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Multi-Objective Adaptive Cruise Control Strategy Based on Variable Time Headway

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Abstract—**To satisfy the requirements of safety, ride comfort and fuel-economy for electric vehicles with four in-wheel motors, a multi-objective Adaptive Cruise Control (ACC) strategy based on Variable Time Headway (VTH) under the framework of Model Predictive Control (MPC) is proposed. The characteristic of mutual longitudinal kinematics between the host and the preceding vehicle is analyzed by considering the dynamic change law of vehicle spacing, relative velocity, acceleration, the variation of acceleration and preceding vehicles' acceleration. The predictive VTH strategy is used to balance the multiple control objectives and ensure the safety of the vehicle as far as possible. The multi-objective control requirements are transformed into the performance indexes and constraints of the ACC system, which is optimized utilizing MPC. Then the expected acceleration is utilized to determine the required torque for each wheel to meet the dynamic requirements of vehicle driving process. Finally, the multi-objective ACC strategy is simulated and analyzed by using the Carsim and Simulink. Results indicate that the proposed method can satisfy the safety and ride comfort objectives with good fuel-economy.**

I. Introduction

Adaptive Cruise Control (ACC) system is one of the most important advanced driver assistance system, which originates from the cruise control system by combining with the vehicle forward collision warning system and safety vehicle spacing control system [1, 2]. In addition to having the entire function of the cruise control system, the ACC system can maintain a safe distance to avoid the rear-end accidents by taking the relative distance and relative velocity between the host vehicle and the preceding vehicle as reference.

To reduce the labor intensity of the driver and ensure the safety of the driving, the longitudinal movement is controlled by the ACC system, which also provides support for the driver through the convenient man-machine interface. Safe car-following has been studied by many researchers when designed the ACC control strategy, where the safety refers to the vehicle to maintain a safe distance between vehicles. Besides the safety, the ride comfort and fuel-economy are the most important factors for designing the ACC system [3]. Therefore, the control goal of ACC is to improve the ride comfort and fuel-economy under the premise of keeping the desired vehicle spacing. The difficulty of ACC lies in the construction of multi-objective control strategy by taking into account the safety, as well as the fuel-economy and ride comfort. Plenty of researches on ACC has been done by domestic and foreign scholars. For example, Shakouri et al. [4] presented an ACC strategy based on variable gain proportional integral and variable gain linear quadratic control strategy to meet the requirement of fuel-economy on the basis of safe car-following. Khayyam et al. [5] proposed the ACC strategy based on adaptive neuro fuzzy inference control strategy that can improve the robustness and efficiency of the system by predicting the environmental factors, such as wind velocity and road inclination angle. Naus et al. [6] introduced a parameterized ACC system based on explicit model predictive control theory, which can parameterize driver behavior characteristics and the effects of road traffic characteristics. To meet the control requirements of the safe car-following, Gerrit et al. [7] proposed an adaptive cruise control strategy based on model predictive control and stop-&-go control strategy.

Considering the requirements of ACC system for safety, fuel-economy and ride comfort for electric vehicles with four in-wheel motors, this paper adopts the model predictive control (MPC) to satisfy the multi-objectives and system constraints [7, 8, 9]. The difficulty of the ACC system is to balance the multiple control objectives under the complex driving environment. Researches indicate that the method of Variable Time Headway (VTH) is able to solve the above problem. Lin et al. [10] studied the effects of vehicle time headway on ACC based on a large number of experiments. They concluded that different time interval values should be used for different driving conditions. Xu et al. [11] fitted the exponential form of VTH by analyzing the data of highway systems. On the basis of the intelligent transportation experimental database in the United States, Fancher et al. [12] proposed a quadratic curve of VTH.

The distance between the host vehicle and the preceding vehicle, the relative velocity, accelerating, braking and jerk are synthesized into a prediction model of longitudinal kinematics between the host vehicle and the preceding vehicle. On the framework of the MPC, the designed prediction model is optimized by using the rolling optimization technique. Meanwhile, the way of VTH is utilized to ensure the driving safety and improve the traffic flows under the complex and changing traffic environments. The proposed multi-objective ACC strategy is verified by using Carsim and Simulink.

The paper is organized as follows. Section II describes the car-following distance strategy based on VTH. Section III

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establishes the longitudinal kinematic model between the host vehicle and the preceding vehicle. Section IV describes the multi-objectives ACC strategy based on MPC. Section V distributes the required torque for each wheel of an electric vehicle with four in-wheel motors according to expected acceleration calculated by MPC. Section VI verifies the feasibility and effectivity of the proposed ACC strategy. Section VII concludes the paper.

II. CAR-FOLLOWING DISTANCE STRATEGY

The research of ACC system starts from the determination of the car-following distance strategy [2], which provides the desired car-following distance for the following control algorithm. In the control process of ACC system, the desired car-following distance is obtained by car-following distance strategy according to the driving environment. Then the desired acceleration is calculated by the control algorithm to allocate driving and braking torque, which can achieve adaptive adjustment for the desired car-following distance. Kumaragovindhan and Rajamani [13] pointed out that the fixed car-following distance strategy cannot adapt to the complex driving environment, and cannot balance the multi-objectives in the driving process. Therefore, to meet the control requirements of ACC system, this paper uses the VTH strategy. The VTH is proposed by Yanakiew and Kanellakopoulos [14], which can be described as follows:

$$t_h = t_o - c_v v_{rel}(k), \tag{1}$$

where t_h refers to the time headway of car-following distance strategy, t_o and c_v are the constants that are greater than zero, $v_{rel}(k)$ represents the relative velocity between the host vehicle and the preceding vehicle at sampling time k.

Based on the VTH strategy, this paper designs a predictable VTH strategy by considering the influence of the velocity variation trend of the preceding vehicle, where the relative speed can be obtained by millimeter wave radar. The acceleration of the preceding vehicle is utilized to represent its future velocity. The predictable VTH strategy can be expressed as:

$$t_h = t_o - c_v v_{rel}(k) - c_a a_p(k), \tag{2}$$

where $a_p(k)$ stands for the acceleration of the preceding vehicle, c_a is a constant that is greater than zero.

To avoid the collision between the host vehicle and the preceding vehicle, the saturation function is used for making the value of time headway more reasonable. The following expression is obtained:

$$t_h = \begin{cases} t_{h\_max} & \text{for } t_h > t_{h\_max} \\ t_o - c_v v_{rel}(k) - c_a a_p(k) & \text{for } t_{h\_min} \le t_h \le t_{h\_max} \\ t_{h\_min} & \text{for } t_h < t_{h\_min} \end{cases}, \tag{3}$$

where t_{h_max} and t_{h_min} are the upper and lower limits of time headway respectively.

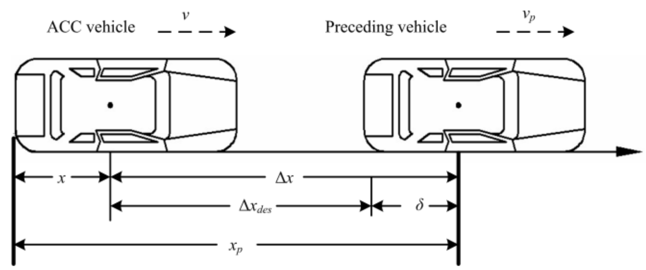

Figure 1. Longitudinal kinematic model of the ACC system.

III. LONGITUDINAL KINEMATIC MODEL

A. Longitudinal kinematic characteristics of ACC system

Fig. 1 indicates that the control effect of longitudinal relative distance is an important evaluation index for the ACC system. Taking the actual distance between the host vehicle and the preceding vehicle as the longitudinal relative distance is mainly for safety distance.

$$\begin{cases} \Delta x(k) = x_p(k) - x(k) \\ \Delta x_{des}(k) = \Delta x_o + t_h v(k) \\ \delta(k) = \Delta x(k) - \Delta x_{des}(k) \end{cases}, \tag{4}$$

where $\Delta x(k)$ is the actual inter-distance between the host vehicle and the preceding vehicle, $x_p(k)$ is the position of the preceding vehicle at sampling time k, $x(k)$ is the position of the host vehicle at sampling time k, $v(k)$ and $\Delta x_{des}(k)$ refers to the velocity and the desired following distance at sampling time k, Δx_o represents the minimum fixed following distance, $\delta(k)$ is the spacing error at sampling time k between the actual inter-distance and the desired following distance, including the formula with braces mainly for the sake of unity, no other role.

Defines $a(k)$ as estimate the acceleration of the host vehicle. Then the jerk $j(k)$ can be achieved by:

$$\begin{cases} a(k) = \dfrac{v(k) - v(k-1)}{T_s} \\ j(k) = \dfrac{a(k) - a(k-1)}{T_s} \end{cases}, \tag{5}$$

where T_s is the sampling time.

The discrete-time expression of the actual acceleration and desired acceleration of the host vehicle can be represented using the difference approximation [8, 15]:

$$a(k+1) = (1 - \frac{T_s}{\tau})a(k) + \frac{T_s}{\tau}u(k), \tag{6}$$

where τ is the control time constant and $u(k)$ is the desired acceleration at sampling time k.

B. State-space model for car-following

To fully reflect the dynamic changing of the ACC system, the acceleration of the preceding vehicle is taken as the disturbance. The acceleration and the variation of acceleration of the host vehicle are taken as the state variables to improve the robustness and control precision of the state-spac0e0 1.model. Therefore, the longitudinal kinematic characteristics between the host vehicle and the preceding vehicle can be presented by taking $\Delta x(k)$, $v(k)$, $v_{rel}(k)$, $a(k)$ and $j(k)$ as the state variables of model and $w(k)$ as the disturbance, the specific meaning of $w(k)$ will be explain in the equation(16) :

$$\begin{aligned} x(k) &= \left[\Delta x(k), v(k), v_{rel}(k), a(k), j(k)\right]^T, \\ x(k+1) &= Ax(k) + Bu(k) + Gw(k) \end{aligned} \quad (7)$$

with

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

To ensure a safe desired car-following distance, the actual distance between the host vehicle and the preceding vehicle is constrained by:

$$\Delta x(k) = x_p(k) - x(k) \geq d_c, \quad (8)$$

where d_c is the minimum actual inter-distance between the host vehicle and the preceding vehicle.

Meanwhile, the car-following behavior is that the ACC system regulates it velocity according to that of the preceding vehicle and keep the inter-distance to the desired value, which means that:

$$\delta(k) \to 0, v_{rel}(k) \to 0 \quad as \quad k \to \infty. \quad (9)$$

The survey conducted by Yi and Chung [16] shows that the absolute values of acceleration and jerk should be decreased during the car-following process in order to improve the comfort to the passengers. Martinez and Canudas-de-Wit [15] pointed out that jerk is an important evaluation index for improving the comfort to the passengers, so it is necessary to optimize the acceleration and jerk:

$$\begin{cases} min \mid a(k) \mid \\ min \mid j(k) \mid \end{cases}. \quad (10)$$

Considering that the performance of the host vehicle, the velocity, acceleration and jerk are constrained by:

$$\begin{cases} v_{min} \leq v(k) \leq v_{max} \\ a_{min} \leq a(k) \leq a_{max} \\ j_{min} \leq j(k) \leq j_{max} \end{cases}, \quad (11)$$

where v_{min}, v_{max}, a_{min}, a_{max}, j_{min} and j_{max} refer to the minimum value and maximum value of velocity, the minimum value and maximum value of acceleration, the minimum value and maximum value of the variation of acceleration, respectively.

The dynamic response curve of the host vehicle should be as smooth as possible to improve the fuel-economy. Therefore, the reference trajectories are used in this study. The reference trajectories of spacing error, relative velocity, acceleration and the variation of acceleration are represented as:

$$\begin{cases} \delta_{ref}(k+i) = \delta(k)+[\delta_{des}(k) - \delta(k)][1-\varphi_1] = \varphi_1^i \delta(k) \\ v_{rel\_ref}(k+i) = v(k)+[v_{des}(k) - v(k)][1-\varphi_2] = \varphi_2^i v(k) \\ a_{ref}(k+i) = a(k)+[a_{des}(k) - a(k)][1-\varphi_3] = \varphi_3^i a(k) \\ j_{ref}(k+i) = j(k)+[j_{des}(k) - j(k)][1-\varphi_4] = \varphi_4^i j(k) \end{cases}, \quad (12)$$

where $\delta_{ref}(k+i)$, $v_{rel\_ref}(k+i)$, $a_{ref}(k+i)$ and $j_{ref}(k+i)$ refers to the spacing error, relative velocity, acceleration and the variation of acceleration at sampling step i in the predictive time domain, respectively. $\delta_{des}(k)$, $v_{des}(k)$, $a_{des}(k)$ and $j_{des}(k)$ refers to the desired spacing error, desired relative velocity, desired acceleration and the desired variation of acceleration, respectively. φ_1, φ_2, φ_3 and φ_4 refers to the attenuation index of the spacing error reference trajectory, relative velocity reference trajectory, acceleration reference trajectory and the variation of acceleration reference trajectory, respectively.

The ACC system needs to meet the basic purposes of safety and car-following. It also serves as the driver, which means that the comfort to the passengers and fuel-economy are also important evaluation index for the ACC system. Therefore, the $\delta(k)$, $v_{rel}(k)$, $a(k)$ and $j(k)$ are selected to be the performance indexes of optimization. The output of the ACC system is as follows:

$$y(k) = Cx(k) - Z, \quad (13)$$

where

$$y(k) = \left[\delta(k), v_{rel}(k), a(k), j(k)\right]^T,$$

$$C = \begin{bmatrix} 1 & -t_h & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, Z = \begin{bmatrix} d_c \\ 0 \\ 0 \\ 0 \end{bmatrix}.$$

The state-space model of car-following can be written as:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) + Gw(k) \\ y(k) = Cx(k) - Z \end{cases}. \quad (14)$$

IV. MPC BASED CONTROL ALGORITHM FOR MULTI-OBJECTIVES ACC SYSTEM

A. The predictive state-space model for car-following

According to the above state-space model, the state variable in the predictive time domain is defined as:

$$
\begin{cases}
\hat{X}_p(k+p \mid k) \\
= \bar{B}U(k+c) + \underbrace{\bar{A}x(k) + \bar{G}W(k+p) + \bar{H}e_x(k)}_{\Phi_1} \\
\hat{Y}_p(k+p \mid k) \\
= \bar{D}U(k+c) + \underbrace{\bar{C}x(k) + \bar{E}W(k+p) + \bar{F}e_x(k) - \bar{Z}}_{\Phi_2}
\end{cases}, \tag{15}
$$

with

$$
\hat{X}_p(k+p \mid k) = \begin{bmatrix} \hat{x}_p(k+1|k) \\ \hat{x}_p(k+2|k) \\ \vdots \\ \hat{x}_p(k+p \mid k) \end{bmatrix}, \hat{Y}_p(k+p \mid k) = \begin{bmatrix} \hat{y}_p(k+1|k) \\ \hat{y}_p(k+2|k) \\ \vdots \\ \hat{y}_p(k+p|k) \end{bmatrix},
$$

$$
U(k+c) = \begin{bmatrix} u(k) \\ u(k+1) \\ \vdots \\ u(k+c\text{-}1) \end{bmatrix}, W(k+p) = \begin{bmatrix} w(k) \\ w(k+1) \\ \vdots \\ w(k+p\text{-}1) \end{bmatrix},
$$

$$
e_x(k) = x(k) - \hat{x}_c(k|k\text{-}1),
$$

where p refers to the predicted horizon, c refers to the control horizon, $\hat{x}_p(k+1|k)$, $\hat{x}_p(k+2|k)$, …, $\hat{x}_p(k+p|k)$ refers to the predictive state variables in the predicted horizon at the sampling time k based on the prediction model; $\hat{y}_p(k+1|k)$, $\hat{y}_p(k+2|k)$, …, $\hat{y}_p(k+p|k)$, refers to the predicted output variables in the prediction horizon at the sampling time k; $u(k)$, $u(k+1)$, …, $u(k+c\text{-}1)$ are the expected acceleration vector; $w(k)$, $w(k+1)$, …, $w(k+p)$ are the disturbance vector in the predicted horizon; $x(k)$ is the state variable at the sampling time k, $\hat{x}_c(k|k\text{-}1)$ is the predicted value of the state variable for the sampling time k at the sampling time k-1; $e_x(k)$ is the error between the state variable and the predicted value at the sampling time k; $\bar{A}$, $\bar{B}$, $\bar{G}$, $\bar{H}$, $\bar{C}$, $\bar{D}$, $\bar{E}$, $\bar{F}$, $\bar{Z}$ is the prediction matrices.

At the sampling time k, the current disturbance is unknown, but it can be approximated by the vehicle acceleration and the relative velocity of between the preceding vehicle and the host vehicle. Assumed that the disturbance value at the sampling time k-1 is equal to the sampling time k and it remains unchanged in the prediction horizon, the estimation of the disturbance value in the prediction horizon at the sampling time k can be calculated as follows:

$$
\begin{cases}
\hat{w}(k\text{-}1|k) = \dfrac{v_{rel}(k) - v_{rel}(k\text{-}1)}{T_s} + a(k\text{-}1) \\
w(k) = \hat{w}(k\text{-}1|k) \\
W(k+p) = \hat{w}(k\text{-}1|k)
\end{cases}, \tag{16}
$$

where $\hat{w}(k\text{-}1|k)$ means the estimated disturbance value for sampling time k at the sampling time k-1.

B. Performance objective function of the ACC system

Based on the framework of MPC, the performance indexes to be optimized are rewritten as a value function in the form of weighting values:

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

where Q and R refer to the weighting coefficients.

Substituting (15) into (17), and omitting the terms that are independent of the control output, the objective function can be rewritten as:

$$
\begin{aligned}
J = {} & 2\{x^T(k)[\bar{C}^T - C^T\bar{\Phi}^T]\bar{Q}\bar{D} + W(k+p)^T \bar{E}^T \bar{Q}\bar{D} \\
& - [\bar{Z}^T - Z^T\bar{\Phi}^T]\bar{Q}\bar{D} + e_x(k)^T \bar{F}^T \bar{Q}\bar{D}\} U(k+c) \\
& + U(k+c)^T (\bar{R} + \bar{D}^T \bar{Q}\bar{D}) U(k+c),
\end{aligned} \tag{18}
$$

where Φ=diag[φ_1; φ_2; φ_3; φ_4], $\bar{\Phi}$ =diag[Φ; Φ; Φ; …, Φ], $\bar{Q}$ =diag[Q; Q; Q; …, Q] and $\bar{R}$ = diag[R; R; R; …, R].

The corresponding constraints are rewritten as:

$$
\begin{cases}
\Delta x(k) \ge d_c \\
v_{min} \le v(k) \le v_{max} \\
a_{min} \le a(k) \le a_{max} \\
j_{min} \le j(k) \le j_{max} \\
u_{min} \le u(k) \le u_{max}
\end{cases}, \tag{19}
$$

where u_{min} and u_{max} are the minimum and maximum values of the expected acceleration, respectively.

The above optimization problem is a typical quadratic programming problem, which can be solved by the efficient set method in the Matlab Optimization Toolbox.

V. TORQUE DISTRIBUTION

Torque distribution plays a critical role for four in-wheel motors driven electric vehicle. In this paper, the expected acceleration of the model is used to determine the required torque for each wheel, which can meet the dynamic requirements of vehicle driving process.

The tire velocity w_w is proportional to the motor velocity w_e

$$
w_w = R_t w_e, \tag{20}
$$

where R_t is the proportionality coefficient different to the formula (21) parameter R .

The vehicle longitudinal velocity can be approximated as the effective radius of tire. Therefore, the longitudinal acceleration can be obtained as:

$$
a = rR_t\dot{w}_e. \tag{21}
$$

The vehicle longitudinal dynamic equation is given as:

$$
ma = F_x - F_f - F_w - F_j, \tag{22}
$$

where F_x is the longitudinal force of all the wheels, F_w is the air resistance, F_f is the rolling resistance, F_j is the acceleration resistance.

Then the longitudinal force of all wheels can be shown as:

$$F_x = mRr\dot{w}_e + F_f + F_w + F_j \ . \tag{23}$$

The dynamic equation of wheel rotation is given by:

$$I_w \dot{w}_w = T_{wheel} - rF_x \ , \tag{24}$$

where I_w refers to the moment of inertia of the wheel, T_{wheel} refers to the torque input to the wheel.

Then the required torque of the wheel can be obtained by:

$$T_{wheel} = I_w R\dot{w}_e + mr^2 R\dot{w}_e + r(F_w + F_f + F_j). \tag{25}$$

The torque can be distributed according to the vertical load values on the wheels, which improve the its driving force

$$\begin{aligned} T_1 &= \frac{F_{z1}}{F_z} T_{wheel}, \quad T_2 = \frac{F_{z2}}{F_z} T_{wheel}, \\ T_3 &= \frac{F_{z3}}{F_z} T_{wheel}, \quad T_4 = \frac{F_{z4}}{F_z} T_{wheel}. \end{aligned} \tag{26}$$

where T_1, T_2, T_3 and T_4 are the driving or breaking torque finally assigned to the front-left wheel, front-right wheel, rear-left wheel, rear-right wheel respectively. F_{z1}, F_{z2}, F_{z3} and F_{z4} are the vertical load of the front-left wheel, front-right wheel, rear-left wheel, rear-right wheel respectively, which can be measured directly from Carsim. F_z refers to the total vertical load of the vehicle.

VI. SIMULATION AND DISCUSSION

The proposed multi-objective ACC strategy is verified by Simulink and Carsim. The following traffic scenarios are simulated: car-following; approaching; far away; emergency braking. These four scenarios are basic and representative traffic environments. During the verification process, the first order inertia link is used to represent the control effect of the actuator [7, 17]. For comparison, the abbreviation ACC-VTH refers to the proposed multi-objective ACC strategy based on the VTH and the abbreviation ACC-CTH refers to the ACC strategy presented by Zhao et al. [18].

Fig. 2 shows the simulation parameters of the preceding vehicle, where describe the actual trajectory. The trajectory of the preceding vehicle condition with the road adhesion coefficient is 0.85, the radius of curvature of the three curves are approximately equal to 155m, 150m and 125m, respectively; the simulation time is 50s. The initial position between the preceding vehicle and the starting point is considered as 45m. The initial position of the host vehicle is set at the starting point. Fig. 2(b) shows the velocity of the preceding vehicle. In order to fully verify the effectiveness of the proposed ACC strategy, the velocity of the preceding vehicles is designed cyclical changing for every 12s.

The result indicates that the change of velocity between the 30.6m/s and 19.5m/s at the first 40s. Then the preceding vehicle will emergency brake at the last 10s, which make the velocity decrease from 30.6m/s to 0m/s. The simulation results are shown in Fig. 3.

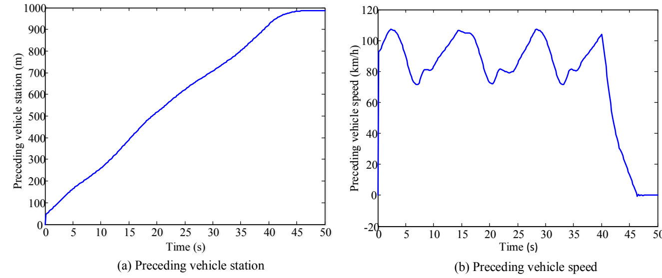

Figure 2. Simulation parameters of the preceding vehicle

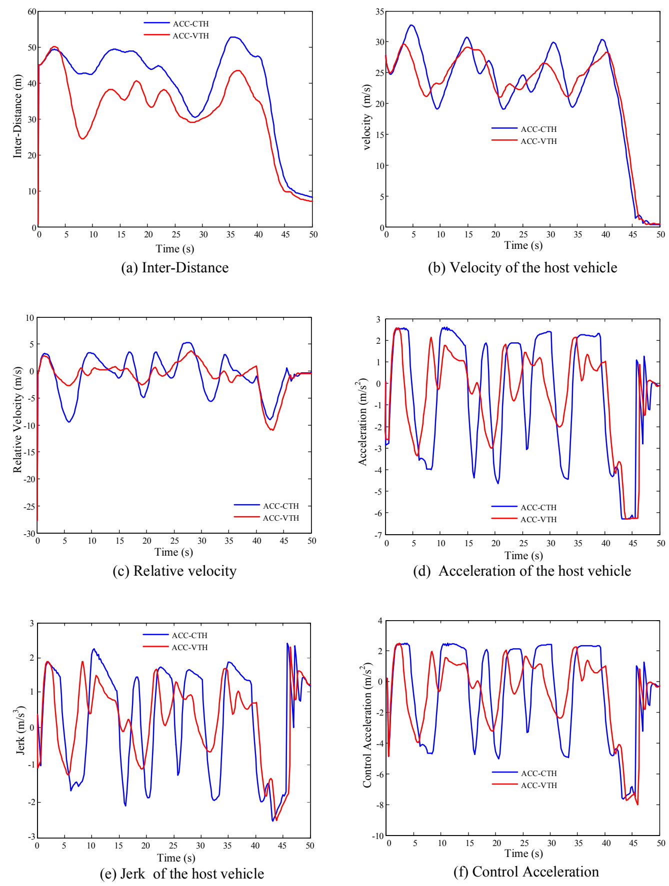

Figure 3. ACC-CTH and ACC-VTH simulation results comparison

It can be seen Fig. 3(a) that the ACC-CTH and ACC-VTH control strategies do not collide with the preceding vehicle (the vehicle inter distance is more than one length of the vehicle body), so as to ensure the safety during driving. Fig. 3(b), (c) and (d) show the vehicle velocity, the relative velocity and the acceleration response curve respectively. It indicates that the ACC-VTH and ACC-CTH can meet the car-following requirements by adjusting the velocity according to the preceding vehicle. However, when the preceding vehicle accelerates or decelerates frequently, ACC-CTH takes a relatively high velocity (19.40-32.71m/s) and acceleration (-4.641-2.604m/s^2) to catch up with the preceding vehicle, whose jerk amplitude can reach 2.946m/s^3, as can be seen from Fig. 3(e).

TABLE I. ACCELERATION PARAMETERS OF THE VEHICLE

Parameters	Control Strategy	
	ACC-CTH	ACC-VTH
Average value(m/s^2)	-0.5489	-0.5249
Standard deviation(m/s^2)	2.805	2.139
Rang value(m/s^2)	8.898	8.324

Actually, the maximum absolute value of jerk that can be accepted by the passengers is $2m/s^3$. The passengers will have discomfort if the maximum absolute value of jerk exceeds $2m/s^3$ [15]. In order to avoid collision and ensure the comfort and economy as much as possible, the ACC-VTH and ACC-CTH vehicles take a larger acceleration to brake to ensure the car-following safety when the preceding vehicle emergency braking in the last 10s. There are many studies shown that the vehicle economy is closely related to its acceleration [19]. From the figure and table I, we can find that the average acceleration value is -0.5249 m/s^2 with the standard deviation of 2.139 for the vehicle with ACC-VTH. Whereas, the acceleration average value is -0.5489 m/s^2 with the standard deviation of 2.805 for the vehicle with ACC-CTH. The result indicates that the economy increases by 4.37% and its acceleration fluctuates more smoothly in for the vehicle with ACC-VTH. The Fig. 3(f) shows the jerk response curve. It shows that the average jerk value is $-0.1492m/s^3$ for the vehicle with ACC-VTH. Whereas the average jerk value is $-0.1548m/s^3$ for the vehicle with ACC-CTH, which means that the driving comfort is improved by 3.6%.

VII. CONCLUSION

In this paper, a MPC based multi-objective ACC strategy with VTH is proposed for electric vehicles with four in-wheel motors. The predictable VTH strategy helps to improve the safety of the driving process and car-following behavior by predicting the velocity disturbance of the preceding vehicle. Simulation results show that the proposed ACC strategy can effectively adapt the complex driving environment and improve the satisfaction of drivers for ACC system. Meanwhile, the economy is increased by 4.37% and the driving comfort is improved by 3.6% for the vehicle equipped with ACC-VTH compared with that with ACC-CTH. In the next research, the proposed ACC-system is to be verified in real traffic situations.

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