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VEHICLE STRING USING SPACING STRATEGIES FOR COOPERATIVE ADAPTIVE CRUISE CONTROL SYSTEM

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The Co-operative Adaptive Cruise Control (CACC) is one of the key subsystems of Connected and Automated Vehicles (CAVs) that have the potential to increase the road traffic capacity and improve traffic safety with shorter inter-vehicle spacing between vehicles. The spacing strategies are the core of all CACC control algorithms which are chosen based on design purposes for the system. This work presents a comparative research to evaluate the effectiveness of two spacing strategies, consisting of the constant spacing strategy and, constant time headway strategy, which is suitable for information flow topologies. The main focus of this research analyzes the benefits of operating mechanisms as well as the characteristics of each spacing strategy. The results of the simulations using software Matlab/Simulink have demonstrated the performances and applicability of each spacing policy.

Keywords: CACC, Connected Vehicles, Time Headway, Spacing Strategies, Vehicle String.

1. Introduction

Nowadays, Intelligent Transport is an area of research to provide a platform to manage traffic, improving driving safety, increasing throughput, decreasing energy consumption, and pollutant emissions [1, 2, 3]. One solution to achieve this aspect is to organize grouping vehicles equipped with the CACC system in the same lane to move, each vehicle in grouping vehicles always keeps short inter-vehicle spacing from the preceding vehicle while guaranteeing safety. String vehicles using the CACC system is an advanced application of the Adaptive Cruise Control (ACC) system [4] where the string of vehicles is enabled by inter-vehicle communication and onboard sensors, like odometer, radar, or lidar. As an interesting research topic, spacing control of strings has been provided by many previous works [4, 5, 6].

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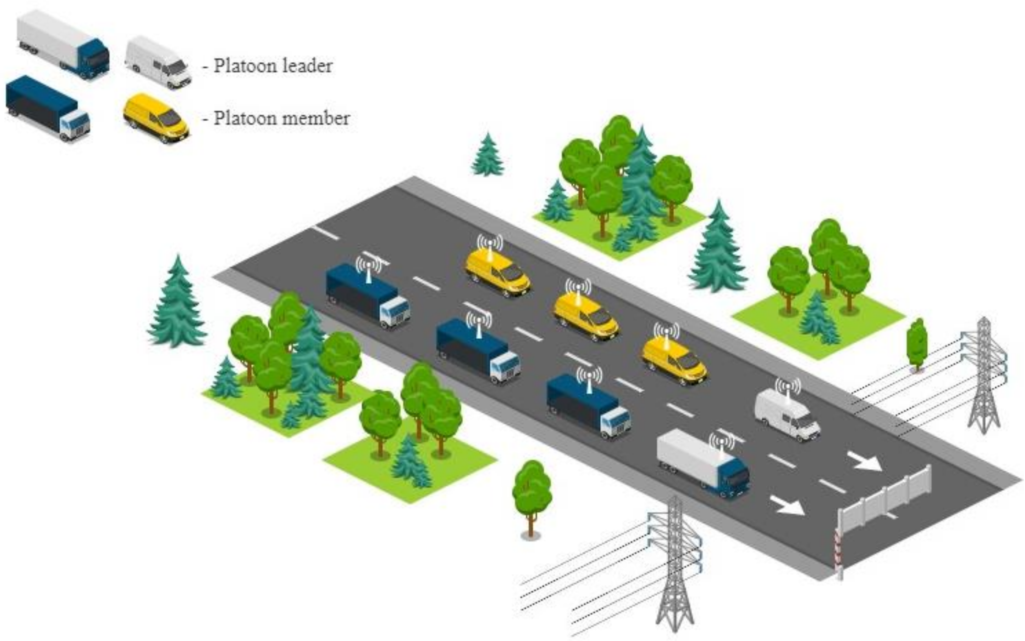

Fig. 1. Vehicular Platoon.

The cooperative vehicle platooning on highways (see in Figure.1) which is analyzed some important related criteria as follows:

For the spacing policies: Spacing strategies used the most commonly to adjust the distances between the vehicles, including the constant spacing strategy (the CSS) called the constant spacing policy (see [6, 7, 8, 9], etc) and the constant time headway strategy (CTHS) called the constant time headway policy (see [10, 11, 12, 13, 14], etc). Strings with the CSS imply that the desired distance between vehicles is constant and independent of the velocity of preceding. While in the CTHS, the desired distance is proportional to its velocity, and that is called the time headway h_i. The distance in both strategies is measured from the front bumper to the rear bumper of the preceding vehicle. String stability is directly affected by the spacing strategies selected in a platoon, it is claimed in [17].

For string stability: many other works on stability analysis and control design have been published and on that basis, we make the concluding remarks on string stability as follows: 1) the CSS cannot guarantee string stability in cases such as the vehicles employ the only on-board signal or employ the predecessor-following (PF) topology or the bidirectional (BD) topology, i.e. the information of the leader vehicle is not utilized [6, 15, 18, 19]. For this reason, we propose one approach for string stability in this paper is to extend the leader's signal to all followers in the vehicle strings, taking the predecessor-leader following (PLF) topology. 2) while the CTHS still ensures string stability when the vehicle have the only on-board signal [16] or without considering the leader's signal [13, 14] and therefore relax the formation rigidity of the string. Of course, vehicle to vehicle (V2V) communication has a significant impact on the behavior of the string [9, 12, 20, 21, 22, 23].

For the communication between vehicles, i.e. considering the topology, the type of information: the success of the CACC systems depends on V2V communication via technologies such as the vehicular ad-hoc networks (VANET). With the development of V2V communications, the information flow topology depicts the connectivity of the CACC system of vehicles [24, 25, 26], including the PF topology, the PLF topology, the BD topology, the predecessor-following leader topology, bidirectional leader topology, two predecessor-following topology, and two predecessor-following leader topology. The type of information can be just the current velocity and acceleration.

Although some criteria for the platoon are analyzed based on the scientific literature above. However, a detailed analysis of operating mechanisms and comparative research between spacing strategies is not enough satisfactory. In this context, the main contributions of this work present a performance analysis and review of two spacing strategies ((i.e. the CSS, the CTHS) for the existing CACC solutions via the operating mechanisms, and characteristics of every spacing strategy, that are explained in detail such as spacing errors, string stability, driving safety, and traffic throughput improvement. Simulating CACC vehicles include a leader and 10 followers by regulating the velocity of the followers on the preceding vehicle while maintaining the spacing at the desired value. The string of vehicles using the CSS applies the (PLF) topology, the information of the leader vehicle is communicated to all followers in the string of vehicles. The string of vehicles using the CTHS applies the (PF) topology, the following vehicle only receives a communication signal from its predecessor.

The rest part of the work is organized as follows: Section 2 briefly introduces the platoon model and longitudinal vehicle model. Section 3 deals with spacing strategies and describes the control algorithm for the CACC system. Section 4 provides the simulation examples to illustrate the efficiency of the proposed method. Finally, the paper ends with concluding remarks in Section 5.

2. System Modeling

A string of vehicles has become a model of nodes that run on a single lane, in which the lateral dynamics of the individual vehicle is neglected, consisting of a leader and N followers, indexed by 0 and 1, 2, 3, ..., N, respectively (see Figure.2). The control objective of every vehicle using CACC technology allows CAVs to make vehicle grouping traveling in a platoon with shorter inter-vehicle spacing while maintaining the desired velocity.

2.1. Vehicle Models

The vehicle longitudinal dynamic model describes the behavior of each node, it is basically a nonlinear model, including the engine, brake system, tire resistance, aerodynamics drag, etc. However, such a detailed nonlinear model brings inconvenience to platoon analysis, as it does not lead to analytical results, for example when we consider the effect of V2V communication, it has been mentioned by Kakan C. Dey et al. [28]. In many studies [12, 24, 27, 28] to strike a balance between accuracy and conciseness, a linearized model is used to study for ACC and CACC systems as well as serving as a basis for theoretical analysis of platoon control.

Here, we use a linear third-order model to illustrate the longitudinal dynamics of each vehicle in a string.

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = a_i(t), \qquad\qquad i \in S_N \\ \varsigma_i \dot{a}_i(t) + a_i(t) = u_i(t) \end{cases} \tag{1}$$

where $x_i(t)$, $v_i(t)$, $a_i(t)$ represent the position, the velocity, the acceleration of i^{th} vehicle, respectively. $S_N = \{i \in \mathbb{N} \mid 1 \leq i \leq N\}$, N is number of following vehicles in a string. $u_i(t)$ is the control input as the desired acceleration. ς_i is the inertial time lag of the actuator dynamics in the powertrain, which is small for cars while it is big for trucks. Note that the equation (1) is a first-order inertial function that approximates the actual acceleration response of the longitudinal dynamics of the vehicle.

As a result, the transfer function of the longitudinal vehicle model can be described by

$$G_v(s) = \frac{X_i(s)}{U_i(s)} = \frac{1}{s^2(\varsigma_i s + 1)} e^{-\tau s} \tag{2}$$

where $\tau = 0.2$s depicts the actuator and an associated nominal internal delay.

2.2. Information flow topology for vehicle platoon

In this section, we adopt the two main types of information flow topologies are the predecessor following (PF) (see in Figure.2a) and the predecessor-leader following (PLF) (see in Figure.2b) , in which the CACC system for vehicles applying the PF topology is controlled based on the CTHS, and applying the PLF topology is controlled based on the CSS.

The controller for this type of topology in vehicle platooning comprise two parts: feedback ACC and feed-forward CACC [11], in which the velocity, acceleration signals are considered the inputs of the system, that behave as an input to the controller.

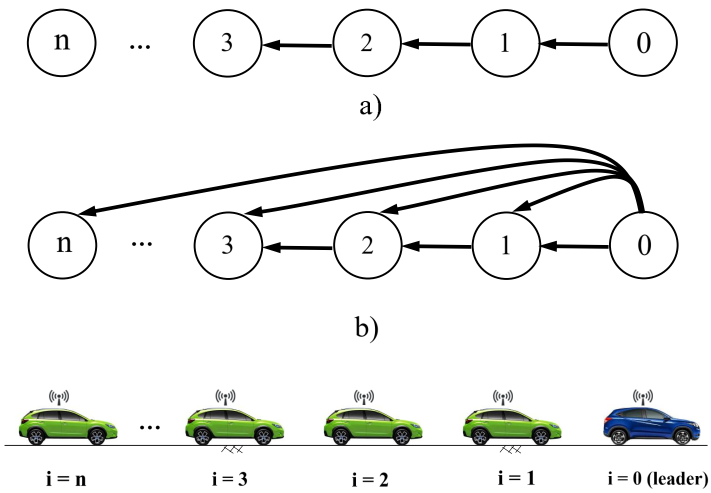

Fig. 2. Topological structure of vehicle platooning: (a) predecessor-following (PF), (b) predecessor-leader following (PLF).

3. Design of CACC

The CACC system is one of the applications of the longitudinal control strategy. Using the CACC system of vehicles is to keep the same velocity with the other vehicles in the string while keeping the value of desired distance with respect to preceding vehicle. Each vehicle allows following its preceding vehicle with the desired spacing defined by the spacing policies. The first step of CACC system design requirements is to choose the spacing policies (taking the CTHS and the CSS). Then the CACC controller is analyzed and proposed for each spacing strategy.

3.1. Control Architectures via Constant Spacing Strategy

The follower vehicles in the string employing the CSS keeps the contant distance between the members of the platoon during CACC operation, that is independent of manually driven vehicles [19, 29]. This is illustrated in Figure.2b with the constant distance spacing policy is generally described as:

$$d_{r,i}^{S} = L_i, \qquad i \in S_N \tag{3}$$

where d_{ref}^{S} defined by the desired distance between adjacent two vehicles, L_i indicates a fixed constant, excluding vehicle length. The desired distance of the i^{th} vehicle with respect to the leader vehicle indicated by this strategy is:

$$d_{r,l}^{S} = \sum_{1}^{i} L_i, \qquad i \in S_N \tag{4}$$

The actual relative spacing of the i^{th} vehicle with respect to the $(i-1)^{th}$ vehicle and the leader vehicle can be written, respectively:

$$d_i^S = x_{i-1} - x_i - l_i \tag{5}$$

$$d_l^S = x_l - x_i - \sum_1^i l_i \tag{6}$$

It is now possible to define the spacing error e_i of the i^{th} vehicle with respect to the $(i-1)^{th}$ vehicle and the leader vehicle in case of the CSS, respectively as:

$$e_i^S = x_{i-1} - x_i - l_i - L_i \tag{7}$$

$$e_l^S = x_l - x_i - \sum_1^i l_i - \sum_1^i L_i \tag{8}$$

Let l_i is the vehicle length, x_l, x_{i-1}, x_i are respectively the positions of the leader vehicle, the $(i-1)^{th}$ vehicle and the i^{th} vehicle in a string of vehicles.

The control input for the CACC controller utilizing the CSS in a string is described as:

$$u_i^S = k_1^S e_i^S + k_2^S \dot{e}_i^S + k_3^S \ddot{x}_{i-1} + k_4^S e_l^S + k_5^S(\dot{x}_l - \dot{x}_i) + k_6^S \ddot{x}_l \tag{9}$$

Where all the control gains $k_1^S, k_2^S, k_3^S, k_4^S, k_5^S, k_6^S$ are designed. u_i^S is the desired acceleration for the closed-loop system of this controller (Upper level as in [12, 30]). Note that the measurements of e_i^S, $\dot{e}_i^S$ are obtained from on-board sensors information such as Lidar.

Using system (1), (7), (8), (9) the state-space representation in terms of the platoon with the CSS can be described:

$$\begin{pmatrix} \dot{e}_i^S \\ \dot{e}_l^S \\ \dot{v}_i \\ \dot{a}_i \end{pmatrix} = \underbrace{\begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\frac{1}{\varsigma_i} \end{pmatrix}}_{A^S} \underbrace{\begin{pmatrix} e_i^S \\ e_l^S \\ v_i \\ a_i \end{pmatrix}}_{X_i^S} + \underbrace{\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}}_{B^S} \underbrace{\begin{pmatrix} e_{i-1}^S \\ e_l^S \\ v_{i-1} \\ a_{i-1} \end{pmatrix}}_{X_{i-1}^S} + \underbrace{\begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}}_{C^S} v_l + \underbrace{\begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{\varsigma_i} \end{pmatrix}}_{D^S} u_i^S \tag{10}$$

and

$$u_i^S = \underbrace{\begin{pmatrix} k_1^S \\ k_4^S \\ 0 \\ -k_2^S - k_5^S \\ 0 \end{pmatrix}^T}_{A_1^S} \begin{pmatrix} e_i^S \\ e_l^S \\ v_i \\ a_i \end{pmatrix} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ k_3^S \end{pmatrix}^T}_{B_1^S} \begin{pmatrix} e_{i-1}^S \\ e_l^S \\ v_{i-1} \\ a_{i-1} \end{pmatrix} + \underbrace{\begin{pmatrix} k_5^S \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}^T}_{C_1^S} v_l \tag{11}$$

which can be rewritten in the following form:

$$\begin{cases} \dot{X}_i^S = A^S X_i^S + B^S X_{i-1}^S + C^S v_l + D^S u_i^S, \qquad i \in S_N \\ Y_i^S = A_1^S X_i^S + B_1^S X_{i-1}^S + C_1^S v_l \end{cases} \tag{12}$$

3.2. Control Architectures via Constant Time Headway Strategy

Using the constant time headway strategy is getting increasingly popular in a string, which is one of the spacing policies used most commonly and it has been discussed in references [31, 32]. This is illustrated in Figure.2a. In some articles, the phrase "time headway" is used [12, 33], which means the time move of the front bumper position of the i^{th} vehicle to its predecessor's rear bumper position..

The CTHS is applied by defining the desired distance with respect to the preceding vehicle as:

$$d_{r,i}^T = d_0 + h.\dot{x}_i, \qquad i \in S_N \tag{13}$$

where, d_0 is the stand still distance or the minimum spacing, which is the required spacing between stopped vehicles, h_i is the time headway utilized by the i^{th} vehicle and $\dot{x}_i = v_i$ is the velocity of the vehicle. The actual relative spacing for the i^{th} vehicle is given by $x_{i-1} - x_i - l_i$ of the i^{th} vehicle with respect to the $(i-1)^{th}$ vehicle. The spacing error of the i^{th} vehicle with respect to the $(i-1)^{th}$ vehicle in case of the CTHS is defined as:

$$e_i^T = x_{i-1} - x_i - l_i - d_0 - h.\dot{x}_i \tag{14}$$

The control input for the CACC controller in this case is of the form:

$$u_i^T = k_1^T(\ddot{x}_{i-1} - \ddot{x}_i) + k_2^T(\dot{x}_{i-1} - \dot{x}_i) + k_3^T e_i \tag{15}$$

where k_1^T, k_2^T, k_3^T are respectively the parameters of the algorithm. u_1^T is the desired acceleration for the closed-loop system base on the CTHS (Upper level as in [30]).

Using system (1), (9), (14), (15) the state-space representation in terms of the platoon with the CTHS can be described:

$$\begin{pmatrix} \dot{e}_i^T \\ \dot{x}_i \\ \dot{v}_i \\ \dot{a}_i \end{pmatrix} = \underbrace{\begin{pmatrix} 0 & 0 & -1 & h \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\frac{1}{\varsigma_i} \end{pmatrix}}_{A^T} \underbrace{\begin{pmatrix} e_i^T \\ x_i \\ v_i \\ a_i \end{pmatrix}}_{X_i^T} + \underbrace{\begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}}_{B^T} \underbrace{\begin{pmatrix} e_{i-1}^S \\ x_{i-1} \\ v_{i-1} \\ a_{i-1} \end{pmatrix}}_{X_{i-1}^T} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ 0 \\ \frac{1}{\varsigma_i} \end{pmatrix}}_{C^T} u_i^T \tag{16}$$

and

$$u_i^T = \underbrace{\begin{pmatrix} k_3^T \\ 0 \\ -k_2^T \\ -k_1^T \end{pmatrix}}_{A_1^T}^T \begin{pmatrix} e_i^T \\ x_i \\ v_i \\ a_i \end{pmatrix} + \underbrace{\begin{pmatrix} 0 \\ 0 \\ k_2^T \\ k_1^T \end{pmatrix}}_{B_1^T}^T \begin{pmatrix} e_{i-1}^T \\ x_{i-1} \\ v_{i-1} \\ a_{i-1} \end{pmatrix} \tag{17}$$

which can be rewritten in the following form:

$$\begin{cases} \dot{X}_i^T = A^T X_i^T + B^T X_{i-1}^T + C^S u_i^T \\ Y_i^T = A_1^T X_i^T + B_1^T X_{i-1}^T, \qquad i \in S_N \end{cases} \tag{18}$$

3.3. String Stability

Stability analysis is a basic problem for the CACC system to adjust the inter-vehicle spacing. An unstable string is one of the causes of driver discomfort, rear-end collision. The string as a whole can be unstable even when the individual vehicle in strings is stable individually [15]. Individual vehicle stability for vehicle strings: each vehicle is asymptotically stable in the closed-loop CACC system, i.e, the spacing error converges to zero for all followers. String Stability: the amplitude of spacing error between consecutive vehicles decreases along the string as propagating towards the tail of the string [15, 34, 35, 36].

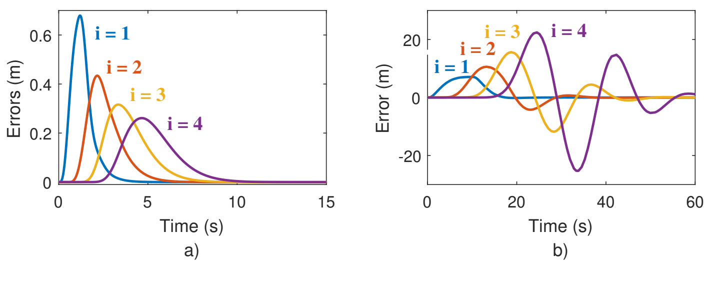

Fig. 3. Intuitive descriptions of string stability of CACC platoon examples: (a) stable string; (b) unstable string.

For this reason, vehicular platoon control must ensure each individual vehicle and string stability. For both cases, the adjacent spacing errors in the frequency domain with a transfer function $\xi_i(s)$ takes the form as below:

$$E_i(s) = \xi_i(s)E_{i-1}(s), \qquad i \in S_N \tag{19}$$

here, $E_i(s), E_{i-1}(s)$ denotes the spacing error of the i^{th} and $(i-1)^{th}$ vehicle in time domain.

Normally, the string stability is evaluated via the magnitude of the error transfer function. A vehicle platoon is said to be string-stable if the tracking errors are not amplified along with the platoon.

$$\|\xi_i(j\omega)\|_\infty \leq 1 \tag{20}$$

In order to find the transfer function of spacing errors between two consecutive vehicles for both strategies. First, in the case of the CSS, the algorithm can be rewritten:

$$u_i^S = k_1^S e_i^S + k_2^S \dot{e}_i^S + k_3^S \ddot{x}_{i-1} + k_4^S(x_l - x_i - i.l_i - i.L_i) + k_5^S(\dot{x}_l - \dot{x}_i) + k_6^S \ddot{x}_l \tag{21}$$

From the equation of the longitudinal dynamics of the individual vehicle, we have

$$\varsigma_i(\dddot{x}_{i-1} - \dddot{x}_i) + \dot{x}_{i-1} - \dot{x}_i = u_{i-1}^S - u_i^S \tag{22}$$

Based on the equation (21), (22), we are obtained:

$$\varsigma.\dddot{e}_i^S + \ddot{e}_i^S = k_1^S e_{i-1}^S + k_2^S \dot{e}_{i-1}^S + k_3^S(\ddot{x}_{i-2} - \ddot{x}_{i-1}) + k_4^*(-x_{i-1} + x_i + l_i + L_i) + k_5^S(-\dot{x}_{i-1} + \dot{x}_i) - k_1^S e_i^S - k_2^S \dot{e}_i^S \tag{23}$$

Bring the equation (7) into the equation (23):

$$\varsigma.\dddot{e}_i^S + \ddot{e}_i^S + (k_2^S + k_5^S)\dot{e}_i^S + (k_1^S + k_4^S)e_i^S = k_3^S \ddot{e}_{i-1}^S + k_2^S \dot{e}_{i-1}^S + k_1^S e_{i-1}^S \tag{24}$$

Using the Laplace transform for the equation (24) with zero initial conditions, results in the transfer function describe the way the tracking errors based on the CSS:

$$\xi_i^S(s) = \frac{k_3^S s^2 + k_2^S s + k_1^S}{\varsigma_i s^3 + s^2 + (k_2^S + k_5^S)s + (k_1^S + k_4^S)} \tag{25}$$

Remark 1: Consider individual vehicle dynamics in the platoon is given in equation (1), the CTHS is given in (3), and the control input is given in (9). Suppose that all the control gains of the individual vehicles in the platoon are homogeneous. Then, the condition (20) of the transfer function of spacing errors is satisfied based on results from [22], if and only if:

$$\begin{cases} k_5^S \geq \sqrt{2(k_1^S + k_4^S)} \\ 0 < k_3^S \leq 1 \\ k_2^S + k_5^S \geq \varsigma\sqrt{k_1^S + k_4^S}, \quad with \quad \varsigma_0 \in (0,1] \end{cases} \tag{26}$$

For the case of the CTHS, the time derivative of the equation (14) is

$$\begin{aligned} \dot{e}_i^T &= \dot{x}_{i-1} - \dot{x}_i - h.\ddot{x}_i \Rightarrow \dot{x}_i = \dot{x}_{i-1} - \dot{e}_i^T - h.\ddot{x}_i \\ \ddot{e}_i^T &= \ddot{x}_{i-1} - \ddot{x}_i - h.\dddot{x}_i \Rightarrow \ddot{x}_i = \ddot{x}_{i-1} - \ddot{e}_i^T - h.\dddot{x}_i \\ \dddot{e}_i^T &= \dddot{x}_{i-1} - \dddot{x}_i - h.\ddddot{x}_i \Rightarrow \dddot{x}_i = \dddot{x}_{i-1} - \dddot{e}_i^T - h.\ddddot{x}_i \end{aligned} \tag{27}$$

Bring the equation (27) into the equation of the longitudinal dynamic model, after a simple the calculation, it becomes:

$$u_{i-1}^T - h\dot{u}_i^T - u_i^T = \varsigma_i \dddot{e}_i^T + \ddot{e}_i^T \tag{28}$$

Then, bring the equation (15) into the equation (28), it results:

$$\begin{aligned} k_1^T(\ddot{x}_{i-2} - \ddot{x}_{i-1} - h\dddot{x}_{i-1}) + k_1^T(-\ddot{x}_{i-1} + \ddot{x}_i + h\dddot{x}_i) \\ + k_2^T(\dot{x}_{i-2} - \dot{x}_{i-1} - h\ddot{x}_{i-1}) + k_2^T(-\dot{x}_{i-1} + \dot{x}_i + h\ddot{x}_i) \\ + k_3^T e_{i-1}^T - k_3^T h\dot{e}_i^T - k_3^T e_i^T = \varsigma_i \dddot{e}_i^T + \ddot{e}_i^T \end{aligned} \tag{29}$$

From both the equation (27) and (29), we have:

$$k_1^T\ddot{e}_{i-1}^T + k_2^T\dot{e}_{i-1}^T + k_3^T e_{i-1}^T = \varsigma_i \dddot{e}_i^T + (1 + k_1^T)\ddot{e}_i^T + (k_2^T + k_3^T h)\dot{e}_i^T + k_3^T e_i^T \tag{30}$$

Finally, using the Laplace transform for the equation (30) with zero initial conditions, results in the transfer function describe the way the tracking errors based on the CTHS:

$$\xi_i(s)^T = \frac{k_1^T s^2 + k_2^T s + k_3^T}{\varsigma_i s^3 + (1 + k_1^T)s^2 + (k_2^T + k_3^T h)s + k_3^T} \tag{31}$$

Remark 2: Consider individual vehicle dynamics in the platoon is given in equation (1), the CTHS is given in (13), and the control input is given in (15). Suppose that all the control gains of the individual vehicles in the platoon are homogeneous. Then, the condition (20) of the transfer function of spacing errors is satisfied based on results from [23], if and only if:

$$h \geq \frac{2\varsigma_0}{1 + 2k_1^T}, \quad with \quad \varsigma_0 \in (0, 1] \tag{32}$$

4. Numerical Example

To verify the effectiveness of the proposed solution, simulations in Matlab/Simulink are deployed for a string of vehicles using the CACC system based on the CTHS with a varied communication range in the PF topology and based on the CSS with a varied communication range in the PLF topology. In order to simplify the analysis, we take 11 vehicles of the same model, including 1 leader with x_0, v_0 and 10 followers with index $i = 1, ..., 10$.

Before the start of the numerical example, the initial inter-space of consecutive vehicles is set as 5m. The parameters of vehicle given as follow: $l_0 = 5m$, $\varsigma_i = 0.5$. For the CSS, by using conditions (26) in Remark 1, the controller parameter gains for the vehicles are chosen as: $k_1^S, k_2^S, k_3^S, k_4^S, k_5^S, k_6^S$ = [0.05; 0.4216; 0.5; 0.001; 0.25; 0.3], $L_i = 5m$. Forthe the CTHS, by using conditions (32) in Remark 2, the controller parameter gains for the vehicles are chosen as: $k_1^T, k_2^T, k_3^T = [0.25,\ 0.8,\ 45]$; $h = 0.65s$, $d_0 = 2m$. Note that, the same scenario is considered to evaluate the ability of the platoon in following the preceding vehicle with the above two spacing strategies.

The velocity changes in the leading vehicle are given as follow:

$$v_0 = \begin{cases} 10m/s, & 0 \leq t \leq 20s \\ 10t - 190m/s, & 20 < t \leq 22s \\ 30m/s, & 22 \leq t \leq 45s \\ -5t + 255m/s, & 45 < t \leq 47s \\ 20m/s, & 47 < t \leq 65s \end{cases} \tag{33}$$

In the simulation, the string of 11 vehicles equipped with the CACC system organized to travel on a single lane to 65(s), the initial state of vehicle strings is set to $x_i(0) = [0,\ 10,\ 20,\ 30,\ 40,\ 50,\ 60,\ 70,\ 80,\ 90,\ 100](m)$ at time $t_0 = 0(s)$. The simulation results have given the position, the velocity, the spacing errors, and length of the platoon for two spacing strategies, respectively as in Figures.4.

The positions of the vehicles on the road are described in Figure.4(a1) and Figure.4(a2), we can see that the case of the CACC system based on the CSS increase traffic throughput more than the CTHS, the distance between the members of the string with the CSS is smaller than that of with the CTHS. More specifically, at a position of 800 (m) on the road and at time t = 42(s), All 11 vehicles apply for the CSS succeeded to pass while having the last 6 vehicles of string vehicles apply for the CTHS did not succeed to pass as in Figure.4(a1) - left zoom and Figure.4(a2) – left zoom).

Furthermore, this is claimed again in Figure.4(b1) and Figure.4(b2). We can see that length of string using the CACC system based on the CSS is shorter than that of the CTHS. The maximum length of the string with the CSS, the CTHS are 120,5(m); 262.5(m), respectively.

In Figure.4(c1) and Figure.4(c2), the accuracy of velocity tracking of the string with the CTHS is better when the string of the vehicles travels at the constant velocity (at $v_i = 10(\frac{m}{s})$, $v_i = 20(\frac{m}{s})$ and $v_i = 30(\frac{m}{s})$). The spacing errors of the string of vehicles with the CTHS and the CSS are illustrated in Figure.4(d1), Figure.4(d2), respectively. We see that the string with the CSS can call "weak string stability" although the propagating spacing errors are attenuated as propagating along the string. The string with the CTHS is always guaranteed "robust string stability", the small tracking errors of the string of 11 vehicles achieve stability, i.e., $|e_1| \geq |e_2| \geq ... \geq |e_9| \geq |e_{10}|$. Further, the comparison between Figure.4(d1) and Figure.4(d2) shows that the PLF string of vehicles using the CSS causes a bigger tracking error of the i^{th} vehicle than the PF string of vehicles using the CTHS does. The maximum spacing error of the string with the CTHS is 0.8 m, while that with the CSS is 8 m.

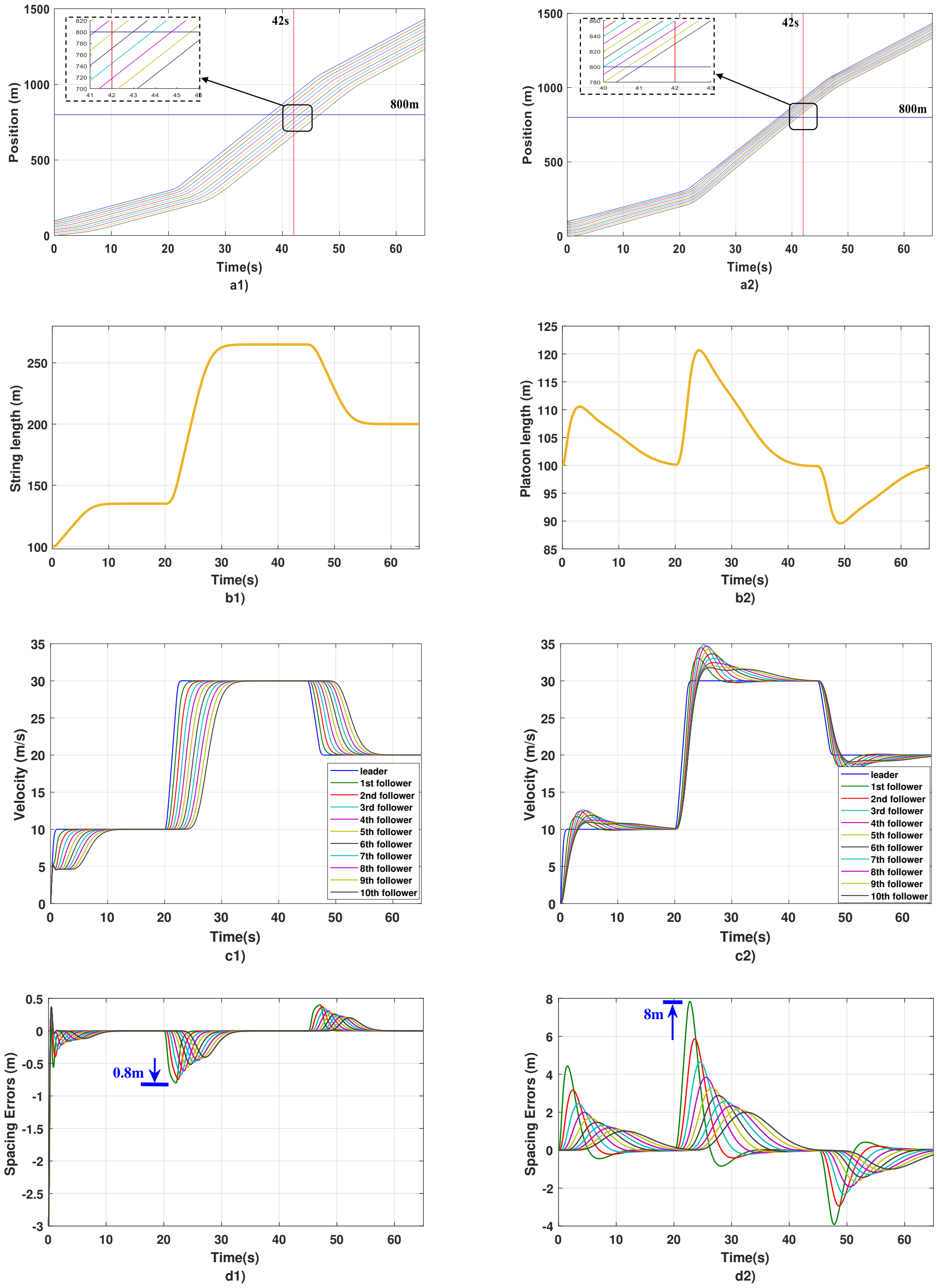

Fig. 4. Comparative results of a string of eleven vehicles: (a1)-(d1) position, length of the string, velocity and spacing errors based on the CTHS with the PF topology. (a2)-(d2) position, length of the string, velocity and spacing errors based on the CSS with the PLF topology.

From the result analysis, the PF string of vehicles using the CTHS provides much better stable string performance but the PLF string of vehicles using the CSS ensures traffic throughput improvement by increasing the urban arterial capacity.

Actually, the selection of spacing strategies for string vehicles is one of the complex problems since a lot of design purposes are inherently contradictory i.e., the smaller distance between the members of the platoon is a method for increasing the capacity of roads, but, the safety can not guarantee when the distance is set too small to lead the drivers no longer have reaction time.

5. Concluding remarks

In this work, the CACC system is presented by numerical example results, that clearly demonstrate the differences, advantages, and disadvantages of two spacing strategies. The effects of the two main types of information flow topologies PF, PLF are applied for the string vehicles using spacing strategies: the CTHS, the CSS, respectively. the detailed linear model of the individual vehicle is established. By the feedback linearization method and the conditions of stability were analyzed.

We remark that the PF string of vehicles employing the CTHS had better performance, such as smaller tracking error, robust string stability. But, the PLF string of vehicles employing the CSS increases traffic capacity by choosing a small L_i.

Therefore, we need to compromise between the safety, stability, and traffic throughput to chose spacing strategies for the CACC system. At last, the efficiency and benefits of the proposed solution such as stable, very fast have demonstrated by numerical simulation results.

Future work on this topic in real-time applications will make a platoon of smart cars that use as few resources as possible including hardware devices such as distance sensors, speed sensors, Arduino Mega2560 microcontrollers, wireless communication devices, and some other devices. Controllers will embed coding for this platoon of smart cars. These smart cars maintain the value desired distance between them while keeping the velocity of the leader in the longitudinal direction. Next step, smart cars will get the data from the preceding car through wireless to control based on the CSS, the CTHS.

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