Predictor-Based Adaptive Cruise Control Design with Integral Action

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Abstract: We develop a predictor-based adaptive cruise control design with integral action (based on a nominal constant time-headway policy) for compensation of long actuator and sensor delays in vehicular systems utilizing measurements of the relative spacing as well as of the speed and the short-term history of the desired acceleration of the ego vehicle. Employing an input-output approach we show that the predictor-based adaptive cruise control law with integral action guarantees all of the four typical performance specifications of adaptive cruise control designs, namely, (1) stability, (2) zero steady-state spacing error, (3) string stability, and (4) non-negative impulse response, despite the long input delay. The effectiveness of the developed control design is illustrated in simulation considering various performance metrics.

1. INTRODUCTION

In traffic systems that incorporate vehicles equipped with Adaptive Cruise Control (ACC) capabilities, significant actuator and sensor delays may appear, due to engine response, throttle or brake actuators, computational time, radar or lidar systems, wheel speed sensors, and sampling of measurements, among other reasons; see Davis (2012), Ge & Orosz (2014), Huang & Ren (1998), Liu et al. (2001), Ploeg et al. (2014), Wang et al. (2016), Xiao & Gao (2011), Yanakiev & Kanellakopoulos (2001), Zhang & Orosz (2013). The negative impact of these delays on traffic flow may be manifested as reduced traffic throughput and increased congestion, reduced comfort and safety, and, last but not least, as increased fuel consumption. Such a degradation of the traffic system is the result of the decrease in capacity as well as of the deterioration of the stability and string stability properties of the traffic flow, when the presence of delays is not taken into account in the ACC design; see, e.g., Davis (2012), Diakaki et al. (2015), Ge & Orosz (2014), Klinge & Middleton (2009), Liu et al. (2001), Sipahi & Niculescu (2010), Wang et al. (2016), Xiao & Gao (2011), Yanakiev & Kanellakopoulos (2001), Zhang & Orosz (2013).

Although several ACC strategies exist, such as, e.g., Huang & Ren (1998), Ioannou & Chien (1993), Klinge & Middleton (2009), Knorn et al. (2014), Liang & Peng (2000), Ploeg et al. (2014), Roncoli et al. (2016), Shladover et al. (2012), Swaroop & Hedrick (1996), van Arem et al. (2006) and despite the existing studies on the robustness properties of ACC laws to actuator (or sensor) delay, e.g., Davis (2012), Ge & Orosz (2014), Sipahi & Niculescu (2010), Xiao & Gao (2011), Zhang & Orosz (2013), rarely the problem of design of delay-compensating ACC laws is investigated, with the notable exception of Bekiaris-Liberis et al. (2016), Yanakiev & Kanellakopoulos (2001), Wang et al. (2016). It is worth to mention that Cooperative Adaptive Cruise Control (CACC) systems may also have delay-compensating capabilities, see, for example, Ge & Orosz (2014), Shladover et al. (2012), van Arem et al. (2006), Zhang & Orosz (2013), yet, such systems are not considered in the present paper.

The present contribution constitutes a substantially improved version of our previous result. Specifically, compared to our previous paper Bekiaris-Liberis et al. (2016), in the present work we (1) develop a new control design that incorporates an additional integral term, (2) present new stability and string stability analyses (since they are both based on a different transfer function), which are, in fact, much more delicate since they deal with a third-order transfer function (in contrast to the second-order transfer function considered in Bekiaris-Liberis et al. (2016)), and (3) present several new experiments for the evaluation of the developed control algorithm in quantitative terms, which show the significant performance improvements achieved (compared to our previous design), such as, for example, the elimination of steady-state errors.

In this paper, utilizing a constant time-headway nominal ACC design, the predictor-based feedback design methodology is employed for compensation of long actuator and sensor delays in vehicular systems modeled or approximated by a second-order linear system. Measurements of the relative spacing as well as the speed and the history, over a window equal to the delay length, of the control input (desired acceleration) of each individual vehicular system are utilized to compute the control input for each vehicle. Employing an input-output approach, we prove that the predictor-based ACC law with integral action guarantees all four typical requirements of ACC designs, see, e.g., Ioannou & Chien (1993), namely, (1) stability of each individual vehicular system, (2) zero steady-state spacing error between the actual and the desired inter-vehicle spacing, (3) string stability of homogenous platoons of vehicular systems, and (4) non-negative impulse response of each individual vehicular system, for any delay value smaller than the desired

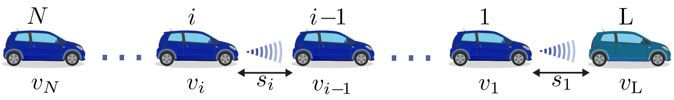

Fig. 1. Platoon of $N+1$ vehicles following each other in a single lane without overtaking. The dynamics of each vehicle $i=1,\dots,N$ are governed by system (1), (2). Each vehicle can measure its own speed and the spacing with respect to the preceding vehicle. The dynamics of the leading vehicle satisfy $\ddot{x}_{\rm L}=a_{\rm L}$, where $x_{\rm L}$ and $a_{\rm L}$ are the position and acceleration of the leading vehicle, respectively.

time-headway (whereas analogous ACC designs without delay compensation require that the delay value is smaller than half the time-headway, e.g., Xiao & Gao (2011), Zhang & Orosz (2013)), which constitutes a physically intuitive limitation. The performance of the developed ACC algorithm is verified in simulation and compared with an existing ACC strategy considering seven different performance indices that provide quantitative performance measures for four common physical requirements of ACC designs, namely, (1) tracking error, (2) safety, (3) fuel consumption, and (4) comfort.

2. PREDICTOR-BASED CONTROL WITH INTEGRAL ACTION OF ACC-EQUIPPED VEHICLES WITH ACTUATOR DELAY

2.1 Vehicle Dynamics

As in, for instance, Bekiaris-Liberis et al. (2016), Ge & Orosz (2014), Sipahi & Niculescu (2010), Wang et al. (2016), Zhang & Orosz (2013), we consider a homogenous string of autonomous vehicles (see Fig. 1) each one modeled by the following second-order linear system with input delay

$$\dot{s}_i(t)=v_{i-1}(t)-v_i(t) \tag{1}$$

$$\dot{v}_i(t)=U_i(t-D), \tag{2}$$

$i=1,\dots,N$, where $s_i=x_{i-1}-x_i-l_i$ is spacing, with x_j being the position of vehicle j and l_i being its length, v_i is speed, U_i is the individual vehicle's control variable, $D>0$ is actuator delay, and $t\geq 0$ is time. System (1), (2) may be also viewed as linearized version of a nonlinear model, around a uniform (for all vehicles) operating point (in this case, s_i and v_i represent error variables), which may be obtained when vehicles have zero acceleration and their speed is dictated by the speed of the leader.

2.2 Delay-Free Control Design

One of the ingredients of our predictor-based ACC design is the nominal (i.e., in the absence of the actuator delay D) constant time-headway control strategy $U_i(t)=\alpha\left(\frac{s_i(t)}{h}-v_i(t)\right)$, where α and h are positive design parameters that represent control gain and desired time-headway, respectively. This nominal ACC law, which is used in several other works, see, e.g., Davis (2012), Ge & Orosz (2014), is a proportional controller for the spacing error defined as

$$\delta_i=s_i-hv_i. \tag{3}$$

The proportional control law is then augmented to incorporate an integral action for the spacing error (3) in order to eliminate a potential steady-state spacing error, see, e.g., Ioannou & Xu (1994). Defining the state of the i-th integrator as

$$\dot{\sigma}_i(t)=\frac{1}{h}s_i(t)-v_i(t),\quad i=1,\dots,N, \tag{4}$$

the nominal ACC laws with integral action are written for all $i=1,\dots,N$ as

$$U_i(t)=\bar{K}\bar{X}_i(t), \tag{5}$$

where

$$\bar{X}_i=\begin{bmatrix} s_i\\ \sigma_i\\ v_i\end{bmatrix} \tag{6}$$

$$\bar{K}=\begin{bmatrix}\bar{k}_1 & \bar{k}_2 & \bar{k}_3\end{bmatrix}, \tag{7}$$

and the gains $\bar{k}_1$, $\bar{k}_2$, $\bar{k}_3$ are yet to be chosen.

The stability and string stability (see, e.g., Bose & Ioannou (2004), Swaroop & Hedrick (1996) for a definition) properties of the nominal closed-loop system (1), (2), (4), (5) can be studied employing the nominal transfer function

$$G_{\rm nom}(s)=\frac{V_i(s)}{V_{i-1}(s)},\quad i=1,\dots,N. \tag{8}$$

Remark 1. In the case of a homogenous platoon, stability and string stability may both be studied merely on the basis of a single transfer function, namely, transfer function $G_{\rm nom}(s)=\frac{V_i(s)}{V_{i-1}(s)}$, $i=1,\dots,N$. This holds true because all transfer functions that may relate either the spacing errors, or the speed, or the acceleration, or the relative speed and acceleration errors, between two consecutive vehicles, are identical to each other (see, e.g., Bose & Ioannou (2004), Liang & Peng (2000)).

2.3 Predictor-Based Control Design

The predictor-based control laws with integral action are given for all $i=1,\dots,N$ by

$$U_i(t)=\bar{K}\left(e^{\bar{\Gamma}D}\bar{X}_i(t)+\int_{t-D}^{t}e^{\bar{\Gamma}(t-\theta)}\bar{B}U_i(\theta)d\theta\right), \tag{9}$$

where $\bar{\Gamma}=\begin{bmatrix}0 & 0 & -1\\ \frac{1}{h} & 0 & -1\\ 0 & 0 & 0\end{bmatrix}$ and $\bar{B}=\begin{bmatrix}0\\0\\1\end{bmatrix}$. One should notice that the control law (9) 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., Huang & Ren (1998), Ioannou & Chien (1993), Liang & Peng (2000), Ploeg et al. (2014), Wang et al. (2016), Xiao & Gao (2011), Yanakiev & Kanellakopoulos (2001). Note also that in the absence of the delay, i.e., when $D=0$, the control law (9) reduces to the nominal, delay-free control design (5). The control law (9) was developed in Artstein (1982), Manitius & Olbrot (1979); not only its stability and robustness properties are extensively studied in the literature Bekiaris-Liberis & Krstic (2013), Karafyllis & Krstic (2016), Krstic (2009), but, in addition, several implementation methodologies were developed Karafyllis & Krstic (2016).

We analyze next, adopting a transfer function approach, the stability and string stability properties of a homogenous platoon of vehicles modeled by system (1), (2) under the ACC law (4), (9).

3. 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 (1), (2) under the control laws (4), (9). There exists $\bar{K}$ such that each individual vehicular system is stable for any $D>0$, and the platoon is $\mathscr{L}_p$, $p\in[1,\infty]$, string stable for any $D<h$.

Proof. We start by deriving for $i=1,\ldots,N$ the transfer function

$$\bar{G}(s)=\frac{V_i(s)}{V_{i-1}(s)}, \tag{10}$$

viewing the preceding vehicle's speed as input and the current vehicle's speed as output, see, e.g., Bose & Ioannou (2004), Ge & Orosz (2014), Liang & Peng (2000). 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 $\bar{G}$.

Taking the Laplace transform of the control law (9) we get

$$U_i(s)=\bar{K}e^{\bar{\Gamma}D}\bar{X}_i(s)+M(s)U_i(s) \tag{11}$$

$$M(s)=\bar{K}\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}\left(I_{3\times 3}-e^{\bar{\Gamma}D}e^{-sD}\right)\bar{B}. \tag{12}$$

Using the i-th vehicle's model (1), (2) and the dynamics of the integral state (4), as well as definition (6) we have

$$\bar{X}_i(s)=\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}\left(\bar{B}e^{-sD}U_i(s)+\bar{B}_vV_{i-1}(s)\right), \tag{13}$$

where $\bar{B}_v=\begin{bmatrix}1 & 0 & 0\end{bmatrix}^{\mathrm{T}}$. Substituting (13) into (11) we get that

$$U_i(s)=\frac{\bar{K}\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}e^{\bar{\Gamma}D}\bar{B}_v}{1-\bar{K}\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}\bar{B}}V_{i-1}(s), \tag{14}$$

and thus, from (13) we arrive at

$$\bar{X}_i(s)=R(s)V_{i-1}(s), \tag{15}$$

where

$$\begin{aligned}R(s)=&\frac{\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}}{1-\bar{K}\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}\bar{B}}\left(\bar{B}_v+\bar{B}e^{-sD}\right.\\&\times\bar{K}\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}e^{\bar{\Gamma}D}\bar{B}_v-\bar{K}\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}\\&\left.\times\bar{B}\bar{B}_v\right).\end{aligned} \tag{16}$$

Note that due to (16), the spectrum of the closed-loop system is finite Jankovic & Magner (2011), Manitius & Olbrot (1979). Using the facts that $e^{\bar{\Gamma}D}=\begin{bmatrix}1 & 0 & -D\\ \frac{D}{h} & 1 & -\frac{D^2}{2h}-D\\ 0 & 0 & 1\end{bmatrix}$ and that $\left(sI_{3\times 3}-\bar{\Gamma}\right)^{-1}=\frac{1}{s^3}\begin{bmatrix}s^2 & 0 & -s\\ \frac{s}{h} & s^2 & -s-\frac{1}{h}\\ 0 & 0 & s^2\end{bmatrix}$, and multiplying (15) from the left with $\begin{bmatrix}0 & 0 & 1\end{bmatrix}$ we obtain

$$\bar{G}(s)=\frac{\left(\left(D+\frac{h\bar{k}_1}{\bar{k}_2}\right)s+1\right)e^{-sD}}{\frac{h}{\bar{k}_2}s^3-\frac{h\bar{k}_3}{\bar{k}_2}s^2+\frac{h\left(\bar{k}_1+\bar{k}_2\right)}{\bar{k}_2}s+1}. \tag{17}$$

Stability: From (17) it follows that there exists choice of $\bar{K}$ that renders the transfer function $\bar{G}$ asymptotically stable. One can see this by matching the denominator of $\bar{G}$ in (17) with any desired third-order polynomial of the form $(T_1s+1)(T_2s+1)(T_3s+1)$, where $T_1>T_2>T_3>0$, that is, the parameters $\bar{k}_1,\bar{k}_2,\bar{k}_3$ can be chosen as

$$\bar{k}_1=\frac{T_1+T_2+T_3-h}{T_1T_2T_3} \tag{18}$$

$$\bar{k}_2=\frac{h}{T_1T_2T_3} \tag{19}$$

$$\bar{k}_3=-\frac{T_1T_2+T_1T_3+T_2T_3}{T_1T_2T_3}. \tag{20}$$

String stability in the $\mathscr{L}_p$, $p\in[1,\infty]$, sense: The impulse response of the transfer function $\bar{G}$ defined in (17) is given by

$$\bar{g}(t)=\begin{cases}0, & 0\leq t\leq D\\ \bar{f}(t-D), & t\geq D\end{cases}, \tag{21}$$

where $\bar{f}$ is the impulse response of the delay-free system under the nominal control design, i.e.,

$$\bar{f}(t)=\mathscr{L}^{-1}\left\{\frac{\left(D+\frac{h\bar{k}_1}{\bar{k}_2}\right)s+1}{\frac{h}{\bar{k}_2}s^3-\frac{h\bar{k}_3}{\bar{k}_2}s^2+\frac{h\left(\bar{k}_1+\bar{k}_2\right)}{\bar{k}_2}s+1}\right\}.$$

Selecting the parameters $\bar{k}_1,\bar{k}_2,\bar{k}_3$ such that $T_1>T_2>T_3>0$, we conclude from Lin & Fang (1997) (Theorem 5) that $\bar{f}(t)\geq 0$, for all $t\geq 0$, when the following hold (see also Astolfi & Colaneri (2004) for similar conditions)

$$D+\frac{h\bar{k}_1}{\bar{k}_2}\leq T_1 \tag{22}$$

$$D+\frac{h\bar{k}_1}{\bar{k}_2}\geq T_2. \tag{23}$$

Using (18)–(20), conditions (22), (23) are rewritten as

$$D-h+T_2+T_3\leq 0 \tag{24}$$

$$D-h+T_1+T_3\geq 0. \tag{25}$$

Conditions (24), (25) can be satisfied by an appropriate choice of $T_1>T_2>T_3>0$ when $D<h$. Since also $\left|\bar{G}(0)\right|=1$, we conclude that the system is string stable in the $\mathscr{L}_p$, $p\in[1,\infty]$, sense, see, e.g., Bose & Ioannou (2004). □

Remark 2. Although stability under the predictor-based ACC law with integral action is guaranteed for any delay value, string stability requires that the delay value is restricted to be smaller than the desired time-headway, which constitutes a considerable improvement compared to the string stability condition that the delay is smaller than half the time-headway imposed by other ACC designs (similar to the nominal, delay-free ACC law that we employ) without delay compensation, such as, for example, Xiao & Gao (2011), Zhang & Orosz (2013). The requirement of a constant time-headway policy that the steady-state spacing is greater than Dv_{d}, where v_{d} is a desired speed

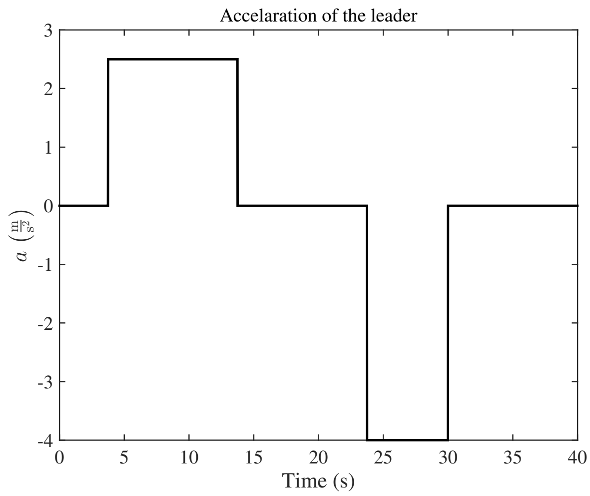

Fig. 2. Acceleration maneuver of the leader.

dictated by the leader, is a physical limitation since during the $D-$second “dead-time” interval of the actuator the vehicle is not able to respond to large disturbances emanating from the preceding vehicle, e.g., rapid changes of its speed [1] . Thus, such a restriction is necessary in order for a vehicle to be able to attenuate disturbances imposed by its preceding vehicle and track it. Moreover, this limitation is in accordance to the result in Karafyllis & Krstic (2016) dealing with the disturbance attenuation limitations of systems with input delays under any time-invariant feedback controller.

4. PERFORMANCE EVALUATION OF THE PREDICTOR-BASED ACC DESIGN

We present a simulation study considering a homogenous platoon of four vehicles with dynamics given by (1), (2) following a leader with dynamics defined as

$$\dot{x}_{\mathrm{L}}(t) = v_{\mathrm{L}}(t) \tag{26}$$

$$\dot{v}_{\mathrm{L}}(t) = a_{\mathrm{L}}(t), \tag{27}$$

where x_{L} and v_{L} are the position and speed of the leading vehicle, respectively, and a_{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 four vehicles to a step acceleration signal a_{L} to the cases where the delay-uncompensated strategy (Fig. 3)

$$U_i(t) = \frac{\alpha}{h} s_i(t) - \alpha v_i(t) + b\left(v_{i-1}(t) - v_i(t)\right), \tag{28}$$

with $\alpha = 1$, $b = 0.8$, see, e.g., Ge & Orosz (2014), and the delay-compensating strategy (Fig. 4) defined in (9) with parameters $\bar{k}_1 = 14$, $\bar{k}_2 = 102$, $\bar{k}_3 = -20$, which satisfy (18)–(20) with $T_1 = 0.5$, $T_2 = 0.125$, and $T_3 = 0.1$ (which in turn satisfy (24), (25)), are employed. Note that there exists no choice of (α, b) in the uncompensated strategy (28) that guarantees both stability and string stability for these values of D and h as it is shown in Zhang & Orosz (2013). However, with the choice $\alpha = 1$, $b = 0.8$, each individual vehicular system is stable Zhang & Orosz (2013). In contrast, with the delay-compensating strategy, one can observe from Fig. 4 that the four typical requirements of an ACC law, see, e.g., Ioannou & Chien (1993), namely a) stability of each individual vehicular system, b) zero steady-state spacing error, c) fulfillment of condition

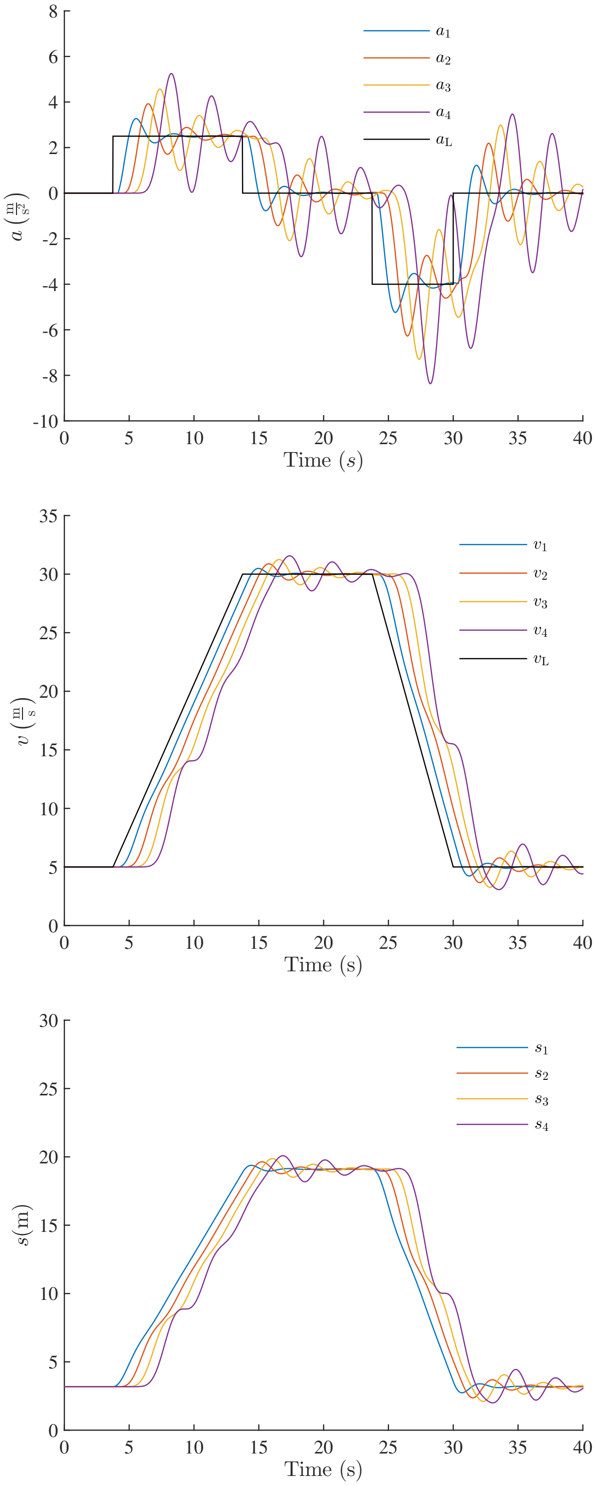

Fig. 3. Acceleration (top), speed (middle), and spacing (bottom) of four vehicles following a leader that performs the acceleration maneuver shown in Fig. 2, under the nominal, uncompensated ACC strategy (28).

[1] Consider, e.g., the case in which the preceding vehicle comes to a complete stop instantaneously from a speed v_{d}, then, due to the $D-$second “dead-time” interval of the actuator, the spacing between the two vehicles remains positive only if $D < h$ since the spacing satisfies $s(t) = (h - t)v_{\mathrm{d}}$, for all $t \leq D$.

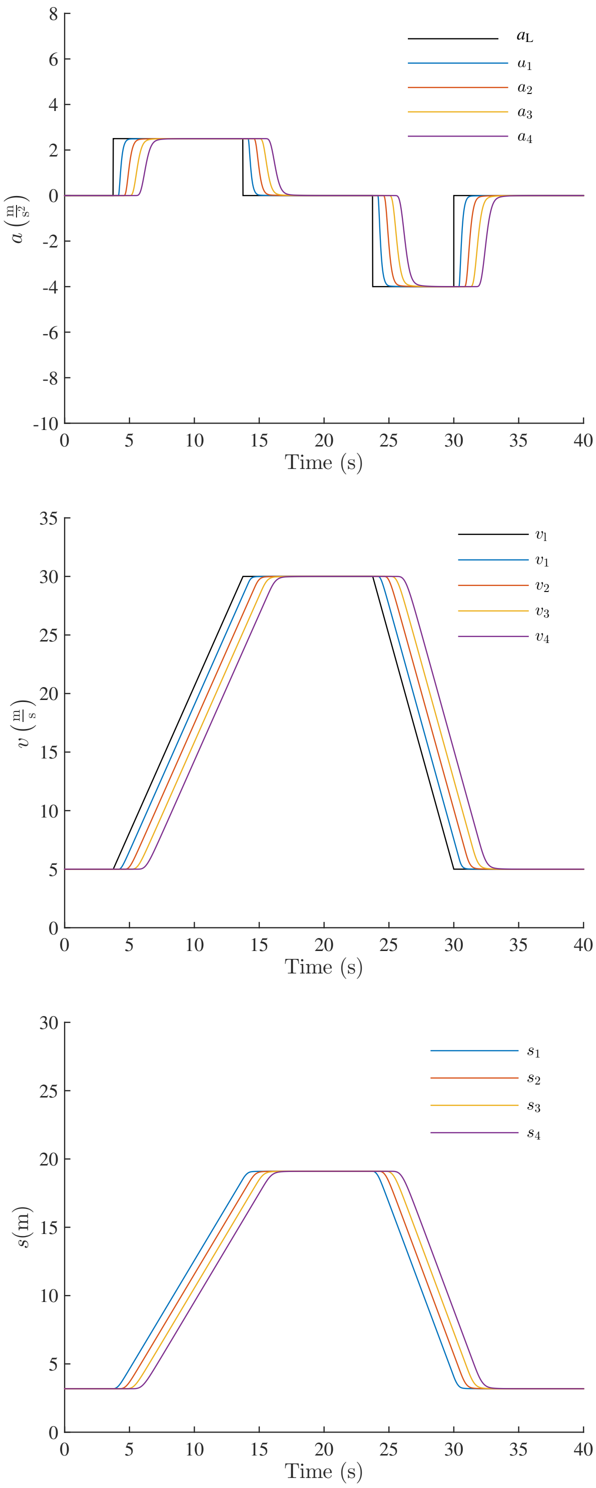

Fig. 4. Acceleration (top), speed (middle), and spacing (bottom) of four vehicles following a leader that performs the acceleration maneuver shown in Fig. 2, under the delay-compensating ACC strategy with integral action (9).

$\sup_{\omega\in\mathbb{R}} \left|\bar{G}(j\omega)\right| \leq 1$, and d) non-negative impulse response are satisfied.

We evaluate further and compare to the control law (28) the performance of the developed ACC design with integral action considering the following four physical requirements a) tracking error, b) safety, c) fuel consumption, and d) comfort. We consider a platoon of six vehicles and employ the following performance indices that quantify each of the four requirements

Table 1. Parameters of the fuel consumption cost (29).

Parameter	Value
β_1	0.666
β_2	0.0717
β_3	0.0578
β_4	0.527
β_5	0.000948
β_6	1.68

Table 2. Performance indices (29), (32)–(35), (37), and (38).

Performance index	Percentage improvement with (9) in comparison to (28)
J_{fuel}	28
$J_{\text{comfort},1}$	90
$J_{\text{comfort},2}$	20
$J_{\text{comfort},3}$	66
J_{safety}	53
$J_{\text{tracking},1}$	83
$J_{\text{tracking},2}$	51

$$J_{\text{fuel}} = \sum_{i=1}^{6} \int_0^T J_i\left(v_i(t), a_i(t)\right) dt \tag{29}$$

$$J_i = \begin{cases} \beta_1 + \beta_2 R_{T_i}\left(v_i(t), a_i(t)\right) v_i(t) & \\ +\beta_3 v_i(t) a_i(t)^2, & \text{if } R_{T_i} > 0 \\ \beta_1, & \text{if } R_{T_i} \leq 0 \end{cases} \tag{30}$$

$$R_{T_i} = \beta_4 + \beta_5 v_i(t)^2 + \beta_6 a_i(t) \tag{31}$$

$$J_{\text{comfort},1} = \sum_{i=1}^{6} \int_0^T \dot{a}_i(t)^2 dt \tag{32}$$

$$J_{\text{comfort},2} = \max_i \sup_{0\leq t\leq T} \left|\dot{a}_i(t)\right| \tag{33}$$

$$J_{\text{comfort},3} = \max_i \sup_{0\leq t\leq T} \left|a_i(t)\right| \tag{34}$$

$$J_{\text{safety}} = \sum_{i=1}^{6} \int_0^T \bar{J}_i\left(s_i(t), v_i(t), v_{i-1}(t)\right) dt \tag{35}$$

$$\bar{J}_i = \begin{cases} e^{\frac{1}{s_i(t)}}\left(v_{i-1}(t) - v_i(t)\right)^2, & \text{if } v_{i-1}(t) \leq v_i(t) \\ 0, & \text{otherwise} \end{cases} \tag{36}$$

$$J_{\text{tracking},1} = \sum_{i=1}^{6} \int_0^T \delta_i(t)^2 dt \tag{37}$$

$$J_{\text{tracking},2} = \sum_{i=1}^{6} \int_0^T \left(v_i(t) - v_{i-1}(t)\right)^2 dt, \tag{38}$$

which are used in the literature, see, e.g., Akcelik & Biggs (1987), Martinez & Canudas-de-Wit (2007), Wang et al. (2014). We choose $T = 40$ s, whereas the parameters of (29) are shown in Table 1. The percentage improvements of each cost when the proposed ACC design (9) is employed in comparison to the case where the ACC law (28) is utilized are shown in Table 2. It is evident that the predictor-based ACC law with integral action achieves better performance in all metrics. Note that the performance improvement with the delay-compensating ACC law (9) compared to the control law (28) would be larger when one considers a larger number of vehicles in the platoon due to the lack of string stability in the case of the uncompensated control law (28).

5. CONCLUSIONS

We presented a predictor-based ACC design methodology for compensation of long input delays in vehicular systems. We showed that the developed ACC algorithm guarantees that four of the most common performance requirements of ACC designs are satisfied. The performance of the proposed ACC strategy is verified in simulation considering various quantitative performance measures.

ACKNOWLEDGMENTS

Nikolaos Bekiaris-Liberis was supported by the funding from the European Unions Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 747898, project PADECOT.

Claudio Roncoli and Markos Papageorgiou were supported by the funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007-2013) / ERC Grant Agreement n. [321132], project TRAMAN21.

REFERENCES

R. Akcelik and D. C. Biggs. Acceleration profile models for vehicles in road traffic. *Transp. Science*, 21: 36–54, 1987.

Z. Artstein. Linear systems with delayed controls: A reduction. *IEEE Trans. on Automatic Control*, 27: 869–879, 1982.

A. Astolfi and P. Colaneri. A note on the existence of positive realizations. *Linear Algebra & its Apps.*, 390: 329–343, 2004.

N. Bekiaris-Liberis and M. Krstic, *Nonlinear Control Under Nonconstant Delays*, SIAM, 2013.

N. Bekiaris-Liberis, C. Roncoli, and M. Papageorgiou. Predictor-based adaptive cruise control design. *IEEE MSC*, Buenos Aires, Argentina, 2016.

A. Bose and P. Ioannou. Analysis of traffic flow with mixed manual and semiautomated vehicles. *IEEE Transactions on Intelligent Transportation Systems*, 4: 173–188, 2004.

L. C. Davis. Stability of adaptive cruise control systems taking account of vehicle response time and delay. *Physics Letters A*, 376: 2658–2662, 2012.

C. Diakaki, M. Papageorgiou, I. Papamichail, and I. K. Nikolos. Overview and analysis of vehicle automation and communication systems from a motorway traffic management perspective. *Transp. Research Part A*, 75: 147–165, 2015.

J. I. Ge and G. Orosz. Dynamics of connected vehicle systems with delayed acceleration feedback. *Transportation Research Part C*, 46: 46–64, 2014.

S. Huang & W. Ren. Autonomous intelligent cruise control with actuator delays. *Journal of Intelligent and Robotic Systems*, 23: 27–43, 1998.

P. A. Ioannou and C. C. Chien. Autonomous intelligent cruise control. *IEEE Transactions on Vehicular Technology*, 42: 657–672, 1993.

P. Ioannou & Z. Xu. Throttle and break control systems for automatic vehicle following. *Journal of Intelligent Transportation Systems*, 1: 345–377, 1994.

M. Jankovic & S. Magner. Disturbance attenuation in time-delay systems–a case study on engine air-fuel ratio control. *American Control Conference*, San Francisco, CA, 2011.

I. Karafyllis and M. Krstic, *Predictor Feedback for Delay Systems: Implementations and Approximations*, Birkhauser, Basel, 2017.

H. Khalil, *Nonlinear Systems*, Prentice-Hall, 2000.

S. Klinge and R. H. Middleton. Time headway requirements for string stability of homogeneous linear unidirectionally connected system. *IEEE Conference on Decision and Control*, Shanghai, China, 2009.

S. Knorn, A. Donaire, J. C. Aguero, and R. H. Middleton. Passivity-based control for multi-vehicle systems subject to string constraints. *Automatica*, 50: 3224–3230, 2014.

M. Krstic, *Delay Compensation for Nonlinear, Adaptive, and PDE Systems*, Birkhauser, 2009.

C.-Y. Liang and H. Peng. String stability analysis of adaptive cruise controlled vehicles. *JSME International Journal Series C*, 43: 671–677, 2000.

S.-K. Lin and C.-J. Fang. Nonovershooting and monotone nondecreasing step responses of a third-order SISO linear system. *IEEE Transactions on Automatic Control*, 42: 1299–1303, 1997.

X. Liu, A. Goldsmith, S. S. Mahal, and J. K. Hedrick. Effects of communication delay on string stability in vehicle platoons. *IEEE ITSC*, Oakland, CA, 2001.

A. Z. Manitius and A. W. Olbrot. Finite spectrum assignment problem for systems with delays. *IEEE Transactions on Automatic Control*, 24: 541–552, 1979.

J.-J. Martinez and C. Canudas-de-Wit. A safe longitudinal control for adaptive cruise control and stop-and-go scenarios. *IEEE Transactions on Control Systems Technology*, 15: 246–258, 2007.

J. Ploeg, D. P. Shukla, N. van de Wouw, and H. Nijmeijer. Controller synthesis for string stability of vehicle platoons. *IEEE Transactions on Intelligent Transportation Systems*, 15: 854–865, 2014.

C. Roncoli, M. Papageorgiou, I. Papamichail. Hierarchical model predictive control for multi-lane motorways in presence of Vehicle Automation and Communication Systems. *Transportation Research Part C*, 62: 117–132, 2016.

S. E. Shladover, D. Su, and X.-Y. Lu. Impacts of cooperative adaptive cruise control on freeway traffic flow. *Transportation Research Record*, 2324: 63–70, 2012.

R. Sipahi & S.-I. Niculescu. Deterministic time-delayed traffic flow models: A survey. *Complex Time-Delay Systems: Theory and Applications*, F. M. Atay (ed.), 2010.

D. Swaroop & J. K. Hedrick. String stability of interconnected systems. *IEEE Trans. Autom. Control*, 41: 349–357, 1996.

B. van Arem, C. van Driel, and R. Visser. The impact of cooperative adaptive cruise control on traffic-flow characteristics. *IEEE Trans. Intelligent Transp. Systems*, 7: 429–436, 2006.

M. Wang, W. Daamen, S. P. Hoogendoorn, and B. van Arem. Rolling horizon control framework for driver assistance systems. Part I: Mathematical formulation and non-cooperative systems. *Transp. Research Part C*, 40: 271–289, 2014.

M. Wang, S. P. Hoogendoorn, W. Daamen, B. van Arem, B. Shyrokau, & R. Happee. Delay-compensating strategy to enhance string stability of autonomous vehicle platoons. *TRB Annual Meeting*, Washington, D.C., 2016.

L. Xiao & F. Gao. Practical string stability of platoon of adaptive cruise control vehicles. *IEEE Transactions on Intelligent Transportation Systems*, 12: 1184–1194, 2011.

D. Yanakiev & I. Kanellakopoulos. Longitudinal control of automated CHVs with significant actuator delays. *IEEE Transactions on Vehicular Technology*, 50: 1289–1297, 2001.

L. Zhang and G. Orosz. Designing network motifs in connected vehicle systems: Delay effects and stability. *ASME DSCC*, Palo Alto, CA, 2013.