Predictor-Based Adaptive Cruise Control Design

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***Abstract*— We develop a predictor-based adaptive cruise control design for compensation of arbitrarily large actuator and sensor delays in vehicular systems utilizing measurements of the relative spacing as well as of the speed and acceleration of each individual vehicular system. Employing an input-output approach we prove that the predictor-based adaptive cruise control law guarantees string stability of platoons of vehicular systems (under a constant time-headway policy) for any delay value. The effectiveness of the developed control design is illustrated in simulation.**

I. Introduction

A. Motivation

Actuator and sensor delays are ubiquitous in vehicles equipped with Adaptive Cruise Control (ACC) systems. Among other reasons, actuator delays may be due to engine response, throttle or brake actuators, and computational time, whereas sensor delays may be due to radar or lidar systems, wheel speed sensors, and sampling of measurements [4], [6], [7], [20], [24], [25], [36], [38], [40], [41].

The presence of such delays deteriorates the performance of ACC algorithms when these algorithms are designed ignoring the presence of the delay. Among the most severe consequences for the emerging traffic flow are the decrease in traffic capacity, the loss of string stability, and even the loss of individual vehicle stability. As a matter of fact, a decrease in capacity implies reduced traffic throughput and increased congestion, whereas the degradation of the stability or string stability properties imply reduced comfort and safety, and increased fuel consumption [4], [5], [6], [20], [23], [24], [30], [36], [38], [39], [40], [41].

B. Literature

Despite the significant need for delay compensation in ACC-equipped vehicles the vast majority of existing ACC strategies does not take into account the effect of such delays [7], [8], [9], [16], [19], [25], [26], [27], [28], [29], [31], [33], [34], [35], [43]. However, robustness analysis tools of various ACC strategies to delays are developed [4], [6], [30], [38], [41], which reveal the need of restricting the delay value in order to guarantee string or vehicle stability.

Exception are the papers [39], [40], and [36]. In the first two papers a discrete-time version of a predictor-based strategy is presented, whereas in the third paper a Model Predictive Control-based (MPC-based) delay-compensating strategy is developed. Yet, none of these papers proves string stability or stability of each individual vehicular system (based on the original, continuous-time system). In addition, no formal connection is made with the classical predictor-based control design methodology developed in the late 1970s [1], [2], [10], [11], [12], [14], [17], [18], [21], [22], [42], which is made in the present paper and which offers an opportunity of exploiting this control design methodology for ACC design. Finally, none of the mentioned papers is addressing the problem of the simultaneous compensation of both actuator and sensor delays.

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C. Contributions

In this paper the predictor-based feedback design methodology is employed for compensation of arbitrarily long actuator and sensor delays in vehicular systems modeled or approximated by a second-order linear system (Section II). Measurements of the relative spacing as well as the speed of each individual vehicular system are utilized by each individual vehicle's actuator, which is a delayed version of the desired acceleration of each individual vehicle. Employing an input-output approach we prove that the predictor-based ACC law guarantees string stability of homogenous platoons of vehicular systems for any delay value (Section III). The performance of the developed ACC algorithm is verified in simulation and compared with an existing ACC strategy (Section IV). Finally, we provide further issues of our current research and discuss possible future directions (Section V).

D. Notation

For a complex number s we denote by $|s|$ its absolute value. The Laplace transform of a function $f(t)$, $t \geq 0$, is denoted by $F(s) = \mathcal{L}(f(t))$. The temporal norm $\mathscr{L}_p$, $p \in [1, \infty]$, of a signal $f(t)$, $t \geq 0$, is defined as

$$\|f\|_p = \begin{cases} \left(\int_0^\infty |f(t)|^p dt\right)^{\frac{1}{p}}, & p \in [1, \infty) \\ \sup_{t\geq 0} |f(t)|, & p = \infty \end{cases} . \tag{1}$$

We denote by $\mathscr{L}_p$ the space of signals with bounded $\mathscr{L}_p$ norm.

E. Definitions

We adopt the classical definition of stability, see, e.g., [15]. Furthermore, we adopt the definition of string stability from [3], which is an adaptation of the original definition of string stability for general interconnected nonlinear systems from [31] to the case of interconnected systems of vehicles following each other in a single lane. We say that an interconnected system of vehicles, indexed by $i = 1, \ldots, N$, where $i = 1$ denotes the first vehicle, following each other

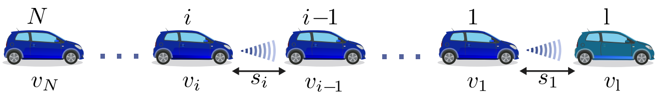

Fig. 1. Platoon of $N+1$ vehicles following each other in a single lane without passing. The dynamics of each vehicle $i=1,\ldots,N$ are governed by system (8), (9). Each vehicle can measure its own speed and the spacing with respect to the preceding vehicle. The dynamics of the leading vehicle satisfy $\ddot{x}_\mathrm{l}=a_\mathrm{l}$, where x_l and a_l are the position and acceleration of the leading vehicle, respectively.

in a single lane without passing, is string stable when the following hold

$$\|\delta_i\|_p \leq \|\delta_{i-1}\|_p \tag{2}$$
$$\|v_{\mathrm{r}_i}\|_p \leq \|v_{\mathrm{r}_{i-1}}\|_p, \quad \forall\ p\in[1,\infty] \text{ and } i=2,\ldots,N \tag{3}$$
$$\|a_{\mathrm{r}_i}\|_p \leq \|a_{\mathrm{r}_{i-1}}\|_p, \tag{4}$$

where

$$\delta_i = s_i - hv_i, \tag{5}$$

with the spacing $s_i = x_{i-1}-x_i-l_i$, $i=1,\ldots,N$, while x_j being the position of vehicle j and l_i being its length; v_i denotes the speed of vehicle i, $h>0$ is the desired constant time-headway, and

$$v_{\mathrm{r}_i} = v_{i-1}-v_i \tag{6}$$
$$a_{\mathrm{r}_i} = a_{i-1}-a_i, \tag{7}$$

where a_i denotes the acceleration of vehicle i. Note that we adopt the convention that $v_0=v_\mathrm{l}$ and $a_0=a_\mathrm{l}$, where v_l and a_l are the speed and acceleration of the string leader, respectively (see Fig. 1).

II. Predictor-Based Control of ACC-Equipped Vehicles with Actuator Delay

A. Vehicle Dynamics

We consider a homogenous string of autonomous vehicles (see Fig. 1) each one modeled by the following second-order linear system, see, e.g., [6], [9], [24], [30], [36], [41]

$$\dot{s}_i(t) = v_{i-1}(t)-v_i(t) \tag{8}$$
$$\dot{v}_i(t) = U_i\left(t-D\right), \tag{9}$$

$i=1,\ldots,N$, where s_i and v_i are defined in Section I-E, U_i is the individual vehicle's control variable, $D>0$ is actuator delay, and $t\geq 0$ is time. Note that a uniform equilibrium point of system (8), (9) for all vehicles is obtained when all vehicles have zero acceleration and their speed is dictated by the speed of the leader. System (8), (9) may come from linearization of a nonlinear model around a uniform (for all vehicles) operating point, and thus, the states s_i and v_i may represent the error between the actual spacing and speed from some nominal constant spacing and speed, respectively.

B. Delay-Free Control Design

In the absence of the actuator delay D, the following constant time-headway control strategy is widely used, either as it is or as a special case of more general control designs, see, e.g., [4], [6], [9]:

$$U_i(t) = \alpha\left(\frac{s_i(t)}{h}-v_i(t)\right), \tag{10}$$

where α and h are positive design parameters that represent control gain and desired time-headway, respectively. Using the nominal transfer function

$$G_{\mathrm{nom}}(s) = \frac{V_i(s)}{V_{i-1}(s)}, \quad i=1,\ldots,N$$
$$= \frac{\frac{\alpha}{h}}{s^2+\alpha s+\frac{\alpha}{h}}, \tag{11}$$

it can be shown that a homogenous platoon of vehicles with dynamics (8), (9) under the control law (10) with $\alpha\geq\frac{4}{h}$, is stable and string stable in the $\mathscr{L}_p$, $p\in[1,\infty]$, sense, see, e.g., [3], [6].

Remark 1: Note that for the case of a homogenous platoon it holds that, see, e.g., [3], [19]

$$G_{\mathrm{nom}}(s) = \frac{\Delta_i(s)}{\Delta_{i-1}(s)}, \quad i=2,\ldots,N, \tag{12}$$
$$G_{\mathrm{nom}}(s) = \frac{A_i(s)}{A_{i-1}(s)}, \quad i=1,\ldots,N. \tag{13}$$

Moreover, it holds that, see, e.g., [3]

$$G_{\mathrm{nom}}(s) = \frac{V_{\mathrm{r}i}(s)}{V_{\mathrm{r}i-1}(s)} \tag{14}$$
$$G_{\mathrm{nom}}(s) = \frac{A_{\mathrm{r}i}(s)}{A_{\mathrm{r}i-1}(s)}. \tag{15}$$

Thus, stability and string stability may be studied via the transfer function $\frac{V_i(s)}{V_{i-1}(s)}$.

C. Predictor-Based Control Design

The predictor-based control laws for system (8), (9) are given by

$$U_i(t) = K\left(e^{\Gamma D}X_i(t)+\int_{t-D}^{t}e^{\Gamma(t-\theta)}BU_i(\theta)d\theta\right), \tag{16}$$

where

$$\Gamma = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix} \tag{17}$$
$$K = \begin{bmatrix} \frac{\alpha}{h} & -\alpha \end{bmatrix} \tag{18}$$
$$X_i = \begin{bmatrix} s_i \\ v_i \end{bmatrix} \tag{19}$$
$$B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \tag{20}$$

One should notice that the control law (16) is suitable for autonomous operation since it employs only measurements of the current spacing s_i and speed v_i, as well as of the past D-second history of the control variable U_i, which are available to vehicle i using on-board sensors, see, e.g., [7],

[8], [19], [24], [25], [32], [36], [38], [40], [43]. Note also that in the absence of the delay, i.e., when $D = 0$, the control law (16) reduces to the nominal, delay-free control design (10). The control law (16) was developed in [1], [21]; not only its stability and robustness properties are extensively studied in the literature [2], [10], [14], [18], but, in addition, several implementation methodologies were developed [22], [14].

We analyze next, adopting a transfer function approach, the stability and string stability properties of a homogenous platoon of vehicles modeled by system (8), (9) under the ACC law (16).

III. Stability and String Stability Analysis Under Predictor-Based Feedback for Homogenous Platoons

Theorem 1: Consider a homogenous platoon of vehicles with dynamics modeled by system (8), (9) under the control laws (16). Then, each individual vehicular system is stable. If, in addition, $\alpha \geq \frac{4}{h}$, then the platoon is string stable in the $\mathscr{L}_p$, $p \in [1, \infty]$, sense, for any $D \geq 0$.

Proof: We start by deriving the transfer function

$$G(s) = \frac{V_i(s)}{V_{i-1}(s)}, \quad i = 1, \ldots, N, \tag{21}$$

viewing the preceding vehicle's speed as input and the current vehicle's speed as output, see, e.g., [3], [6], [19]. In view of Remark 1, for studying stability and string stability under the predictor-based control law, it is sufficient to study the properties of G.

Taking the Laplace transform of (16) we get

$$U_i(s) = K e^{\Gamma D} X_i(s) + M(s) U_i(s) \tag{22}$$

$$M(s) = K \left(sI_{2\times 2} - \Gamma\right)^{-1} \left(I_{2\times 2} - e^{\Gamma D} e^{-sD}\right) B, \tag{23}$$

where we used the fact that $\mathcal{L}\left(K \int_{t-D}^{t} e^{\Gamma(t-\theta)} B U_i(\theta) d\theta\right) = \mathcal{L}\left(K \int_{0}^{D} e^{\Gamma(D-y)} B U_i(t+y-D) dy\right) = K \left(sI_{2\times 2} - \Gamma\right)^{-1} \left(I_{2\times 2} - e^{(\Gamma - sI_{2\times 2})D}\right) B U_i(s)$. Using the i-th vehicle's model (8), (9) we have

$$X_i(s) = \left(sI_{2\times 2} - \Gamma\right)^{-1} \left(B e^{-sD} U_i(s) + B_v V_{i-1}(s)\right), \tag{24}$$

where $B_v = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$. Substituting (24) into (22) we get that

$$U_i(s) = \frac{K \left(sI_{2\times 2} - \Gamma\right)^{-1} e^{\Gamma D} B_v}{1 - K \left(sI_{2\times 2} - \Gamma\right)^{-1} B} V_{i-1}(s), \tag{25}$$

and thus, from (24) we arrive at

$$X_i(s) = R(s) V_{i-1}(s), \tag{26}$$

where

$$\begin{aligned} R(s) = & \frac{\left(sI_{2\times 2} - \Gamma\right)^{-1}}{1 - K \left(sI_{2\times 2} - \Gamma\right)^{-1} B} \left(B_v + B e^{-sD}\right. \\ & \times K \left(sI_{2\times 2} - \Gamma\right)^{-1} e^{\Gamma D} B_v - K \left(sI_{2\times 2} - \Gamma\right)^{-1} \\ & \left.\times B B_v\right). \end{aligned} \tag{27}$$

Note that it is clear from (27) that the spectrum of the closed-loop system is finite [10], [21]. Using the facts that $e^{\Gamma D} = \begin{bmatrix} 1 & -D \\ 0 & 1 \end{bmatrix}$ and $\left(sI_{2\times 2} - \Gamma\right)^{-1} = \frac{1}{s^2} \begin{bmatrix} s & -1 \\ 0 & s \end{bmatrix}$, and multiplying (26) from the left with $\begin{bmatrix} 0 & 1 \end{bmatrix}$ we obtain

$$G(s) = \frac{\frac{\alpha}{h} e^{-Ds}}{s^2 + \alpha s + \frac{\alpha}{h}}. \tag{28}$$

Stability: From the denominator of G in (28) it follows that for any positive α, h the transfer function G is asymptotically stable (see also [2], [14], [18] for detailed studies on the stability properties of predictor-based feedbacks).

String stability in the $\mathscr{L}_2$ sense: String stability in the $\mathscr{L}_2$ sense is guaranteed when $\sup_{\omega \in \mathbb{R}} |G(j\omega)| \leq 1$, see, e.g., [3]. Using (28) we obtain the condition

$$\frac{\frac{\alpha^2}{h^2}}{\left(\frac{\alpha}{h} - \omega^2\right)^2 + \alpha^2 \omega^2} \leq 1, \quad \text{for all } \omega \in \mathbb{R}, \tag{29}$$

which is satisfied when the following holds

$$\omega^4 + \omega^2 \alpha \left(\alpha - \frac{2}{h}\right) \geq 0, \quad \text{for all } \omega \in \mathbb{R}. \tag{30}$$

Relation (30) holds when $\alpha \geq \frac{2}{h}$.

String stability in the $\mathscr{L}_p$, $p \in [1, \infty]$, sense: The impulse response of the transfer function G defined in (28) is given by

$$g(t) = \begin{cases} 0, & 0 \leq t \leq D \\ f(t-D), & t \geq D \end{cases}, \tag{31}$$

where f is the impulse response of the delay-free system under the nominal control design, i.e.,

$$f(t) = \mathcal{L}^{-1}\left(\frac{\frac{\alpha}{h}}{s^2 + \alpha s + \frac{\alpha}{h}}\right).$$

Choosing $\alpha > \frac{4}{h}$ the characteristic polynomial $s^2 + \alpha s + \frac{\alpha}{h}$ has two distinct real roots, say, p_1 and p_2, and hence,

$$g(t) = \begin{cases} 0, & 0 \leq t \leq D \\ \frac{\alpha}{h(p_1 - p_2)} \left(e^{p_1(t-D)} - e^{p_2(t-D)}\right), & t \geq D \end{cases} \tag{32}$$

$$\geq 0, \quad \text{for all } t \geq 0. \tag{33}$$

Since $|G(0)| = 1$, we get from (33) that the system is string stable in the $\mathscr{L}_p$, $p \in [1, \infty]$, sense, see, e.g., [3]. For $\alpha = \frac{4}{h}$ the impulse response (32) becomes

$$g(t) = \begin{cases} 0, & 0 \leq t \leq D \\ \frac{\alpha}{h}(t-D) e^{-\frac{2}{h}(t-D)}, & t \geq D \end{cases} \tag{34}$$

$$\geq 0, \quad \text{for all } t \geq 0. \tag{35}$$

Employing the same arguments with the case $\alpha > \frac{4}{h}$, one can conclude that the system is string stable for $\alpha = \frac{4}{h}$. ■

Remark 2: One best appreciates the stability and string stability results of Theorem 1 by considering the fact that no restriction on the magnitude of the delay is imposed (which is inherit to the nature of such predictor-based control laws since the delay is completely compensated, see, e.g., [2], [18]), in contrast to the case of the uncompensated control law, which requires $h \geq 2D$ for a choice of α and h to exist such that the system is both stable and string stable, see, e.g., [6], [41]. In fact, the condition $h \geq 2D$ is necessary also in the case where one employs an extra term of the form $b\,(v_{i-1} - v_i)$ in the nominal feedback law (10), see, e.g., [6], [41].

Moreover, in the case of the uncompensated control law the resulting transfer function is given by

$$G(s) = \frac{e^{-Ds}\frac{\alpha}{h}}{s^2 + \alpha s e^{-Ds} + \frac{\alpha}{h} e^{-Ds}}. \tag{36}$$

Although the analytical study of string stability based on (36) is performed, for instance, in [6], [41], it is very difficult to analytically study $\mathscr{L}_p$, $p \in [1, \infty]$, string stability using (36). In contrast, due to the fact that the denominator in (28) is a second-order polynomial in s, $\mathscr{L}_p$, $p \in [1, \infty]$, string stability can be established much more easily.

Remark 3: Note that in the case of sensor delay, i.e., when a measurement of $X_i\,(t - D)$ is available, and there is no actuator delay, one could employ the following control law, see, e.g., [18], [37]

$$\begin{aligned} U_i(t) &= K\left(e^{\Gamma D} X_i\,(t-D)\right. \\ &\quad \left. + \int_{t-D}^{t} e^{\Gamma(t-\theta)} B U_i(\theta) d\theta\right). \end{aligned} \tag{37}$$

Repeating the computations in the proof of Theorem 1 it can be shown that the resulting transfer function $G(s) = \frac{V_i(s)}{V_{i-1}(s)}$ is identical to (28), and thus, the same stability (see also [18], [37]) and string stability results hold in this case as well. In the case where there are both input and sensor delays, say, D and $D_{\rm s}$, respectively, the control law can be modified to, see, e.g., [18]:

$$\begin{aligned} U_i(t) &= K\left(e^{\Gamma(D+D_{\rm s})} X_i\,(t-D_{\rm s})\right. \\ &\quad \left. + \int_{t-D-D_{\rm s}}^{t} e^{\Gamma(t-\theta)} B U_i(\theta) d\theta\right). \end{aligned} \tag{38}$$

The resulting transfer function $G(s)=\frac{V_i(s)}{V_{i-1}(s)}$ is given by

$$G(s) = \frac{e^{-(D+D_{\rm s})s}\frac{\alpha}{h}}{s^2 + \alpha s + \frac{\alpha}{h}}. \tag{39}$$

Stability (see also [18], [37]) and string stability follow by Theorem 1.

Remark 4: Note that the steady-state spacing error of the first vehicle in the string, which follows the leader, under the delay-compensating control law (16) is not zero. One can see this by deriving the transfer function $\frac{\Delta_1(s)}{X_1(s)}$, which satisfies

$$\begin{aligned} \frac{\Delta_1(s)}{X_1(s)} &= 1 - (1 + sh)\, G(s) \\ &= \frac{s^2 + \alpha s\left(1 - e^{-sD}\right) + \frac{\alpha}{h}\left(1 - e^{-sD}\right)}{s^2 + \alpha s + \frac{\alpha}{h}}, \end{aligned} \tag{40}$$

and is different than (28). Since each vehicular system is stable, for a constant steady-state speed of the leader, say equal to $v_{\rm ss}$, which implies that $X_1(s) = \frac{v_{\rm ss}}{s^2}$, the steady-state spacing error is given by the final value theorem as

$$\begin{aligned} \delta_{1\rm ss} &= \lim_{s\to 0} s\left(1 - (1+sh)\, G(s)\right)\frac{v_{\rm ss}}{s^2} \\ &= v_{\rm ss} \lim_{s\to 0} \frac{s^2 + \alpha s\left(1 - e^{-sD}\right) + \frac{\alpha}{h}\left(1 - e^{-sD}\right)}{s\left(s^2 + \alpha s + \frac{\alpha}{h}\right)} \\ &= D v_{\rm ss} \neq 0, \end{aligned} \tag{41}$$

where we used the fact that $\lim_{s\to 0} \frac{s^2 + \alpha s\left(1 - e^{-sD}\right) + \frac{\alpha}{h}\left(1 - e^{-sD}\right)}{s} = \frac{D\alpha}{h}$[1]. This is in accordance to the result in [13] in which the disturbance attenuation limitations of systems with input delays, under any time-invariant feedback controller, are provided.

IV. Simulation

We present a simulation study considering a homogenous platoon of 4 vehicles with dynamics given by (8), (9) following a leader with dynamics defined as $\dot{x}_{\rm l}(t) = v_{\rm l}(t)$, $\dot{v}_{\rm l}(t) = a_{\rm l}(t)$, where $x_{\rm l}$ and $v_{\rm l}$ are the position and speed of the leading vehicle, respectively, and $a_{\rm l}$ is the leader's acceleration, which is regarded as a reference input chosen as the step input signal shown in Fig. 2. We choose the desired time headway as $h = \frac{2}{\pi}$ s and the delay as $D = 0.4$ s. We compare the response of the string of the 4 vehicles to a step acceleration signal $a_{\rm l}$ to the cases where the delay-uncompensated strategy (Fig. 3)

$$U_i(t) = \frac{\alpha}{h} s_i(t) - \alpha v_i(t) + b\left(v_{i-1}(t) - v_i(t)\right), \tag{42}$$

with $\alpha = 1$, $b = 0.8$, see, e.g., [6], and the delay-compensating strategy (16) with $\alpha = 2\pi$ (Fig. 4) are employed. Note that there exists no choice of (α, b) in the uncompensated strategy (42) that guarantees both stability and string stability for these values of D and h as it is shown in [41]. However, with the choice $\alpha = 1$, $b = 0.8$, each individual vehicular system is stable [41]. In contrast, the delay-compensating strategy achieves both stability and $\mathscr{L}_p$, $p \in [1, \infty]$, string stability since the condition $\alpha \geq \frac{4}{h}$ is satisfied. Note that, as explained in Remark 4, the delay-compensating strategy does not guarantee that the steady-state spacing error is zero as shown in Fig. 4.

V. Conclusions and Discussion

Due to the steady-state spacing error of the predictor-based ACC strategy developed in this paper, we are currently developing a version of the control design presented here that incorporates an integral action for elimination of the steady-state spacing error.

Acknowledgments

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[1] Another way to see that the final value theorem can be applied is by noting that $\frac{D\alpha}{h} < \infty$, which implies that $s = 0$ is not a pole of the function $s\Delta_1(s)$, and thus, all poles of $s\Delta_1(s)$ are on the left-hand complex plane.

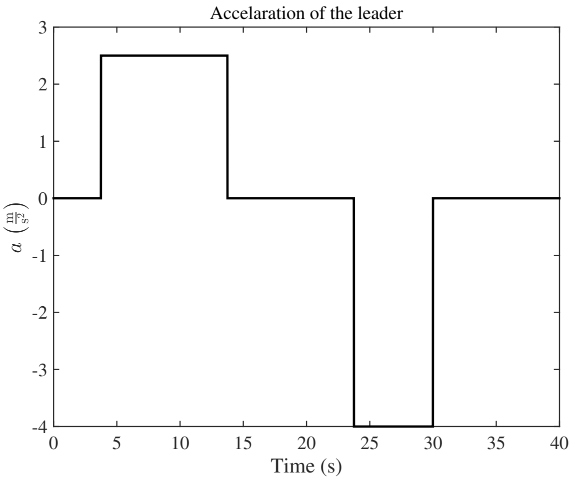

Fig. 2. Acceleration maneuver of the leader.

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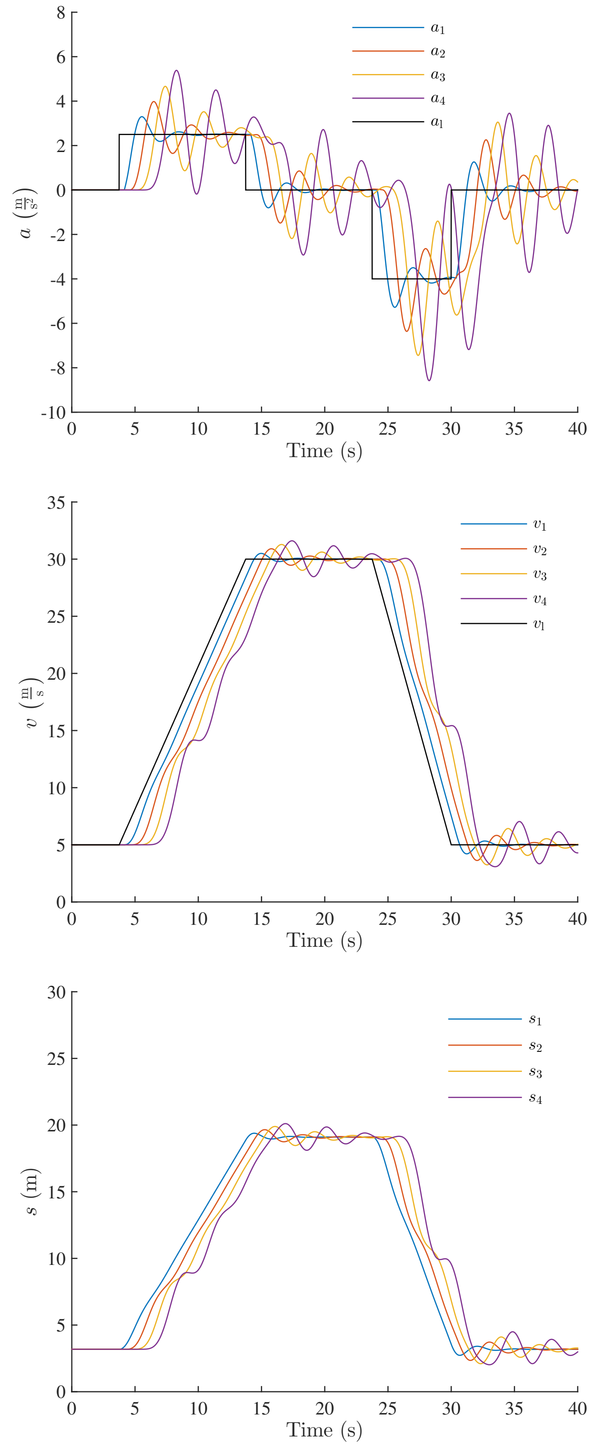

Fig. 3. Acceleration (top), speed (middle), and spacing (bottom) of 4 vehicles following a leader that performs the acceleration maneuver shown in Fig. 2, under the nominal, uncompensated ACC strategy (42).

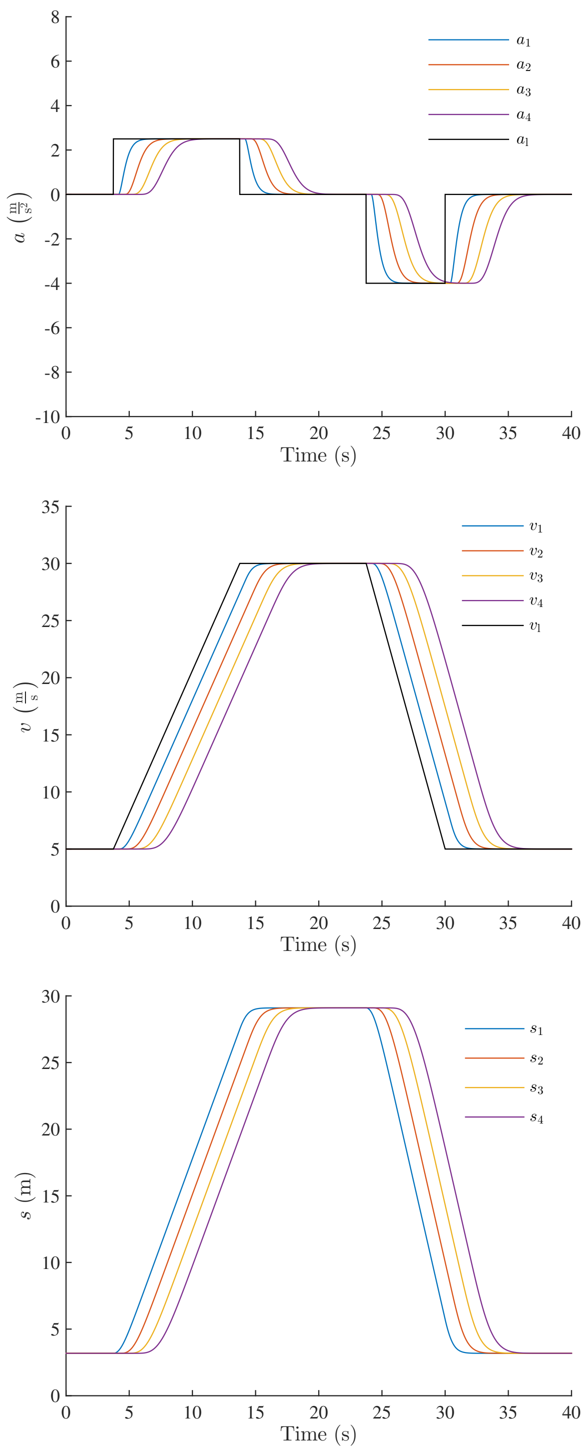

Fig. 4. Acceleration (top), speed (middle), and spacing (bottom) of 4 vehicles following a leader that performs the acceleration maneuver shown in Fig. 2, under the delay-compensating ACC strategy (16).

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