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Adaptive Vehicle Following Control System with Variable Time Headways

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Abstract—**In this paper, we design a vehicle following control system with variable time headways, using adaptive control design methodology. It is shown that the designed vehicle following control system guarantees closed-loop system stability, and that it regulates the speed and separation errors towards zero when the lead vehicle is at a constant speed. Simulation results are presented to demonstrate the performance of the proposed vehicle following control system when applied to a validated nonlinear vehicle model.**

I. Introduction

During last decade, considerable progress has been made in the area of Automated Highway Systems (AHS). The design of Adaptive Cruise Control (ACC) system serves as a preliminary step towards AHS, which allows one vehicle to cruise at a constant speed in the absence of obstacles in the longitudinal direction or to follow a preceding vehicle in the same lane automatically while maintaining a desired intervehicle spacing. Many efforts have been made to design ACC systems for both passenger vehicles and commercial trucks [1]-[3], and to study their impacts on highway traffic [3]-[9].

The intervehicle spacing policy between traveling vehicles in the same lane, or equivalently the time headway used by ACC systems, is a critical parameter of an AHS system. It should be chosen as small as possible to increase the highway capacity but never to violate the safety constraint. Several vehicle following controllers have been proposed and tested on a real vehicles with a constant time headway in [1]. Some studies indicate using variable time headways in the ACC systems may lead to better impacts on highway traffic [2], [6]-[9]. In [6] and [7], the vehicle following controller with variable time headways is designed using feedback linearization methodology based on a simplified second-order vehicle model. Though the design procedure is straightforward, this controller may generate high control effort, which is not desired due to the constraints for driving comfort. Furthermore, it is not applicable for certain time headways such as the one given in [2], as we will show in section II-*D*. In this paper, we design vehicle following controllers that can provide desired stability properties for all of the variable time headways that have been considered in [2], [6]-[9] as well as the constant time headway. Simulation results are presented to demonstrate the validation of the proposed controllers.

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II. Vehicle Following Control Design

A. Simplified Vehicle Model

The vehicle model used for simulation is taken from [1], which is built based on physical laws and has been experimentally validated. This model can be characterized by a set of differential equations, algebraic relations and look-up tables. Though the full nonlinear model is complicated, it can be simplified as a first-order system for control design purpose as [1], [2]

$$\dot{v} = -a(v - v_d) + b(u - u_d) + d \tag{1}$$

where v is the longitudinal speed, u is the throttle/brake command, v_d is the desired steady state speed, u_d is the corresponding steady state fuel command, d is the modeling uncertainty, and a and b are positive constant parameters that depend on the operating point. For a given vehicle, the relation between v_d and u_d can be described by a look-up table, or by a 1-1 mapping continuous function

$$v_d = f_u(u_d) \tag{2}$$

In our analysis, we assume f_u is differentiable and the derivative is bounded. In the vehicle following mode, the desired speed for the following vehicle is v_l, the speed of the preceding vehicle. Hence, the simplified vehicle model used for vehicle following control design is described by (1) and (2), with v_d replaced by v_l. It is reasonable to assume that d, v_l and their derivatives are all bounded.

B. Control Objective and Constraints

In the vehicle following mode, The control objective is to regulate the vehicle speed v to track the speed of the preceding vehicle v_l while maintaining the intervehicle spacing x_r as close to the desired spacing s_d as possible, as shown in Fig. 1.

With the time headway policy, the desired intervehicle spacing is given by

$$s_d = s_0 + hv \tag{3}$$

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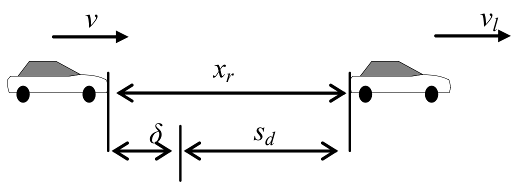

Fig. 1. Diagram of the vehicle following mode

where s_0 is a fixed safety intervehicle spacing to avoid vehicle contact at low or zero speeds, v is the speed of the following vehicle, and h is the time headway. The control objective in the vehicle following mode can be expressed as

$$v_r \to 0, \delta \to 0 \text{ as } t \to \infty \tag{4}$$

where $v_r = v_l - v$ is the speed error and $\delta = x_r - s_d$ is the separation error. The following two constraints should also be satisfied:

C1. $a_{\min} \leq \dot{v} \leq a_{\max}$ where $a_{\min}$ and $a_{\max}$ are specified.

C2. The absolute value of jerk defined as $|\ddot{v}|$ should be small.

The above constraints are the results of driving comfort concerns and are established using human factor considerations [1].

C. Variable Time Headways

Most of the previous studies for vehicle following control consider the constant spacing rule (h=0) [10] and the constant time headway spacing rule (h = nonzero constant) [1], [5]. Some studies indicate using variable time headways in the ACC systems may lead to better impacts on highway traffic. In [8], the spacing policy is chosen as

$$s_d = s_0 + h_1 v + h_2 v^2 \tag{5}$$

where h_1 and h_2 are two positive constants. The time headway incorporated in (5) can be expressed as

$$h = h_1 + h_2 v \tag{6}$$

This time headway increases with v. In practice, however, vehicle speed cannot exceed certain limit $v_{\max}$. Hence the time headway in (6) in fact is the same as

$$h = \begin{cases} h_1 + h_2 v, & \text{if } v < v_{\max} \\ h_1 + h_2 v_{\max}, & \text{otherwise} \end{cases} \tag{7}$$

In [6] and [7], the time headway is chosen based on the hypothesis proposed by Greenshields [11], and it can be written as

$$h = \frac{1}{k_{jam}\left(v_{free} - v\right)} \tag{8}$$

where k_{jam} is the traffic density corresponding to the jam conditions and v_{free} is the free speed when the traffic density is low. The time headway in (8) is expressed differently from that in [7] since the spacing considered in [7] incorporates the vehicle length. In [2], the time headway h proposed for tightly vehicle following control is given as

$$h = sat\left(h_0 - c_h v_r\right) \tag{9}$$

where h_0 and c_h are positive constants to be designed, the saturation function $sat(\bullet)$ has an upper bound 1 and a lower bound 0. Though $sat(\bullet)$ is not analytical when v_r is equal to h_0/c_h or $(h_0-1)/c_h$, slight modifications will change h to a smooth function of v and v_l.

In this paper, we consider a general time headway as a smooth function of v and v_l, which has bounded partial derivatives. Let us define

$$H \triangleq \frac{\partial}{\partial v} s_d\left(v, v_l\right) \tag{10-a}$$

$$H_l \triangleq \frac{\partial}{\partial v_l} s_d\left(v, v_l\right) \tag{10-b}$$

This general time headway has the properties that $H \geq 0$ and H and H_l are bounded. With the practical consideration as given in (7), and the proper modification for the smoothness of h in (9), we can see the general time headway includes all the time headways mentioned above. In particular, H and H_l are zeros for the constant spacing polity. For the constant time headway spacing rule, H is equal to the time headway h and H_l is zero.

D. Control Design

The simplified longitudinal model described by (1) and (2) is used for the vehicle following control design. In [6] and [7], a vehicle following controller using the variable time headway in (8) was proposed based on feedback linearization. The desired closed-loop system is described by

$$\dot{\delta} = -k\delta \tag{11}$$

where k is a positive constant. If all the parameters in the simplified model are known, the vehicle following controller

$$u = \frac{1}{bH}\left(v_r + k\delta\right) - \frac{a}{b} v_r + u_d - \frac{d}{b} - \frac{H_l}{bH}\dot{v}_l \tag{12}$$

can be used to achieve the desired closed-loop system in (11). The design procedure is straightforward, but the controller in (12) has some obvious flaws. The control gains in (12) are high when H is small, which may not be desired due to the control constraints. Furthermore, this controller cannot be implemented when H is equal to zero. Obviously H is zero in the constant spacing rule and may also be zero when the nonlinear time headway given in (9) is employed. The vehicle following controllers proposed this paper guarantee global stability for any variable time headway that has bounded H and H_l with $H \geq 0$, and the control parameters can be properly chosen so that high control gains can be avoided. We first consider the simple situation in which the parameters a, b and d in (1) are known and design a fixed-gain controller to solve the vehicle following problem. In the practical situation, where the parameters are unknown and may vary with time, we propose adaptive vehicle following controllers to accomplish the task.

Lemma 1: Consider the system in (1) and (2), with the following controller

$$u = k_1^* v_r + k_2^* \Delta(\delta, t) + k_3^* \tag{13}$$

where $k_1^* = (a_m - a)/b$, $k_2^* = a_m/b$, $k_3^* = u_d - d/b$, Δ is a design time varying function of δ satisfying

$$k_l \delta \leq \Delta(\delta, t) \leq k_u \delta \tag{14}$$

and a_m, k_l and k_u are positive design constants. All the signals in the closed-loop system are bounded if a_m, k_l and k_u are designed such that there exists a positive constant p_1 satisfying

$$a_m p_1 > 1 \tag{15a}$$
$$a_m p_1^2 (k_u - k_l)^2 - 4k_u (a_m p_1 - 1) < 0 \tag{15b}$$
$$a_m + a_m k_l p_1 - k_u \geq 0 \tag{15c}$$
$$\frac{4 p_1 k_l}{a_m + a_m k_l p_1 - k_l} > \sup H \tag{15d}$$

where $\sup H$ is the supremum of H. Furthermore, if v_l is a constant, then the control objective in (4) is achieved, i.e. $v_r, \delta \to 0$ as $t \to \infty$.

Proof: Let $\Delta(\delta, t) = k\delta$, where k is a time varying function of δ and satisfies $k_l \leq k \leq k_u$. Using (13) in (1) and (2), the closed-loop system is

$$\dot{v} = a_m (v_r + k\delta) \tag{17}$$

Denote $x_1 = v_r$ and $x_2 = \delta$, then

$$\begin{cases} \dot{x}_1 = -a_m (x_1 + kx_2) + u_1 \\ \dot{x}_2 = (1 - a_m H) x_1 - a_m kHx_2 - H_l u_1 \end{cases} \tag{18}$$

where $u_1 = \dot{v}_l$, H and H_l are bounded with $H \geq 0$. Consider the following candidate Lyapunov function

$$V_a = \tfrac{1}{2} x^T P x \tag{19}$$

where $P = \begin{bmatrix} p_1 & 1 \\ 1 & p_2 \end{bmatrix}$ a positive definite matrix, and p_1 and p_2 are positive constants. Hence,

$$\begin{aligned} \dot{V}_a &= p_1 x_1 \dot{x}_1 + p_2 x_2 \dot{x}_2 + x_1 \dot{x}_2 + \dot{x}_1 x_2 \\ &= p_1 x_1 [-a_m (x_1 + kx_2) + u_1] \\ &+ p_2 x_2 [(1 - a_m H) x_1 - a_m kHx_2 - H_l u_1] \\ &+ x_1 [(1 - a_m H) x_1 - a_m kHx_2 - H_l u_1] \\ &+ x_2 [-a_m (x_1 + kx_2) + u_1] \\ &= -x_1^2 (a_m p_1 - 1 + a_m H) - x_2^2 (a_m k + a_m kHp_2) \\ &- x_1 x_2 (a_m kp_1 + a_m - p_2 + a_m Hp_2 + a_m kH) \\ &+ u_1 (p_1 x_1 - H_l x_1 + x_2 - H_l p_2 x_2) \end{aligned} \tag{20}$$

We choose

$$p_2 = a_m k_l p_1 + a_m \tag{21}$$

When (15a) holds, the coefficient of x_1^2 in (20) is negative and (21) guarantees that P is positive definite. With (21), (20) can be rewritten as

$$\begin{aligned} \dot{V}_a &= -x_1^2 (a_m p_1 - 1 + a_m H) - x_2^2 [a_m k + a_m^2 kH (k_l p_1 + 1)] \\ &- x_1 x_2 (a_m kp_1 - a_m k_l p_1 + a_m^2 H + a_m^2 k_l Hp_1 + a_m kH) \\ &+ u_1 (w_1 x_1 + w_2 x_2) \end{aligned} \tag{22}$$

where $w_1 = p_1 - H_l$ and $w_2 = 1 - H_l (a_m k_l p_1 + a_m)$. Suppose u_1 is zero. Then $\dot{V}_a$ is negative definite if

$$\begin{aligned} &(a_m kp_1 - a_m k_l p_1 + a_m^2 H + a_m^2 k_l Hp_1 + a_m kH)^2 \\ &< 4(a_m p_1 - 1 + a_m H)[a_m k + a_m^2 kH (k_l p_1 + 1)] \end{aligned} \tag{23}$$

always holds. (23) can be rewritten as

$$\begin{aligned} &a_m (a_m + a_m k_l p_1 - k)^2 H^2 \\ &- 2a_m p_1 (k + k_l)(a_m + a_m k_l p_1 - k) H \\ &+ a_m p_1^2 (k - k_l)^2 - 4k (a_m p_1 - 1) < 0 \end{aligned} \tag{24}$$

One necessary condition for (24) to be true for all $H \geq 0$ is that

$$a_m p_1^2 (k - k_l)^2 - 4k (a_m p_1 - 1) < 0 \tag{25}$$

for all $k \in [k_l, k_u]$. This condition is equivalent to that (15b) is true. When (15a) and (15b) hold, a sufficient condition for (24) to hold is that (15c) and (15d) hold. Now we have shown that if (15a) - (15d) hold and u_1 is zero then $\dot{V}_a$ is negative definite. Since w_1 and w_2 in (22) are bounded, it is easy to show that V_a is bounded, and then all the signals in the closed-loop system are bounded [12]. Furthermore, if v_l is a constant, i.e. u_1 is zero, it can be verified that $x_1, x_2 \in L_2 \cap L_\infty$, $\dot{x}_1, \dot{x}_2 \in L_\infty$. It follows from Barbalat's Lemma [12] that $x_1, x_2 \to 0$ as $t \to \infty$, i.e., the control objective in (4) is achieved.

□

The controller in (13) cannot be implemented in practice because a, b and d are unknown parameters which may change with vehicle speed and other conditions. However, we can estimate k_i^* (i=1,2,3) on-line and use their estimate k_i in the control law. In the next Lemma, we show that with proper update laws for k_i, the control law (13) where the k_i^* (i=1,2,3) are replaced with their on-line estimates stabilizes the closed-loop system and meets the control objective when v_l and d are constants.

Lemma 2: Consider the system in (1) and (2), with the control law

$$u = k_1 v_r + k_2 \Delta(\delta, t) + k_3 \tag{26}$$

where k_i is the estimate of k_i^* (defined in Lemma 1) with initial condition k_{i0} (i=1,2,3), generated by the adaptive laws

$$\begin{cases} \dot{k}_1 = \mathrm{Proj}\{\gamma_1 x_1 [(p_1 x_1 + x_2) + (x_1 + a_m k_l p_1 x_2 + a_m x_2) H]\} \\ \dot{k}_2 = \mathrm{Proj}\{\gamma_2 k x_2 [(p_1 x_1 + x_2) + (x_1 + a_m k_l p_1 x_2 + a_m x_2) H]\} \\ \dot{k}_3 = \mathrm{Proj}\{\gamma_3 [(p_1 x_1 + x_2) + (x_1 + a_m k_l p_1 x_2 + a_m x_2) H]\} \end{cases} \tag{27}$$

where a_m, p_1, γ_1 , γ_2, and γ_3 are positive design parameters, Proj{•} is the projection function keeping k_i within the intervals $[k_{il}, k_{iu}]$ (i=1,2,3). k_{il} and k_{iu} are chosen such that $k_i^* \in [k_{il}, k_{iu}]$. If we choose the parameters a_m, k_l, k_u and p_1 such that (15a) - (15d) hold, then all the signals in the closed-loop system are bounded. Furthermore, if v_l and d are constants, then the control objective in (4) is achieved, i.e. $v_r, \delta \to 0$ as $t \to \infty$.

Proof: With the proposed control law, the closed-loop system becomes

$$\dot{v} = a_m (v_r + k\delta) + b\tilde{k}_1 v_r + b\tilde{k}_2 \Delta(\delta, t) + b\tilde{k}_3 \tag{28}$$

where $\tilde{k}_i = k_i - k_i^*$ (i=1,2,3). We rewrite $\Delta(\delta, t)$ as $k\delta$ and denote $x_1 = v_r$ and $x_2 = \delta$. Now we have

$$\begin{cases} \dot{x}_1 = -a_m (x_1 + kx_2) - b\tilde{k}_1 x_1 - bk\tilde{k}_2 x_2 - b\tilde{k}_3 + u_1 \\ \dot{x}_2 = (1 - a_m H) x_1 - a_m k H x_2 - bH\tilde{k}_1 x_1 \\ \qquad - bHk\tilde{k}_2 x_2 - bH\tilde{k}_3 - H_l u_1 \end{cases} \tag{29}$$

where $u_1 = \dot{v}_l$. Consider the following Lyapunov function

$$V = V_a + \sum_{i=1}^{3} \frac{b}{2\gamma_i} \tilde{k}_i^2 \tag{30}$$

where V_a is the same as in (19). It is easy to verify by using the adaptive laws (27) and the knowledge of $k_i^* \in [k_{il}, k_{iu}]$ that

$$\dot{V} \le \dot{V}_a - \frac{b}{\gamma_3} \tilde{k}_3 \dot{k}_3^* \tag{31}$$

where $\dot{V}_a$ is given in (22) and

$$\dot{k}_3^* = \dot{u}_d - \frac{\dot{d}}{b} \tag{32}$$

Since $\dot{d}$, $\dot{v}_l$ and the derivative of the function in (2) are bounded, it follows that $\dot{k}_3^*$ is bounded. It is easy to show that if all the conditions in (15a) - (15d) are satisfied then $\dot{V}$ is negative when x_1 or x_2 or both are large. This implies that V is bounded, and therefore all the signals in the closed-loop system are bounded [12].

When v_l and d are constants, $\dot{V} < 0$ when either x_1 or x_2 is nonzero. It is true that $x_1, x_2 \in L_2 \cap L_\infty$ and $\dot{x}_1, \dot{x}_2 \in L_\infty$. It follows from Barbalat's Lemma that $x_1, x_2 \to 0$ as $t \to \infty$, i.e., the control objective in (4) is achieved .

□

In [2], an adaptive controller was proposed with the nonlinear time headway in (9), and the gain k was chosen as

$$k = c_k + (k_0 - c_k) e^{-\sigma\delta^2} \tag{33}$$

where k_0, c_k, and σ are positive constants to be designed (with $c_k < k_0$). Even though it was shown in [2] that such choices for h and k could lead to good platoon performance, the system stability was not established. Since k in (33) is bounded by c_k and k_0 all the time, Lemma 2 points out that if we choose the parameters properly, the adaptive controller in (26) with the update law in (27) makes the closed-loop system stable with h and k as chosen in [2]. Simulation results in Section III will demonstrate that the proposed controller can achieve the desired performance.

Since we have the flexibility to choose $\Delta(\delta, t)$, we can set $\Delta(\delta, t) = k\delta$ where k is a positive constant. Hence we have the following lemma, which is a special case of Lemma 2 with the fact that $k_l = k = k_u$. The proof follows the same steps as the proof for Lemma 3, and is omitted.

Lemma 3: Consider the system in (1) and (2), with the control law

$$u = k_1 v_r + k_2\delta + k_3 \tag{34}$$

where k_i (with proper initial condition k_{i0} (i=1,2,3)) is generated according to the adaptive laws:

$$\begin{cases} \dot{k}_1 = \mathrm{Proj}\{\gamma_1 x_1 [(p_1 x_1 + x_2) + (x_1 + a_m k p_1 x_2 + a_m x_2)H]\} \\ \dot{k}_2 = \mathrm{Proj}\{\gamma_2 x_2 [(p_1 x_1 + x_2) + (x_1 + a_m k p_1 x_2 + a_m x_2)H]\} \\ \dot{k}_3 = \mathrm{Proj}\{\gamma_3 [(p_1 x_1 + x_2) + (x_1 + a_m k p_1 x_2 + a_m x_2)H]\} \end{cases} \tag{35}$$

where a_m, p_1, γ_1, γ_2, and γ_3 are positive design parameters, and Proj{•} is defined in Lemma 2. All the signals in the closed-loop system are bounded if the design parameters are chosen such that

$$a_m p_1 > 1 \tag{36a}$$

$$\frac{4p_1 k}{a_m + a_m k p_1 - k} > \sup H \tag{36b}$$

Furthermore, if v_l and d are constants, then the control objective in (4) is achieved, i.e. $v_r, \delta \to 0$ as $t \to \infty$.

□

To avoid unnecessary switching between the brake and fuel systems, the following switching rules are incorporated in the vehicle following mode:

S1. If the separation distance x_r is larger than $x_{\max}$ ($x_{\max}$>0 is a design constant), then the fuel system is on.

S2. If the separation distance x_r is smaller than $x_{\min}$ ($x_{\min}$>0 is a design constant), then the brake system is on.

S3. If $x_{\max} \le x_r \le x_{\max}$, then the fuel system is on when u>0, while the brake system is on when $u < -u_0$ (u_0>0 is a design constant). When $-u_0 \le u \le 0$, the brake system is inactive and the fuel system is operating as in idle speed.

There are several other practical issues associated with the application of the controller (26) or (34). To guarantee that the constraints **C1**, **C2** are not violated, we should avoid the generation of high or fast varying control signals. Though the controller in (26) or (34) is proposed without high gains, such high or fast varying control signals can still be generated if the lead vehicle accelerates rapidly or changes lanes creating a large spacing error or the ACC vehicle switches to a new target with large initial spacing error. To eliminate the adverse effect of large separation error, the control parameter k shown in (33) is proposed in [2]. When a constant k is to be used, the function $sat(\delta)$ defined as

$$sat(\delta) = \begin{cases} e_{\max}, & \text{if } \delta > e_{\max} \\ e_{\min}, & \text{if } \delta > e_{\min} \\ \delta, & \text{otherwise} \end{cases} \tag{37}$$

should be used instead of δ in order to eliminate the adverse effects of large separation error [1]. To eliminate the adverse effect of fast varying v_l, the nonlinear filter shown in Fig. 2 is used in [1] to smooth the speed trajectory of the lead vehicle. The filtered speed trajectory $\hat{v}_l$ is then used by the controller. This modification is adopted in our vehicle following control system and.

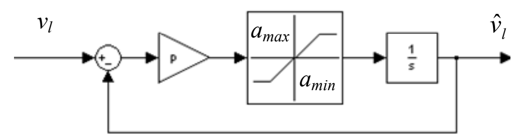

Fig. 2. Nonlinear filter used to smooth v_l

III. Simulation Results

In this section, we present the simulation results that demonstrate the performance of the vehicle following controller given by (26) when applied to the validated nonlinear vehicle model used in [1]. In the simulation, the controller given by (26) with the update laws in (27) is tested using the h in (9) and k in (33). The control parameters are chosen as

$s_0 = 4.5$m, $h_0 = 0.5$, $c_h = 0.1$, $k_0 = 0.5$, $c_k = 0.1$,
$a_m = 2$, $p_1 = 20$,
$a_{\max} = 1.0$m/s^2, $a_{\min} = -2.0$m/s^2, $p = 10$
$k_{10} = 6$, $k_{1u} = 12$, $k_{1l} = 4$, $\gamma_1 = 0.1$,
$k_{20} = 2$, $k_{2u} = 3$, $k_{2l} = 0.5$, $\gamma_2 = 0.05$,
$k_{30} = 0$, $k_{3u} = 30$, $k_{3l} = -30$, $\gamma_3 = 0.02$

It can be verified that the control parameters are chosen such that (15a)-(15d) are satisfied.

Two vehicles are used in the simulation, and the following vehicle is equipped with the controller in (26). At time zero, the two vehicles have zero speed and are separated with a distance of s_0. From t = 0s to t = 20s, the lead vehicle increases its speed with a constant acceleration 0.8m/s^2, and then cruises at 16m/s. From t = 50s to t = 53s, the lead vehicle increases its speed with a constant acceleration 2.0m/s^2, and then cruises at 22m/s. From t = 90s to t = 100s, the lead vehicle increases its speed with a constant acceleration 0.6m/s^2, and then cruises at 28m/s. From t = 140s to t = 144s, the lead vehicle decreases its speed deceleration –2.0m/s^2, and then cruises at 20m/s. The speed of the lead vehicle is presented using the dotted line in Fig. 3(a). The speed, acceleration, speed error, separation error, throttle angle and brake pressure responses of the following vehicle are presented in Fig. 3(a)-(f), respectively. As we can see, when the acceleration of the lead vehicle is not too large (0.8 or 0.6m/s^2), the throttle controller regulates the fuel system smoothly and the ACC vehicle follows the lead vehicle with small speed and separation errors. These errors are regulated towards zero when the lead vehicle reaches a constant speed. When the acceleration of the lead vehicle is large (2.0m/s^2) for a short time, the following vehicle increases its speed in a smooth and comfortable way. The transient speed and separation errors are large due to the high acceleration of the lead vehicle. However, the errors are regulated towards zero as soon as the lead vehicle reaches a constant speed. When the lead vehicle decreases its speed rapidly, the brake system on the following vehicle is active to reduce the speed. From the acceleration and separation error responses, we can see that the vehicle following control system regulates the vehicle speed in a comfortable and safe way.

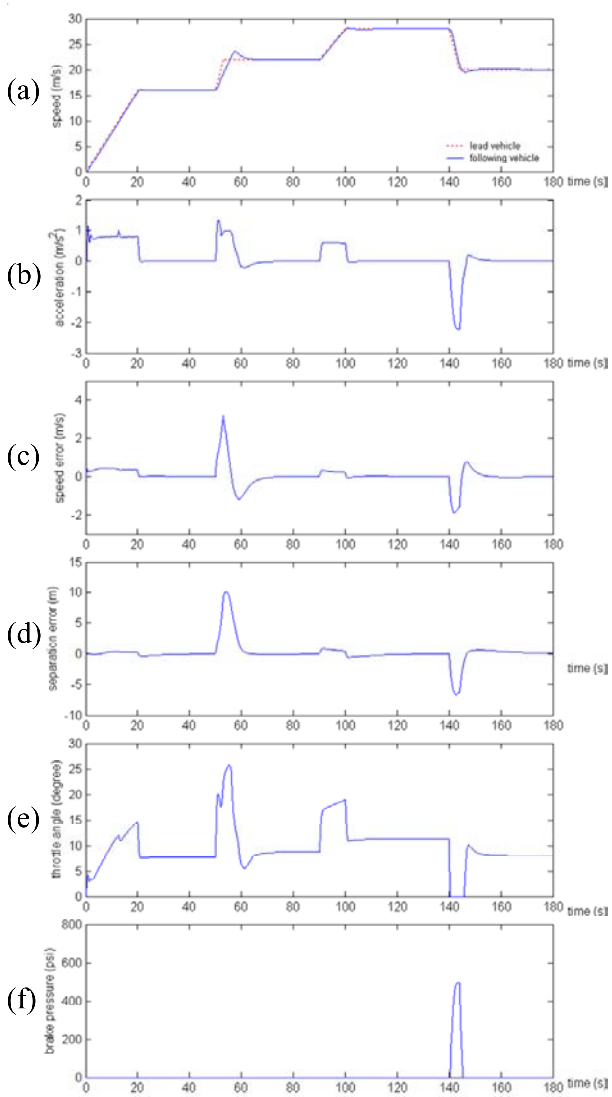

Fig. 3. Responses of the following vehicle: (a) speed, (b) acceleration, (c) speed error, (d) separation error, (e) throttle angle and (f) brake pressure in the simulation.

IV. Conclusion

In this paper, we design an adaptive vehicle following control system using a general time headway, which guarantees system stability and achievement of control objective when the speed of the lead vehicle is a constant. The analysis can be extended to any time headway with bounded partial derivatives with respect to v and v_l. The simulation results have demonstrated the performance of the proposed vehicle following control system when applied to the validated nonlinear vehicle model.

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