETER FOR SPEED TRACKING MODE

Para.	q_1	q_2	q_3	r_1	r_2	r_3	ρ	α
Value	10	30	15	30	30	30	20	20
Para.	$v_{\max}$	d_{des}	d_{safe}	$a_{\min}$	$a_{\max}$	$\Delta u_{\max}$	-	-
Value	20	10	5	-6	2.5	1.5	-	-

IV. CONCLUSIONS

In this paper, an EACC framework is proposed and it can work on different modes autonomously satisfying desired characteristics for multiple driving situations. A virtual preceding vehicle is introduced to make the conventional ACC system applicable for the driving scene that there is no vehicles ahead. Then, we fitted the relationship between optimal initial distance and reference speed. In this way, it widens the application of conventional ACC system. Besides, a conversion method for different working modes is established in this paper. Two real vehicle test scenarioes are provided to illustrate the performance of the EACC framework. This paper focuses on the engineering aspects and experimental evaluation of a test vehicle. The speed of preceding vehicle was obtained by millimetre wave radar. Since error rate exists, it is necessary to use kalman prediction algorithm to obtain reliable speed information of the preceding vehicle.

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