# Control of Heavy Road Vehicle Platoons Incorporating Actuation Dynamics

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***Abstract*—This paper focuses on the design of controllers that ensure string stability in Heavy Commercial Road Vehicle (HCRV) platoons. While dealing with controller design for HCRVs, due to the sluggish nature of a pneumatic brake actuation system, the actuator dynamics has to be considered explicitly. Sliding Mode Control (SMC), which is a widely accepted control strategy for string stability has been considered and the effects of actuator dynamics during deceleration as well as acceleration phase were analysed. It was observed that, the actuation delays caused string instability using the designed SMC controller. In this context, a Variable Time Headway (VTH) based controller redesign that is capable of ensuring string stability despite actuation delays is presented. The efficacy of the presented VTH policy has been evaluated through simulations and it was observed that this policy could make the platoon string stable while accounting for real world actuator dynamics.**

***Index Terms*—Heavy Commercial Road Vehicle, Sliding Mode Control, String Stability, Time Delay, Vehicle Platoon**

## I. Introduction

Freight transportation and logistics is an important domain that can aid the economic growth of any nation. The expanding freight transportation sector demands the efficient use of Heavy Commercial Road Vehicles (HCRVs) for cost-effective freight movement. Due to this, the growth rate of registered HCRVs is rising annually, which ultimately results in traffic congestion and increased fuel consumption. As per 2014 statistics, in the United States, the annual growth rate of HCRVs was 3.1 % [1]. In India, during the period 2001-2015, the number of registered HCRVs has increased by 200 % [2].

The technique known as vehicle platooning[1] is gaining great interest nowadays especially, while dealing with HCRV based transportation. In platoons, vehicles operate at close inter-vehicular distances such that the overall aerodynamic drag is reduced. In HCRVs, up to one fourth of the fuel consumption is spent on overcoming the aerodynamic drag [3]. Hence, it is clear that platooning has the capability to potentially reduce the operational cost of HCRVs. The efficient fuel consumption in platoons also leads to reduced greenhouse gas emission. In addition to this meritorious aspects, since vehicles are operated at close inter-vehicular distances, more efficient utilization of the existing road infrastructure can be achieved and hence the overall traffic throughput can be improved. Due to the increasing penetration of electrified vehicles, which are more amenable for real time control, HCRV platooning is gaining greater attention in the transportation sector currently [4].

The most crucial factor in the realization of vehicle platoons is the notion of string stability[2] [5], [6]. String stability reflects to the ability to attenuate spacing error along the platoon in the downstream direction. Controller design based on constant spacing as well as variable spacing policies are available in the literature [6]– [9]. Constant Time Headway (CTH), which is a variable spacing policy has gained great research interest since it does not require more information about other vehicles compared to the constant spacing policy [6], [10].

Since vehicle platoon is an interconnected coupled system, disturbances acting on one vehicle may affect the entire platoon. This may amplify spacing errors between vehicles in the platoon along the string and may ultimately lead to string instability. Hence, it is advisable that the controller design for string stability should rely on adequate robust control strategies for confident on-road operation. In this regard, Sliding Mode Control (SMC), being a well accepted robust control technique, has been widely used for achieving string stability in platoons [11]– [14].

Most research in this area has been conducted on the efficacious operation of passenger car platoons. However, while dealing with HCRV platooning, one additional constraint has to be considered, i.e., the pneumatic brake actuation system. Unlike hydraulic brake actuation systems in passenger cars, the pneumatic brake system in HCRVs is sluggish in nature [15]. Hence, the effect of actuator dynamics and its inherent time delays have to be considered while designing string stability controllers in HCRV platoons. Brake dynamics comes into picture during deceleration phase in the platoon. Similarly, during acceleration phase, the time delay from the powertrain also needs to be considered. Xiao and Gao in [16] have analysed the effects of parasitic time delays and response time of the actuators and sensors on the string stability of vehicle platoons and have established that the effect of time delays was significant than that of the response time. In [5],

[1]A vehicular platoon is a string of two or more closely travelling vehicles with desired cruising velocity and distance [5].

[2]A vehicle platoon is said to be string stable if the inter-vehicular spacing errors of all the vehicles are bounded uniformly in time, provided the initial spacing errors of all the vehicles are bounded [5].

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the relationship between CTH and parasitic time delays for string stability has been presented. However, the effect of time delay in actuators has not been accounted for. A proportional-derivative (PD) controller for string stability in the presence of time delays and response time of actuators was presented in [17]. Though Yanakiev and Kanellakopoulos in [18] have designed two nonlinear controllers in the presence of large delays for commercial heavy vehicles, they did not present string stability analysis using their proposed controllers.

As far as the practical realization of an HCRV platoon is concerned, the crucial factors to be considered are, (1) longitudinal vehicle model including aerodynamic drag and rolling resistance, (2) brake/powertrain actuator dynamics, (3) tyre model and wheel dynamics. This paper attempts to address the first two factors and the third one would be addressed in the near future.

The vehicle model considered in this study has explicitly considered the resistive forces due to aerodynamic drag and rolling resistance. To the best of authors' knowledge, any investigation on string stability of HCRV platoons, considering appropriate actuator dynamics is not available in the literature. In this context, the current paper studies the effectiveness of string stability controllers in the presence of an accurate actuator dynamics. For this, the brake system model obtained from a Hardware-in-Loop (HiL) experimental system was used in this study [15]. This helped in including realistic magnitudes of time delay and time constant. Since actuation delays during braking were reported to be in agreement with delays during acceleration [19], the same brake model was used for analysing string stability even in acceleration phase. Thus the proposed approach encompassed possible system delays during platooning of HCRVs. Moreover, in order to circumvent the limiting effects due to actuator dynamics and time delays on string stability, this study also revisited the SMC controller design and proposed a Variable Time Headway (VTH) based SMC scheme.

This paper is organised as follows. Section II briefly presents the vehicle model, actuator model and SMC controller design. Section III, through simulation studies, analyses the effect of actuator dynamics on string stability, while using CTH policy. The redesign of SMC controller based on VTH policy is presented in section IV. Section V concludes the paper.

## II. Platoon Model and Control Description

The operation of one of the follower vehicles in the platoon is given in Figure 1. Each components of this block diagram are described below. Following are the assumptions made in this study:

- Only longitudinal dynamics of vehicles are considered.
- The brake/traction force calculated by the string stability controller is available at the wheels.
- Tyre model is not considered since wheels are assumed to operate in low slip region.
- Wheel dynamics is neglected.
- Road gradient is not considered.

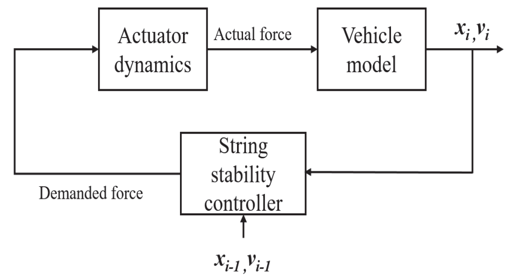


Fig. 1: System block diagram

- Velocity and position information of preceding vehicle is available.

### A. Vehicle Model

The platoon consists of a leader vehicle and $N$ number of following vehicles. The longitudinal dynamics of the leader is given by

$$\dot{x}_o(t) = v_o(t), \tag{1}$$

where, $x_o(t)$ and $v_o(t)$ are the position and longitudinal speed of the leader vehicle. Leader takes action independently such that $v_o(t)$ is the input from the leader to the follower vehicles in the platoon. Dynamics of the follower vehicles is described by

$$\dot{x}_i(t) = v_i(t), \tag{2}$$

$$\dot{v}_i(t) = \frac{1}{m_i}(F_i(t) - F_a(t) - F_r(t)), \tag{3}$$

where, $i = 1...N$.
$x_i(t)$ and $v_i(t)$ are the position and longitudinal speed of the follower vehicles in the platoon. $F_i(t)$ is the brake/traction force of the vehicles and $m_i$ is the mass of the vehicles in the platoon. $F_a(t)$ and $F_r(t)$ represent forces due to aerodynamic drag and rolling resistance respectively.
Spacing between a pair of vehicles is given by

$$d_i(t) = x_{i-1}(t) - x_i(t). \tag{4}$$

Desired inter-vehicular distance is given by

$$s_d(t) = s_o + h_i v_i(t), \tag{5}$$

where, $s_o$ is the standstill spacing and $h_i$ is the time headway. Spacing error is given by

$$e_i(t) = d_i(t) - s_d(t). \tag{6}$$

### B. Actuator Model

A first order model of the actual pneumatic brake system equipped with an electro-pneumatic regulator (EPR) has been developed by Sridhar et al. in [15]. The model was obtained using HiL experiments and hence provides a close approximation of the real brake system and is utilized in this paper. The model transfer function is given by,

$$\frac{F_{out}(s)}{F_{in}(s)} = \frac{1}{1+\tau s} e^{-T_d s}, \tag{7}$$

where, $F_{in}$ and $F_{out}$ represent the demanded brake force and actual brake force developed. $\tau$ and $T_d$ represent the time constant and time delay respectively. For the brake system under consideration, $\tau$=260 ms and $T_d$=45 ms. From literature, it can be seen that the dynamics during acceleration phase also can be approximated as first order models with time constants and delays [19]. Hence, the above discussed brake model was considered during acceleration phase too. Literature also agree that the choices, $\tau$= 260 ms and $T_d$=45 ms are appropriate even during acceleration phase [19].

### C. Controller Design

The control objective is to drive the spacing error to zero, such that the desired inter-vehicular distance is maintained in the platoon. The control objective can be represented as:

$$d_i(t) \to s_o + h_i v_i(t), \tag{8}$$

$$v_i(t) \to v_o(t). \tag{9}$$

Now, in order to design SMC controllers for individual vehicle stability and string stability, the approach used in [12] is followed in this paper. The sliding surface was chosen as

$$s_i(t) = e_i(t) + \int_0^t \lambda e_i(\tau) d\tau. \tag{10}$$

A sliding surface including an integral term was selected so as to avoid the demand for acceleration commands from the preceding vehicles. This sliding surface definition is capable of guaranteeing individual vehicle stability. For string stability, the sliding surface was redefined as [12]

$$S_i(t) = \begin{cases} q s_i(t) - s_{i+1}(t), & i = 1, ..., N-1 \\ q s_i(t), & i = N \end{cases} \tag{11}$$

where, $q$>0.
SMC controller was designed based on the following reaching law [20],

$$\dot{S}_i(t) = -G sign(S_i(t)), \tag{12}$$

where, $G$ is a positive constant. Using equations (2), (3), (10) and (11), the control equations (brake/traction force) were obtained as:

$$F_i(t) = \frac{m_i G}{q\lambda h}(sign(S_i(t)) + F_a(t) + F_r(t)) + \frac{m_i}{q\lambda h}(q\ddot{e}_i(t) - \lambda\dot{e}_{i+1} - \ddot{e}_{i+1}) + \frac{m_i}{h}(v_{i-1} - v_i), \tag{13}$$

$$F_N(t) = \frac{m_N G}{q\lambda h}(sign(S_N(t)) + F_a(t) + F_r(t)) + \frac{m_N}{q\lambda h} q\ddot{e}_N(t) + \frac{m_N}{h}(v_{N-1} - v_N). \tag{14}$$

In this paper, it was assumed that $m_1, .., .m_N = m$ and $h_1, ..., h_N = h$.

The presence of 'sign' term in the SMC control equation induces chattering, which is characterized by high frequency control signal switching. Since this phenomenon may affect actuator life, a chattering mitigation method using boundary layer method was used here. In this method, the sign function in control equation was replaced with a saturation function for smooth control action [21].

## III. Performance Evaluation with Constant Time Headway Policy

A platoon of six follower vehicles and a leader vehicle was considered. The initial position and longitudinal speed of the leader vehicle were, $x_0(0)$ = 200 m and $v_0(0)$ = 20 m/s respectively. The platoon was considered to be a homogeneous one with HCRVs of mass, $m$=10000 kg each. The platoon was assumed to be initially string stable, with the initial longitudinal speed of each vehicle is $v_i(0)$ = 20 m/s, $i$=1,..,6. For the design, $s_0$=5 m and $h$=1 s were considered, such that the safe separation distance between the follower vehicles was 25 m and initial positions of the follower vehicles were, $x_1(0)$=175 m, $x_2(0)$=150 m, $x_3(0)$=125 m, $x_4(0)$=100 m, $x_5(0)$=75 m and $x_6(0)$=50 m.

The presented SMC design was initially evaluated for its performance without considering the actuator dynamics and the results are shown in Figure 2. The leader vehicle was assumed to take a maneuver as shown in Figure 2(a), which included a deceleration phase and an acceleration phase. The brake/traction force synthesized by the string stability controller was given directly to the follower vehicles. For string stability, SMC gain, $G$=25 was used. As seen from Figure 2(b), the vehicles adjusted their longitudinal speeds such that collision was avoided (Figure 2(c)) and finally they retraced the string velocity of 20 m/s. From Figure 2(d) it can be seen that the spacing between the vehicles were adjusted for collision free operation of the platoon and once the maneuver was completed, the desired inter-vehicular distance of 25 m was again established. During the entire maneuver period, the controller synthesized brake/traction force (Figure 2(e)) such that the follower vehicles did not collide with each other (Figure 2(c)). The total force that can be generated at the tyre-road interface for a road surface with tyre-road traction coefficient, $\mu$, is $F_{imax} = \mu m g$, where, $g$ is acceleration due to gravity. For a vehicle of mass, $m$=10000 kg and for a dry road surface with, $\mu$=0.8, the total limiting force available at the wheels from the above equation is 78400 N. From Figure 2(e), it can be seen that the demanded force from the controller was well within this limit. This ensured stable vehicle operation.

For an efficacious platoon with improved traffic throughput and less fuel consumption, by virtue of reduced aerodynamic drag between the vehicles, the length of the platoon should be as minimum as possible. In order to investigate this aspect, the temporal variation of platoon length during the entire maneuver was also obtained and shown in Figure 2(f). Platoon length was calculated without explicitly considering the length of each vehicle in the platoon. From this study, it was observed that the platoon length decreased as the leader vehicle decelerated and finally went back to the original platoon length as the leader vehicle accelerated to the string velocity of 20 m/s. The platoon reached back to its original operating length of 150 m (possibly the optimal length) in 18.9 s.

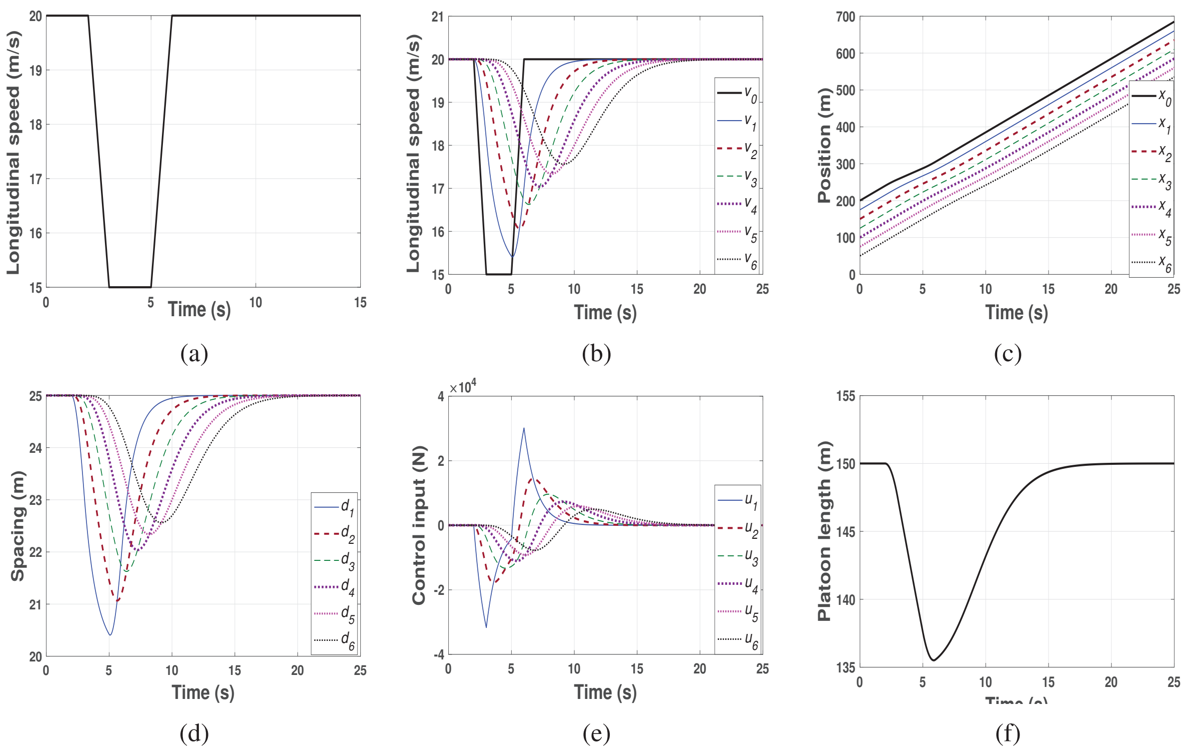


Fig. 2: Performance without actuator: (a) leader vehicle longitudinal speed profile, (b) Longitudinal speed , (c) Position, (d) Inter-vehicular spacing, (e) Control inputs (brake/traction force), (f) Length of the platoon

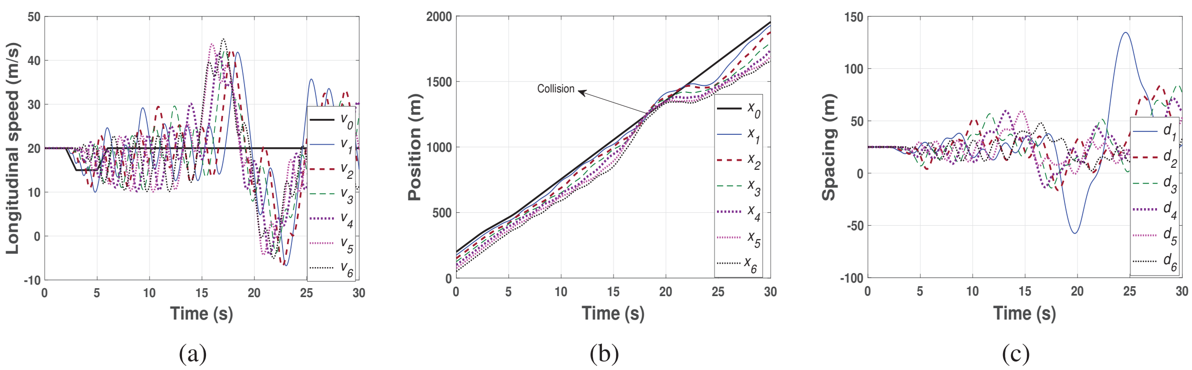


Fig. 3: Performance with actuator (with CTH policy): (a) Longitudinal speed, (b) Position, (c) Inter-vehicular spacing

Now, in order to investigate the performance of the string stability controller in the presence of actuator dynamics, the brake/traction force developed by the controller was assumed to reach the wheels through the actuator model. The results are shown in set of plots in Figure 3. The actuator model presented in the previous section has been used for the study. It was observed that the total demanded force from the controller was going beyond the traction limit of 78400 N. It is shown in the next section that the use of a variable time headway brings this control force within practical traction limits. Further, collision between vehicles can be observed from Figure 3(b), and even controller retuning was not able to avert the same.

## IV. Controller Redesign via Variable Time Headway Policy

From the above discussion, it can be seen that an SMC controller based on CTH policy was not capable of maintaining string stability in a practical HCRV platoon. A solution to this problem is being presented here in the form of a time headway based controller redesign. Since the accumulation of spacing error along the platoon leads to string instability, the idea here is to drive spacing error to zero such that, error accumulation is prevented. This can be achieved by judiciously choosing time headway at each instant such that error is right away nullified. For this, a Variable Time Headway (VTH) policy as

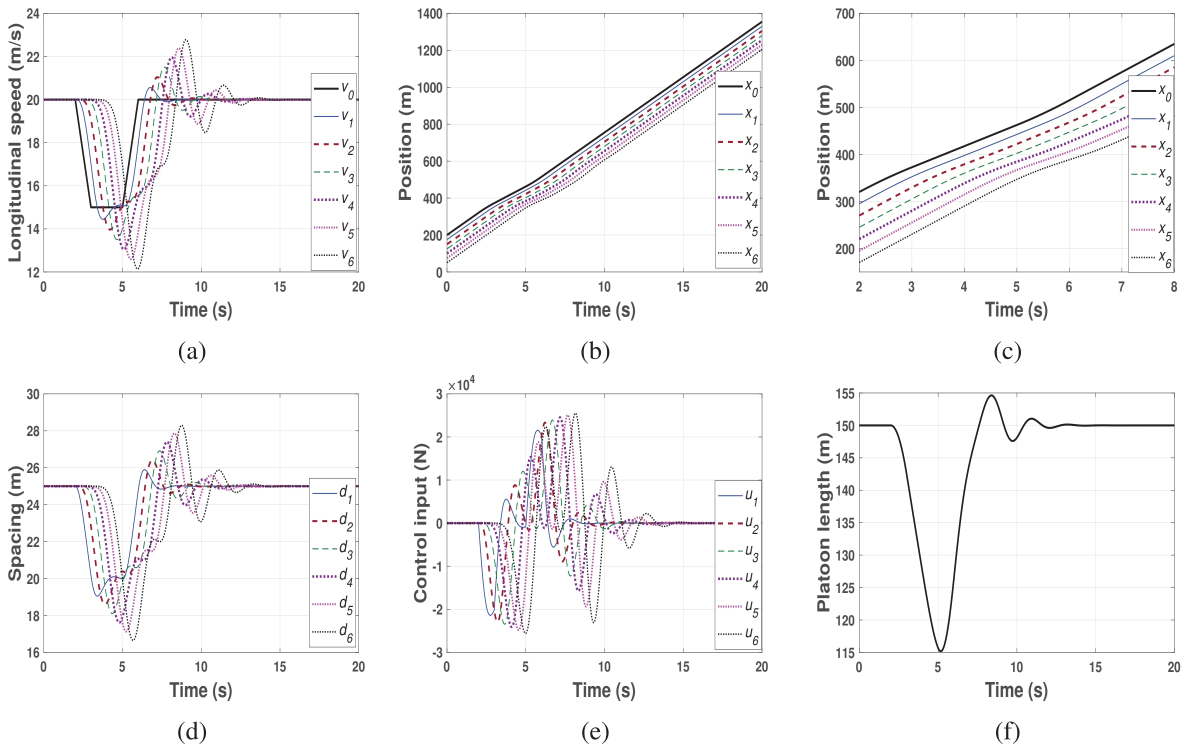


Fig. 4: Case 1: Performance with actuator (with VTH policy): (a) Longitudinal speed, (b) Position, (c) Position: Zoomed, (d) Inter-vehicular spacing, (e) Control inputs (brake/traction force), (f) Length of the platoon

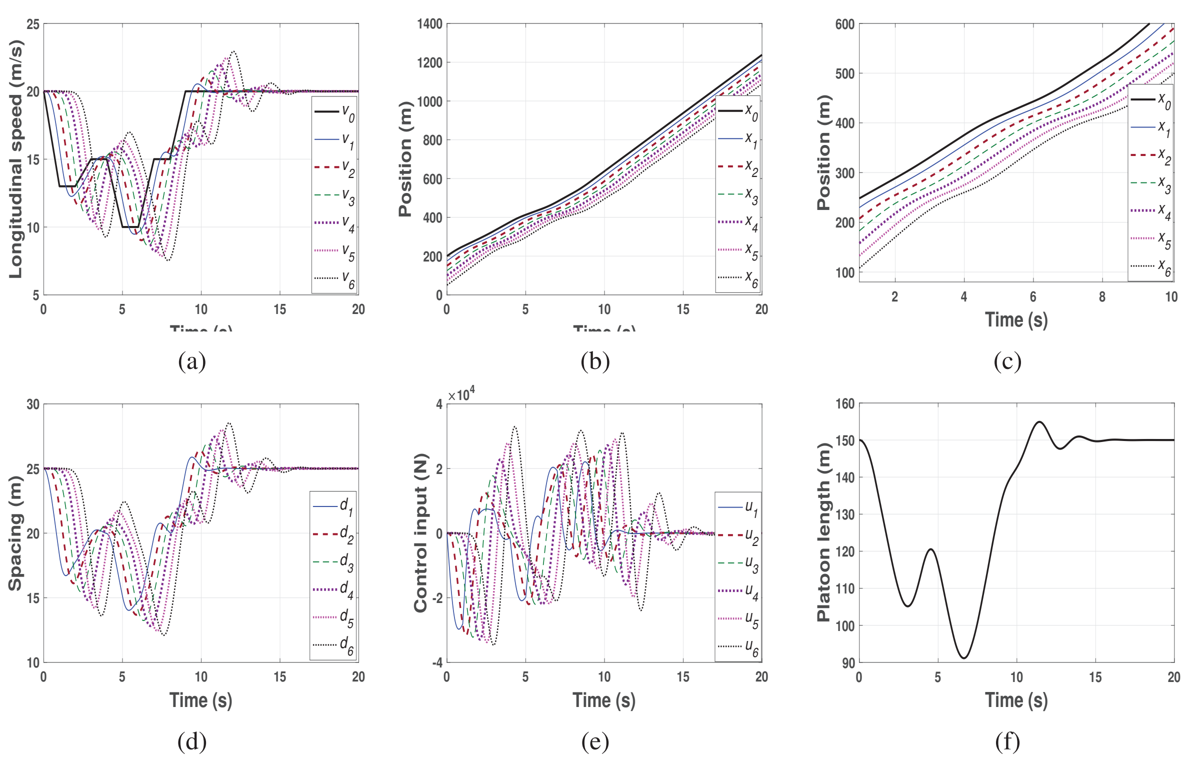


Fig. 5: Case 2: Performance with actuator (with VTH policy): (a) Longitudinal speed, (b) Position, (c) Position: Zoomed, (d) Inter-vehicular spacing, (e) Control inputs (brake/traction force), (f) Length of the platoon

shown below is proposed:

$$h_i(t) = \frac{x_{i-1}(t) - x_i(t) - s_o}{v_i(t)}. \tag{15}$$

It is worth mentioning that, in this policy for time headway calculation at each instant, the current position of the preceding vehicle and the current position and longitudinal speed of the host vehicle, which have already been assumed to be available for CTH policy, are sufficient. Hence this policy can practically be implemented without any additional information from neighbouring vehicles. The new control equations can be obtained by replacing $h$ in Equations (13) and (14) with $h(t)$, given by Equation (15), in VTH policy.

Figure 4 gives the results of VTH based SMC for the leader vehicle maneuver as given in section IV. The investigation was done by including the actuator dynamics with the same time constant and time delay used in CTH policy. Unlike CTH policy, the proposed VTH based SMC was capable of maintaining string stability during the maneuver. As seen in Figure 4(f), the platoon reached its original length in 13.7 s which implies that, VTH policy is acting faster than the CTH policy. The sooner the platoon retraces its original length, more efficient the platoon can be. However, it is to be noted that, unlike in CTH policy, here, the platoon elongated to a larger length before settling back to its original length. But, faster settling to the desired length compensates for the increased platoon length so that the platoon may remain efficient in terms of road occupancy and fuel consumption.

The presented VTH policy was tested for another leader vehicle maneuver, in which leader took multiple deceleration and acceleration phases. In order to comment on the tolerance level of the VTH policy, a time constant of 400 ms and time delay of 60 ms were used here. The results are shown in Figure 5 and these results also corroborated the efficacy of VTH policy to maintain string stability even in the presence of actuator dynamics with higher time constants and delays. As seen from Figures 4(e) and 5(e), the demanded forces for string stability in both the cases were within the calculated traction limit, $F_{imax}$ of 78400 N.

## V. Conclusion

This paper investigated the effects of time delays due to actuator dynamics in heavy vehicle platoon and it was observed that constant time headway based controller was insufficient to establish string stability in the platoon. In this context, this paper proposed a variable headway based controller design to account for the impediments due to actuator dynamics. The proposed VTH policy was able to retrace the desired platoon length faster than the existing CTH policy, which did not consider actuator dynamics. This work can be treated as an initial step towards the practical realization of heavy vehicle platoons. Other aspects like significant mass variation in HCRVs during laden and unladen operation, wheel dynamics, dynamic load transfer, different road conditions with tyre models, etc., will be considered and addressed adequately in future research.

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