INTELLIGENT CRUISE CONTROL DESIGN WITH DISTURBANCE REJECTION[1]

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Abstract: In this paper, a new intelligent cruise control (ICC) system is designed to provide better transient performance than existing ones during traffic disturbances. Stability properties are established for a general variable time headway. Simulations with validated nonlinear vehicle model are conducted to demonstrate our analytical results. It is demonstrated that vehicles with the proposed ICC system operating in mixed traffic can improve fuel economy and reduce pollution over a wide range of traffic disturbances.

Keywords: intelligent cruise control, adaptive control, velocity control, autonomous vehicles, automotive emissions

1. INTRODUCTION

In recent years, extensive studies have been done on Automated Highway Systems (AHS). The design of Intelligent Cruise Control (ICC) systems, often referred to as Adaptive Cruise Control (ACC), serves as a preliminary step towards AHS. The ICC system allows the vehicle to cruise at constant speed in the absence of obstacles in the longitudinal direction or to follow a preceding vehicle in the same lane while maintaining a desired intervehicle spacing (or equivalently time headway). Many efforts have been made to design ICC systems for both passenger vehicles and commercial trucks (Zhang and Ioannou, 2004a; Yanakiev et al., 1998; Ioannou and Xu, 1994), and study their impact on highway traffic (Zhang and Ioannou, 2004a; Wang and Rajamani, 2002; Bose and Ioannou, 2001; Swaroop and Rajagopal, 2001, 1999; Broqua et al., 1991).

Most of the ICC systems proposed in literature are designed to tightly follow the preceding vehicle. The transient response of the ICC vehicles may violate the control constraints when the preceding vehicle accelerates rapidly or changes lane. In Zhang and Ioannou (2004a), this problem has been addressed by treating the vehicle following as a special speed tracking task, and introducing a nonlinear reference speed generator that leads to an ICC system with improved performance in the presence of traffic disturbances. However, no global stability has been established and the design is based on constant time headway. In this paper, we use the same idea, but extend the ICC design to a general variable time headway in order to improve performance further under all traffic conditions especially in the presence of traffic disturbances. Global stability has been established for the proposed ICC system. Simulation results demonstrate that the proposed ICC system works in a safe way meeting all comfort constraints in addition to providing better performance when compared with other ICC systems proposed in literature in the presence of traffic disturbances.

2. INTELLIGENT CRUISE CONTROL DESIGN

2.1 *Simplified Longitudinal Vehicle Model*

The longitudinal vehicle model used for simulations is from Ioannou and Xu (1994), which was built based on physical laws and had been experimentally

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validated. For control design purpose, it can be simplified to a first-order system

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

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 modelling uncertainty, and a and b are positive constant parameters that depend on the operating point. For a given vehicle, the relationship between v_d and u_d can be described by a 1-1 mapping continuous function

$$v_d = f_u(u_d) \quad (2)$$

It is assumed that f_u is a smooth function and has bounded derivative. 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. In our analysis, it is assumed that d, $\dot{d}$, v_l and $\dot{v}_l$ are all bounded.

2.2 Control Objective and Constraints

The ICC system regulates the vehicle speed v towards the speed of the preceding vehicle v_l while maintaining the intervehicle spacing x_r close to the desired spacing s_d, as shown in Fig. 1. The control objective can be expressed as

$$v_r \to 0, \delta \to 0 \text{ as } t \to \infty \quad (3)$$

where $v_r = v_l - v$ is the speed error and $\delta = x_r - s_d$ is the separation error. With the time headway policy, the desired intervehicle spacing can be expressed as

$$s_d = s_0 + hv \quad (4)$$

where s_0 is a fixed safety intervehicle spacing and h is the time headway.

The following two constraints should be satisfied:

C1. $a_{\min} \le \dot{v} \le a_{\max}$ where $a_{\min}$ and $a_{\max}$ are specified.
C2. The absolute value of jerk, $|\ddot{v}|$, should be small.

The above constraints were established based on driving comfort and human factor concerns (Ioannou and Xu, 1994).

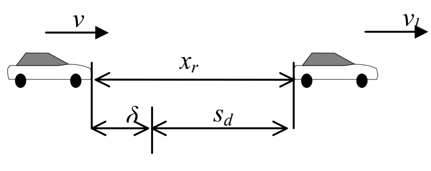

Fig. 1. Diagram of the vehicle following mode

2.3 Variable Time Headways

Most of the previous studies for vehicle following control considered the constant spacing rule (h=0) and the constant time headway spacing rule (h is a positive constant). Different variable time headways were introduced in order to achieve better traffic or platooning performance. Broqua et al. (1991) chose the speed dependent time headway

$$h = h_1 + h_2 v \quad (5)$$

where h_1 and h_2 are two positive constants. This time headway increases with v. In practice, however, vehicle speed cannot exceed certain limit $v_{\max}$. Hence the time headway in (5) in fact is the same as

$$h = \begin{cases} h_1 + h_2 v, & \text{if } v < v_{\max} \\ h_1 + h_2 v_{\max}, & \text{otherwise} \end{cases} \quad (6)$$

Swaroop and Rajapopal (1999) used the time headway based on the hypothesis proposed by Greenshields (1934)

$$h = \frac{1}{k_{jam}(v_{free} - v)} \quad (7)$$

where k_{jam} is the traffic density corresponding to the congestion conditions and v_{free} is the free speed. Similarly, (7) is only applicable to speeds lower than $v_{\max}$. The time headway proposed by Yanakiev et al. (1998) for tightly vehicle following is

$$h = sat(h_0 - c_h v_r) \quad (8)$$

where h_0 and c_h are positive constants to be designed,and the saturation function sat(•) has an upper bound 1 and a lower bound 0.

We consider a general variable time headway as a smooth function of v and v_l, i.e. $h(v, v_l)$. Let us define

$$H = \frac{\partial}{\partial v} s_d(v, v_l) \quad (9\text{-a})$$

$$H_l = \frac{\partial}{\partial v_l} s_d(v, v_l) \quad (9\text{-b})$$

The general time headway considered in this paper has the properties that $H \ge 0$ and H and H_l are bounded. It includes the constant time headway (zero or positive) and those variable ones suggested in literature such as (5), (7) and (8) provided that in (8) a minor modification is used to guarantee smoothness of h.

2.4 Control Design

In most of the previous ICC systems, vehicle following and speed tracking were considered as two separate tasks, and the vehicle following controller can be expressed as

$$u = K_1 v_r + K_2 \delta + K_3 \tag{10}$$

where K_1 and K_2 are fixed or variable gains, and K_3 is an integration term. Due to the control constraints, generation of high or fast varying control signals should be avoided. The nonlinear filter shown in Fig. 2 can be used to smooth v_l, where p is a positive design parameter. To eliminate the adverse effects of large δ, the function $sat(\delta)$ defined as

$$sat(\delta) = \begin{cases} e_{\max}, & \text{if } \delta > e_{\max} \\ e_{\min}, & \text{if } \delta > e_{\min} \\ \delta, & \text{otherwise} \end{cases} \tag{11}$$

where $e_{\max}$ and $e_{\min}$ are two design parameters, can be used to replace δ in (10) (Ioannou and Xu, 1994). These modifications are adopted in our comparison simulations.

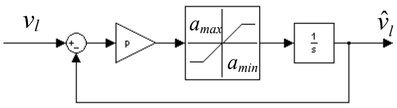

Fig. 2. Nonlinear filter used to smooth v_l .

In our ICC design, the vehicle following task is treated as a special case of the speed tracking task.

Lemma 1: For the vehicle following problem described in Section 2.2, if the controller is designed such that $v_r+k\delta \to 0$ as $t \to \infty$ (k is a positive constant) and $\frac{d}{dt}(v_r+k\delta)$ is uniformly continuous, then v_r and δ are bounded. In addition, if v_l is a constant, then the control objective in (3) is achieved.

The proof of Lemma 1 can be established using Barbalat's Lemma (Ioannou and Sun, 1996) and the fact that H and H_l are bounded, and is omitted.

Lemma 1 indicates that if v is regulated towards $v_l+k\delta$ in a proper way, then v_r and δ are guaranteed to be bounded, and the control objective in (3) is achieved when v_l is a constant. We propose the speed tracking controller

$$u = f_u^{-1}(v_{ref}) + k_1 e_v + k_2 + k_3 \dot{v}_{ref} \tag{12}$$

where v_{ref} is the reference speed, $e_v = v_{ref} - v$ and the control parameters k_i (i =1,2,3) are updated by

$$\begin{aligned} \dot{k}_1 &= \mathrm{Proj}\{\gamma_1 e_v^2\} \\ \dot{k}_2 &= \mathrm{Proj}\{\gamma_2 e_v\} \\ \dot{k}_3 &= \mathrm{Proj}\{\gamma_3 e_v \dot{v}_{ref}\} \end{aligned} \tag{13}$$

where γ_i (i =1,2,3) are positive design parameters, and Proj{·} limits k_i within $[k_{il}, k_{iu}]$ (i =1,2,3).

Lemma 2: Consider the system represented in (1) and (2) with the adaptive speed tracking controller in (12) and (13). If k_{li} and k_{ui} (i =1,2,3) are properly chosen and $\dot{v}_{ref} \in L_\infty$, then all the signals inside the closed-loop system are bounded. In addition:
(i) If d is a constant, $e_v \to 0$ as $t \to \infty$.
(ii) If d is a constant and $\dot{v}_{ref}$ is uniformly continuous, then $e_v, \dot{e}_v \to 0$ as $t \to \infty$.

Proof: For the system represented in (1) and (2), if a, b and d are known, then the controller

$$u = f_u^{-1}(v_{ref}) + k_1^* e_v + k_2^* + k_3^* \dot{v}_{ref} \tag{14}$$

where $k_1^* = \frac{a_m - a}{b}$, $k_2^* = -\frac{d}{b}$, $k_3^* = \frac{1}{b}$ and a_m is a positive constant, can make $e_v, \dot{e}_v \to 0$ as $t \to \infty$. Since a, b and d are unknown, we apply the control law in (13), and the closed-loop system can be rewritten as

$$\dot{e}_v = -a_m e_v - \tilde{k}_1 e_v - \tilde{k}_2 - \tilde{k}_3 \dot{v}_{ref} \tag{15}$$

Consider the following candidate Lyapunov function

$$V = \frac{e_v^2}{2} + \frac{b\tilde{k}_1^2}{2\gamma_1} + \frac{b\tilde{k}_2^2}{2\gamma_2} + \frac{b\tilde{k}_3^2}{2\gamma_3} \tag{16}$$

If k_{li} and k_{ui} are chosen such that $k_{li} \le k_i^* \le k_{ui}$ is true for each i, then it can be derived that

$$\dot{V} \le -a_m e_v^2 + \frac{1}{\gamma_2} \tilde{k}_2 \dot{d} \tag{17}$$

It can be shown that all signals are bounded. (17) implies that if d is a constant, then $e_v \in L_2$. With $\dot{e}_v \in L_\infty$, it can be shown $e_v \to 0$ by Barbalat's Lemma. Furthermore, if $\dot{v}_{ref}$ is uniformly continuous, it can be verified that $\dot{e}_v$ is also uniformly continuous. Barbalat's Lemma implies $\dot{e}_v$ also converges to zero.

□

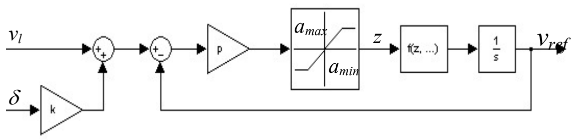

Fig. 3. Nonlinear filter used to generate v_{ref} .

Since the selected desired speed $v_l+k\delta$ may vary fast, we employ the nonlinear filter in Fig. 3 to generate a smooth signal v_{ref} to be tracked. The saturation function inside the nonlinear filter serves as an acceleration limiter that restricts the change rate of v_{ref} between $a_{\min}$ and $a_{\max}$. The signal generated by the acceleration limiter is $z=\mathrm{sat}\{p(v_l+k\delta-v_{ref})\}$, where p is a positive design parameter. The function after the acceleration limiter is designed to accept or ignore the change rate signal z, and is given as

$$f(z, v_{ref}, v_l) = \begin{cases} z, & \text{if } v_l + m_v \le v_{ref} \le v_l + M_v \text{ and } z \le 0; \\ & \text{or } v_l - m_v < v_{ref} < v_l + m_v; \\ & \text{or } v_{ref} \le v_l - m_v \text{ and } z \ge 0 \\ 0, & \text{if } v_l + m_v \le v_{ref} \le v_l + M_v \text{ and } z > 0; \\ & \text{or } v_{ref} \le v_l - m_v \text{ and } z < 0 \\ a_{\min}, & \text{if } v_{ref} > v_l + M_v \end{cases} \tag{18}$$

where m_v and M_v are constant design parameters with $0<m_v<M_v$. When $v_l-m_v<v_{ref}<v_l+m_v$, which means the reference speed for the following vehicle is not too low or too high, v_{ref} can vary with any value provided by z. If v_l increases and stays at some constant value, v_{ref} will never exceed $v_l + m_v$. Similarly if v_l decreases and stays at some constant value, v_{ref} will never be lower than $v_l - m_v$. If for some reasons the condition $v_l+m_v \le v_{ref} \le v_l+M_v$ is satisfied, then v_{ref} decreases when $v_{ref}>v_l+k\delta$, or remains constant when $v_{ref} \le v_l+k\delta$. If $v_{ref} \le v_l-m_v$ is true, then v_{ref} increases when $v_{ref}>v_l+k\delta$, or remains constant otherwise. In the last case, when $v_{ref}>v_l+M_v$, v_{ref} decreases with the deceleration $a_{\min}$ to avoid a reference speed too much higher than v_l.

Remark 1: Though the signal z within the nonlinear filter in Fig. 3 is continuous, the function (18) may generate discontinuous signals that may cause problems in the analysis related to the existence and uniqueness of solutions to the resulting differential equation. The discontinuities may arise when v_{ref} varies around $v_l - m_v$, $v_l + m_v$ or $v_l + M_v$. The function (18) can be slightly modified so that it will always generate continuous signals when z is continuous. For example, we can choose a small positive constant ε, and when z>0 and $v_l+m_v-\varepsilon \le v_{ref}<v_l+m_v$, we set f equal to $(v_l+m_v-v_{ref})\cdot z/\varepsilon$ instead of z.

Lemma 3: Consider the system in (1) and (2) with the controller given as in (12) and (13). If k_{li} and k_{ui} (i=1,2,3) are properly chosen and v_{ref} is generated by the nonlinear filter in Fig. 3, then u, v, v_r and v_{ref} are bounded. In addition:

(i) If d is a constant, $v \to v_{ref}$ and $\dot{v} \to \dot{v}_{ref}$ as $t \to \infty$.

(ii) If v_l and d are constants, and the control parameters are chosen such that

$$(1/k + \inf H)|a_{\min}| > m_v \tag{19a}$$

$$(1/k + \inf H)a_{\max} > m_v \tag{19b}$$

where inf H is the infimum of H, then all the signals are bounded.

Proof: With the function in (18), it is easy to see that (v_l-v_{ref}) is bounded. It is followed from Lemma 2 that $(v-v_{ref})$ is bounded. With the fact that v_l is bounded, it is easy to show that u, v, v_r and v_{ref} are all bounded. It can also be shown that $\frac{d}{dt}(v_l+k\delta)$ is bounded, so it follows that $\dot{v}_{ref}$ generated by (18) (with the modifications suggested in Remark 1) is uniformly continuous. Hence part (i) is proven by Lemma 2.

For part (ii), when v_l and d are two constants, we consider the following candidate Lyapunov function:

$$V = \tfrac{1}{2} x^T P x \tag{20}$$

where $P = \begin{bmatrix} 1/k + 1/p & 1 \\ 1 & k \end{bmatrix} > 0$, and $x = [v_l - v_{ref}, \delta]^T$.

Hence,

$$\begin{aligned} \dot{V} &= -[(1/k + 1/p + H)x_1 + (1 + kH)x_2]\dot{x}_1 \\ &+ (x_1 + kx_2)x_1 + (x_1 + kx_2)(\eta_1 + H\eta_2) \end{aligned} \tag{21}$$

where $\eta_1 = v_{ref} - v$ and $\eta_2 = \dot{v}_{ref} - \dot{v}$. In the following analysis, we only consider the situations in which $v_l-m_v \le v_{ref} \le v_l+m_v$ is satisfied since v_{ref} will be bounded by v_l-m_v and v_l+m_v in finite time for any bounded initial conditions.

① In the cases that $v_l-m_v<v_{ref}<v_l+m_v$, or $v_{ref}=v_l+m_v$ with $z \le 0$, or $v_{ref}=v_l-m_v$ with $z \ge 0$, z is set as $-\text{sat}\{p(x_1+kx_2)\}$. Hence

$$\begin{aligned} \dot{V} &= -(1/k + H)(x_1 + kx_2)\text{sat}\{p(x_1 + kx_2)\} \\ &- (1/p)x_1 \text{sat}\{p(x_1 + kx_2)\} + (x_1 + kx_2)x_1 \\ &+ (x_1 + kx_2)(\eta_1 + H\eta_2) \end{aligned} \tag{22}$$

If $a_{\min} \le p(x_1+kx_2) \le a_{\max}$, then (22) becomes

$$\dot{V} = -p(1/k + H)(x_1 + kx_2)^2 + (x_1 + kx_2)(\eta_1 + H\eta_2) \tag{23}$$

Hence $\dot{V} < 0$ if $|x_1+kx_2|>|\eta_1+\eta_2 H|/[p(1/k+H)]$. If $p(x_1+kx_2)> a_{\max}$, then (22) becomes

$$\begin{aligned} \dot{V} &= -(1/k + H)(x_1 + kx_2)a_{\max} - (1/p)x_1 a_{\max} \\ &+ (x_1 + kx_2)x_1 + (x_1 + kx_2)(\eta_1 + H\eta_2) \end{aligned} \tag{24}$$

When t is sufficiently large and (19b) is satisfied, $\dot{V}$ is always negative. If $p(x_1+kx_2)< a_{\min}$, it can also be verified that when t is sufficiently large and (19a) is satisfied, $\dot{V}$ is always negative.

For the cases of ② $v_{ref}=v_l+m_v$ with $z>0$ and ③ $v_{ref}=v_l+m_v$ with $z>0$, it is easy to verify that when t is sufficiently large, $\dot{V}$ is always negative.

We have shown that when t is sufficiently large, $\dot{V}$ might be positive only when $|x_1+kx_2|$ is smaller than $|\eta_1+\eta_2 H|/[p(1/k+H)]$. Since we have shown that x_1 is bounded, it is easy to conclude that V is bounded and all the signals inside the closed-loop system are bounded.

□

Remark 2: In the proof for Lemma 3, we have assumed that (18) always generates continuous signals when z is continuous. One can verify that using the modifications for (18) suggested in Remark 1, the proof for Lemma 3 can be achieved in the same way but with more regions for v_{ref}.

Remark 3: If η_1 and η_2 are zeros in (21), it can be shown that $x_1, x_2 \to 0$ as $t \to \infty$. The simulation results demonstrate that (3) can be achieved when v_l is a constant, even though we cannot prove it analytically.

The new ICC system is formed by the reference speed generator in Fig. 3 and the adaptive speed tracking controller given as in (12) and (13). The following switching rules are applied to avoid unnecessary switchings between fuel and brake systems.

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

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

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

3. SIMULATIONS

In this section, we present the simulation results that demonstrate the performance of the new ICC system. The acceleration limits in the control constraint **C1** are

$a_{\max} = 1.0\text{m/s}^2$, $a_{\min} = -2.0\text{m/s}^2$.

The variable time headway in (6) is used with

$s_0 = 4.5\text{m}$, $h_1 = 0.5$, $h_2 = 0.016$ and $v_{\max} = 30\text{m/s}$.

and the control parameters of the new ICC system are chosen as

$k = 0.4$, $p = 10$, $m_v = 2\text{m/s}$, $M_v = 8\text{m/s}$,
$k_{10} = 6$, $k_{1u} = 16$, $k_{1l} = 6$, $\gamma_1 = 5$,
$k_{20} = 0$, $k_{2u} = 30$, $k_{2l} = -30$, $\gamma_2 = 0.8$,
$k_{30} = 4$, $k_{3u} = 8$, $k_{3l} = 2$, $\gamma_3 = 0.4$.

To make a comparison, we also simulate a vehicle following controller in the form of (10), with the control gains updated as (Zhang and Ioannou, 2004b)

$$\begin{cases} \dot{K}_1 = \text{Proj}\{\gamma_1 x_1 [(p_1 x_1 + x_2) + (x_1 + a_m k p_1 x_2 + a_m x_2) H]\} \\ \dot{K}_2 = \text{Proj}\{\gamma_2 x_2 [(p_1 x_1 + x_2) + (x_1 + a_m k p_1 x_2 + a_m x_2) H]\} \\ \dot{K}_3 = \text{Proj}\{\gamma_3 [(p_1 x_1 + x_2) + (x_1 + a_m k p_1 x_2 + a_m x_2) H]\} \end{cases} \tag{25}$$

where the parameters are chosen as

$k = 0.4$, $a_m = 2$, $p_1 = 10$,
$K_{10} = 8$, $K_{1u} = 12$, $K_{1l} = 6$, $\gamma_1 = 0.4$,
$K_{20} = 2$, $K_{2u} = 3$, $K_{2l} = 0.5$, $\gamma_2 = 0.15$,
$K_{30} = 0$, $K_{3u} = 30$, $K_{3l} = -30$, $\gamma_3 = 0.12$,

The modifications used by Ioannou and Xu (1994) are adopted for the controller in (10) and (25) with the parameters

$p = 10$, $e_{\max} = 5\text{m}$, $e_{\min} = -30\text{m}$,

This ICC system, referred as ICC01, has very similar properties as most existing ICC systems (shown by Zhang and Ioannou, 2004b), and is a good benchmark to be used in evaluating the performance of the newly developed ICC system, referred as ICC02.

Two vehicles are used in the simulations to evaluate the performance of the ICC systems. The lead vehicle accelerates in an aggressive manner and its speed oscillates before settling to a constant value. This situation may arise in today's traffic where traffic disturbances downstream create a situation where the driver speeds up and then slows down in an oscillatory fashion before reaching steady state.

In the first simulation, the following vehicle is equipped with ICC01. At time t = 0s the lead vehicle begins to accelerate from 0m/s with a constant acceleration of 2.0m/s^2 for 6 seconds, and its speed oscillates around 12m/s before settling to the constant speed of 12m/s. At time t = 50s, the lead passenger vehicle accelerates again with 2.0m/s^2 for another 6 seconds and its speed oscillates around 24m/s before settling to the constant. The speed of the lead vehicle is plotted in Fig. 4(a) as dotted line. The speed, acceleration, speed error and separation error responses of the following vehicle are presented in Fig. 4(a)-(d) as dashed lines, respectively. As we can see, ICC01 regulates the vehicle speed aggressively and the oscillations in the speed of the lead vehicle are unattenuated. This is typical of the ICC systems proposed in the literature where in an effort to guarantee tight vehicle following they follow closely oscillatory speed responses of the lead vehicle.

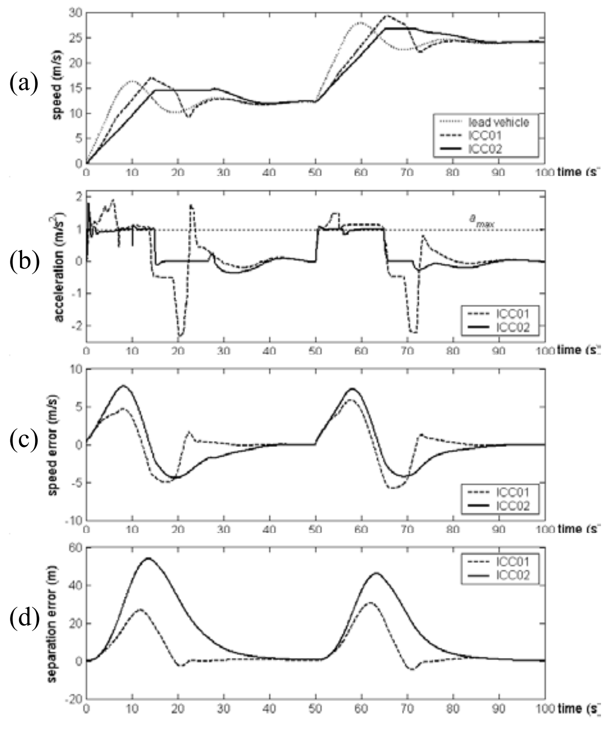

Fig. 4. (a) Speed, (b) acceleration, (c) speed error and (d) separation error responses of the two ICC vehicles.

The second simulation is the same as the first one, except that the following vehicle is equipped with ICC02, the new ICC system. The speed, acceleration, speed error and separation error responses of the following vehicle are presented in Fig. 4(a)-(d) as solid lines, respectively. The new ICC system regulates the vehicle speed in a smooth way such that the control constraints are not violated (see Fig. 4(b)). Furthermore, the oscillations in the speed of the lead vehicle are attenuated due to the use of the switching function in (18). It is noticed that when v_l becomes a constant, v_r and δ go towards zero.

4. FUEL ECONOMY AND EMISSIONS

In this section, we investigate the performance of ICC02, compared with ICC01, in terms of travel time, fuel consumption and emissions using the simulation results presented in Section 3. The Comprehensive Modal Emissions Model (CMEM) developed at UC Riverside is used to analyse the vehicle data and calculate the air pollution and fuel consumption (Barth et al., 2001). The inputs for CMEM are vehicle longitudinal speed and acceleration data, and the outputs are tailpipe emissions (HC, CO and NO_x), and fuel consumption.

We record the travel time, fuel consumption and emissions of the following ICC vehicle from the time when the lead vehicle begins to accelerate, until the following vehicle covers a distance of 1.7km and reaches a steady state speed. As shown in Table 1, the ICC system developed in this paper (ICC02) efficiently filters the oscillation created by the lead vehicle and leads to better fuel and emission results. The percentage numbers shown in the last column are the improvements in fuel consumption and emissions by ICC02. It is also shown in Table 1 that ICC02 has little effect on the travel time, though it responses more sluggishly than ICC01.

Table 1 Travel time, fuel consumption and emission data of the two ICC vehicles.

	ICC01	ICC02
Travel Time (sec)	97.6	97.5
Fuel (g)	160	133 (16.9%)
CO (g)	37.3	20.4 (45.3%)
HC (g)	0.645	0.394 (38.9%)
NO_x (g)	0.869	0.594 (31.7%)

5. CONCLUSIONS

In this paper, a new ICC system with a general variable time headway is designed based on a longitudinal vehicle model and shown to guarantee global stability. This new ICC system treats the vehicle following as a special speed tracking task. By using a nonlinear reference speed generator, the new ICC system can provide better transient performance during traffic disturbances when compared with previous ICC systems. Simulation results with a validated nonlinear vehicle model demonstrate that the new ICC system meets the control objectives and constraints. It is also shown that the presence of vehicles with the new ICC system in mixed traffic will lead to smoother traffic flow and better fuel economy and emission results when compared with other ICC systems proposed in literature.

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