Longitudinal Control of Connected Truck Platoon based on PreScan

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Abstract: This paper proposes a general framework of connected truck platoon control based on PreScan, which includes scenario building, control algorithm loading, graphical user interface (GUI) developing, and 3D visualized display. In particular, a distributed longitudinal controller for connected truck platoon is developed by considering the car-following interactions between trucks based on the combination with feedback and feedforward. Then, the plant stability and string stability of the truck platoon are analyzed, respectively. Finally, a scenario of platoon with five trucks is constructed in PreScan to conduct the co-simulations. Results verify the effectiveness of the proposed platoon controller in terms of velocity, acceleration, and spacing error profiles.

Key Words: Truck platoon control, Car-following behavior, PreScan, Co-simulation

1 INTRODUCTION

Nowadays, with the rapid development of the automotive industry, the trucks play an important role in this development. However, due to the length, heavy mass, high center of gravity and high inertia, the truck not only increases the consumption of energy, but also brings a series of accidents during the process of road transportation. Fortunately, with the development of technologies such as 5G, vehicle-to-everything (V2X), and autonomous driving, the intelligent transportation system [1, 2] has become a potential solution, which is a combination of power electronics, information transmission, automatic control and other high-tech technologies. It aims to alleviate and solve a series of problems such as fuel consumption and road traffic safety by coordinating the relationship among vehicles, roads and drivers. At the same time, the platooning of vehicles technology has also emerged, which means vehicles with common interests cooperate on the road through vehicle-to-vehicle (V2V) communication to form independent vehicles into a platoon to move at consensual velocity while maintaining desired spaces between adjacent vehicles [3].

For the control of vehicle platoon, it can be traced back to the partners for advanced transit and highways (PATH) program [4] implemented in California in the 1980s. Since then, many issues on vehicle platoon control have been widely concerned by many scholars, and the main objectives of the platoon, control tasks, communication technologies and control laws etc. were studied [5-12].

Considering the car-following (CF) behavior in longitudinal direction and heterogeneous time delays, Li et al. [13] proposed a nonlinear consensus algorithm for connected vehicle (CV) to achieve the consensus of vehicle platoon. Further, focuses on multi-vehicle systems in a realistic communication environment, Li et al. [14] proposed a new nonlinear consensus based longitudinal control algorithm by considering the interactions between CVs and carried out a series of field experiments of platoon forming, exhibiting favorable performance of the controller in realistic scenarios. To improve robust performance and response speed of CVs, considering the acceleration information of CVs, Ge and Orosz [15] proposed an interconnected cruise control algorithm with acceleration feedback and studied string stability of vehicle platoon. Since unstable V2V communication connections lead to the change of communication topologies and delays for electric CVs, Zhao et al. [16] developed a communication topology characterization method and a new CF model to evaluate the effects of the switching period of communication topology and delay on the dynamic performance and energy consumption of an electric CVs stream. Li et al. [17] proposed a distributed integral-sliding-mode (ISM) control strategy based on second-order model to achieved braking control of CVs. Ma et al. [18] proposed an optimized control approach based on third-order model to achieve the control of vehicle platoon, considering the non-ideal communication condition and actuator time delay. Considering the authenticity of scenarios and practical significance of traffic simulation software, Li et al. [19] developed a vehicular platoon control system based on TransModeler and achieved the monitoring and controlling of vehicle platoon. For the problem of heavy-duty vehicle (HDV) platoon, Deng [20] proposed a general simulation framework to facilitate the study of HDV platooning and establishes the corresponding concept and operations. Guo and Wang [21] proposed a two-layered hierarchical framework for truck platoon coordination. Saeednia and Menendez [22] proposed a cooperative distributed

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approach for forming/modifying platoons of trucks based on consensus algorithm.

Motivated by the above research, considering the car-following interactions between trucks, it can effectively avoid negative velocity and negative inter-vehicle gap. On the other hand, designing a feedforward loop using the information of the vehicle ahead, it can significantly improve the response speed and following accuracy. Therefore, this study focuses on the design and application of the platoon control algorithm to guarantee that truck platoon moves with the consensual velocity while maintaining desired spaces between adjacent trucks. In particular, a general development framework based on PreScan is introduced. Then, a new distributed longitudinal controller for connected autonomous trucks with a focus on car-following behavior and combination of feedback control and feedforward control is designed. Finally, the effectiveness of the proposed platoon controller is verified in PreScan.

The remainder of this study is organized as follows: In Section II, this study illustrates a general development framework based on PreScan. In Section III, the kinematic model of truck, platoon controller and control objectives are presented, respectively. In Section IV, the plant stability and string stability of the platoon are analyzed, respectively. In Section V, we conduct truck platoon control experiments in PreScan to demonstrate the effectiveness of the designed controller. In Section VI, conclusions are presented in this study.

2 FRAMEWORK

The general framework of connected truck platoon control based on PreScan is explained in detail as follows:

(1) Scenario building

Build a basic traffic scenario using predefined models (including environment library elements, infrastructure library elements and actor library elements) in PreScan GUI or import external 3D models through Google SketchUp. Then, the kinematic model and initial states of truck and the parameters of sensor need to be configured.

(2) Control algorithm loading

Since Matlab/Simulink being a control core of PreScan, users need to precompile the simulation project in PreScan GUI firstly, and then load control algorithm into the compilation sheet in Matlab. On the other hand, there are three ways to control the movement of trucks in PreScan, which includes: (i) Design a trajectory and edit parameters of the SpeedProfile; (ii) Control the parameters related to truck states; (iii) Control the steer, throttle, brake and gearshift. In particular, this study focuses on kinematic states of truck. As a result, this study takes the second way of controlling truck. The control interface is shown in Fig. 1.

(3) GUI developing

In order to observe real-time information of all the trucks, control simulation experiment, and analyze simulation results, we develop a GUI using s-function in Matlab to do all this conveniently.

(4) 3D visualized display

Running an experiment takes place in Matlab/Simulink. At this time, VisViewer as an adjunct software of PreScan that provides the function of generating pictures, animations, and 3D visualized display. Meanwhile Matlab/Simulink, as a solver, is used for calculation results and display information in real-time.

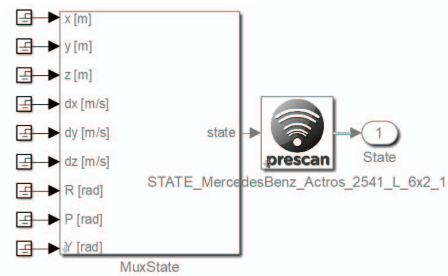

Fig 1. The control interface of truck.

3 PLATOON CONTROL

3.1 Communication Topology

A homogeneous connected truck platoon consisting of $n+1$ trucks is depicted in Fig. 2(a). The information flow topology in this scenario is shown in Fig. 2(b), where the green dotted lines represent the communication link. Based on Fig. 2, it shows that a predecessor following (PF) topology is adopted in this paper. It implies that a following truck can receive the state information (position, velocity, acceleration) of the immediately preceding truck.

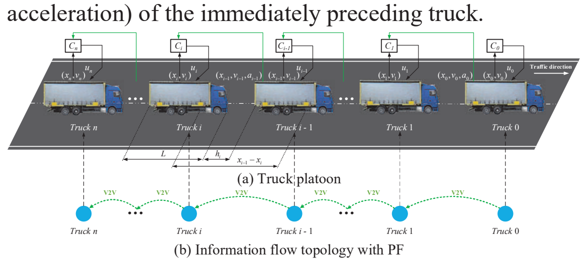

Fig 2. A homogeneous connected truck platoon control system: (a) truck platoon, (b) information flow topology with PF.

Remark 1: The communication topology structures can be classified into the PF type, predecessor following leader (PLF) type, two predecessor-following (TPL) type, bidirectional (BD) type, etc. [23]. To reduce the communication between trucks, the PF topology is used in this study to characterize the connections among connected trucks.

3.2 Spacing Policy

This study adopts a constant time headway (CTH) to define desired inter-vehicle gap, its representation as follows:

$$d_i(t) = r + h_d v_i(t) \quad (1)$$

where r is the constant that forms the gap between consecutive trucks at standstill. h_d is the headway-time constant. $v_i(t)$ is the velocity of truck i. t is the time.

Remark 2: The spacing policy can be classified into the constant distance (CD), CTH and nonlinear distance (NLD) [23]. To improve the string stability and safety, the CTH policy is adopted.

3.3 Truck Model

The kinematic model of truck can be described as follows [13, 24]:

$$\begin{cases} \dot{x}_i(t) = v_i(t) \\ \dot{v}_i(t) = u_i(t) \end{cases} \tag{2}$$

where $x_i(t)$ is the position of center of gravity of truck *i*. $u_i(t)$ is the desired acceleration given by the platoon controller.

Remark 3: The truck model can be classified into the dynamic model and the kinematic model. This study focuses on kinematic states of truck, and the kinematic model of truck is adopted accordingly.

3.4 Platoon Controller Design

Previous literature has proved that the acceleration can improve the following accuracy and response speed [18], and the usage of car-following behavior can avoid negative velocity, negative inter-vehicle gap [13, 17]. Thus, combining with car-following behavior, feedback control and feedforward control, this study designs a new longitudinal controller as follows:

$$\begin{aligned} u_i(t) =& K_o(V(h_i(t)) - v_i(t)) \\ &+ K_p(x_{i-1}(t) - x_i(t) - L - (r + h_d v_i(t))) \\ &+ K_v(v_{i-1}(t) - v_i(t)) + K_a a_{i-1}(t) \end{aligned} \tag{3}$$

where $a_{i-1}(t)$ is the actual acceleration of truck *i*-1. $h_i(t) = x_{i-1}(t) - x_i(t) - L$ is the inter-vehicle gap that between the rear bumper of preceding truck *i*-1 and the front bumper of following truck *i*. K_o, K_p, K_v, K_a are the sensitivity coefficients. *L* is the length of truck. In particular, $V(\bullet)$ is a range policy that represents car-following behavior, which contributes to avoid negative velocity and negative inter-vehicle gap. It is shown as follows [25]:

$$V(h_i(t)) = \begin{cases} 0, & if\ h_i(t) \le h_{st} \\ \dfrac{v_{\max}}{h_{go} - h_{st}}(h_i(t) - h_{st}), & if\ h_{st} < h_i(t) < h_{go} \\ v_{\max}, & if\ h_i(t) \ge h_{go} \end{cases} \tag{4}$$

where h_{st} and h_{go} are the allowed minimum and maximum inter-vehicle gap, respectively. $v_{\max}$ is the allowed maximum velocity. The optimal velocity is zero when the inter-vehicle gap between the preceding truck *i*-1 and the following truck *i* at time *t* satisfies $h_i(t) \le h_{st}$. The optimal velocity equal to the velocity limitation $v_{\max}$ when the inter-vehicle gap satisfies $h_i(t) \ge h_{go}$. Between these, the optimal velocity is a monotone increasing function with the inter-vehicle gap linearly.

3.5 Control Objectives

The goal of this study is to achieve consensus with respect to velocity and inter-vehicle gap for truck platoon, and the mathematical expression is as follows:

$$\begin{aligned} &\lim_{t\to\infty} \| x_{i-1}(t) - x_i(t) - L - (r + h_d v_i(t)) \| = 0 \\ &\lim_{t\to\infty} \| v_{i-1}(t) - v_i(t) \| = 0 \end{aligned} \tag{5}$$

4 STABILITY ANALYSIS

In this section, this study focuses on the two kinds of stability: plant stability and string stability. A platoon is a plant stable if all vehicles can asymptotically approach the same constant velocity as the leader vehicle. Further, a platoon is a string stable if the fluctuations are not amplified when propagating along the vehicle string [25, 26].

4.1 Plant Stability

The plant stability can be guaranteed by ensuring that all the eigenvalues of the closed-loop system are located in the left half complex plane [25, 26]. From the uniform flow theory, we have

$$\begin{aligned} &h_i(t) = h^* \\ &v_i(t) = v^* = V(h^*) \end{aligned} \tag{6}$$

for *i*=1, 2, … , n, where v^* and h^* are equilibrium velocity and inter-vehicle gap respectively.

We define inter-vehicle gap perturbations $\tilde{h}_i(t) = h_i(t) - h^*$ and the velocity perturbations $\tilde{v}_i(t) = v_i(t) - v^*$. By algebraic manipulation for (3) and (6), one derives that:

$$\begin{aligned} \dot{\tilde{v}}_i(t) =& K_o(\dot{V}(h^*)\tilde{h}_i(t) - \tilde{v}_i(t)) \\ &+ K_p(\tilde{h}_i(t) - h_d\tilde{v}_i(t)) \\ &+ K_v(\tilde{v}_{i-1}(t) - \tilde{v}_i(t)) + K_a\dot{\tilde{v}}_{i-1}(t) \end{aligned} \tag{7}$$

Definition of $\tilde{V}_i(s)$ denote the Laplace transform of $\tilde{v}_i(t)$ at time *t*, and the above formula is changed to the following expression after Laplace transforming:

$$\begin{aligned} s\tilde{V}_i(s) =& K_o(\dot{V}(h^*)\frac{\tilde{V}_{i-1}(s) - \tilde{V}_i(s)}{s} - \tilde{V}_i(s)) \\ &+ K_p(\frac{\tilde{V}_{i-1}(s) - \tilde{V}_i(s)}{s} - h_d\tilde{V}_i(s)) \\ &+ K_v(\tilde{V}_{i-1}(s) - \tilde{V}_i(s)) + K_a s\tilde{V}_{i-1}(s) \end{aligned} \tag{8}$$

Then the transfer function is defined as follows:

$$\begin{aligned} G(s) &= \frac{\tilde{V}_i(s)}{\tilde{V}_{i-1}(s)} \\ &= \frac{K_a s^2 + K_v s + K_o\dot{V}(h^*) + K_p}{s^2 + (K_o + K_p h_d + K_v)s + K_o\dot{V}(h^*) + K_p} \end{aligned} \tag{9}$$

To guarantee plant stability, all eigenvalues of $G(s)$ must be located in the left half complex plane. According to the Routh-Hurwitz stability criterion, we have

$$K_o + K_p h_d + K_v > 0,\ K_o\dot{V}(h^*) + K_p > 0 \tag{10}$$

That is, when (10) is satisfied by choosing suitable gain K_o, K_p, K_v, K_a , plant stability can be guaranteed.

4.2 String Stability

The string stability can be guaranteed by ensuring that the output-input amplitude ratio stays below one for all excitation frequencies [27]. To ensure string stability, replacing s by $j\omega$ in (9), and it should satisfy [18, 27]:

$$|G(j\omega)| = \left|\frac{\tilde{V}_i(j\omega)}{\tilde{V}_{i-1}(j\omega)}\right| \le 1, \ \forall \omega > 0 \tag{11}$$

Since string stability is broken when the maximum of $|G(j\omega)|$ is greater than one, the string stability boundary is given by the following formula:

$$|G(j\omega_c)| = 1, \ \frac{\partial |G(j\omega_c)|}{\partial \omega_c} = 0, \ \frac{\partial^2 |G(j\omega_c)|}{\partial \omega_c^2} < 0 \tag{12}$$

The above expression ensures that the amplitude of G is decreases from one when $\omega > 0$. Where ω_c is the location of the maximum of $|G(j\omega)|$. From (11, 12) we have

$$\begin{gathered} 2(K_o\dot{V}(h^*) + K_p) < \frac{(K_o + h_d K_p)(K_o + h_d K_p + 2K_v)}{1 - K_a} \\ -1 < K_a < 1 \end{gathered} \tag{13}$$

when (13) is satisfied by choosing suitable gain K_o, K_p, K_v, K_a, string stability can be guaranteed.

5 VERIFICATION AND SIMULATION

In this section, truck platoon control experiments is conducted in PreScan to verify the effectiveness of the designed distributed longitudinal controller. For this purpose, we test the performance of the designed controller in the highway scenario using a five-truck platoon consisting of one leader and four followers. Moreover, to observe the real-time states of every truck in the platoon during the simulation process, we develop a GUI for truck platoon control.

5.1 Experiment Scenario

An experiment scenario for truck platoon control is built in PreScan as shown in Fig. 3. The road network of this experiment is a highway with a length of one kilometer and a lane width of 3.75 meters.

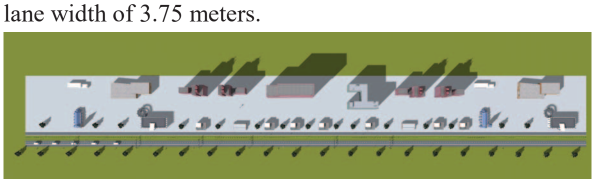

Fig 3. Experiment scenario in PreScan.

Fig 4. Initial state of truck platoon.

5.2 Simulation Setting

In this study, the sampling interval is set as 0.05s. In order to verify the effectiveness of the designed controller, we assume that at the initial moment, the inter-vehicle gap and velocity are inconsistent, which means that the five trucks are moves independently at this time, as shown in Fig. 4.

When the simulation starts, the first truck in Fig. 4 as the leader, and the other trucks as followers. Under the command of the platoon controller, five trucks will achieve the goal of truck platoon. The velocity of the leader is set as follows:

$$v_0(t) = 20m/s, \ t \ge 0s \tag{14}$$

thus the desired inter-vehicle gap is 25 meters. The initial states of trucks are shown in Table 1. To ensure the plant stability and string stability, the relevant control parameters are shown in Table 2.

Table1. The Initial States of Trucks

Truck Index	Position(m)	Velocity(m/s)
Truck 0	164.92	20.00
Truck 1	125.93	22.22
Truck 2	89.93	20.83
Truck 3	55.94	18.61
Truck 4	23.45	16.67

Table2. Control Parameters in the Experiment

Parameter	Value	Unit
K_o	0.2	s^{-1}
K_p	0.4	s^{-2}
K_v	0.8	s^{-1}
K_a	0.5	-
v_{max}	30	m/s
h_{st}	5	m
h_{go}	35	m
h_d	1	s
r	5	m
L	9.99	m

Table3. Meaning of the key information in GUI

Text	Meaning
P./Cont.(Pause/Continue)	Control the progress of simulation.
Acc.(Acceleration)	The acceleration of truck.
I.V.G.(Inter-vehicle Gap)	The inter-vehicle gap of follower.
S.E.(Spacing Error)	The spacing error of follower.
D.V.(Desired Velocity)	The desired velocity of platoon.
D.I.V.G.(Desired Inter-vehicle Gap)	The desired inter-vehicle gap of platoon.

5.3 Result Analysis

When running truck platoon control experiment, the first truck as a leader moves at a constant velocity. Meanwhile, every following truck will receive information (position, velocity, acceleration) of the immediately preceding truck to adjust their state to achieve the same velocity and inter-vehicle gap. Eventually, all the trucks reach a consistent state under the command of the designed platoon controller, as shown in Fig. 5. In particular, in Fig. 5, the upper part is a 3D visual experiment scenario, and the lower part is the GUI for truck platoon control. The GUI is developed by the s-function in Matlab, and the functions is monitoring the state of truck platoon and controlling simulation experimental progress. The details are illustrated as follows.

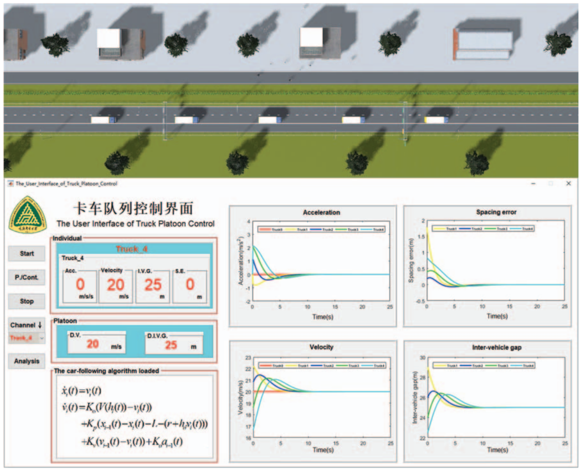

Fig 5. The stable traveling state of truck platoon.

The left side of the GUI is the button area. The middle part is the real-time information display area meanwhile the bottom can display loaded kinematic model of truck and control algorithm of truck platoon. The right part is the dynamic curve display area. In particular, the channel button can change the information displayed in individual area. The analysis button is used to analyze the data of each truck or whole truck platoon after the end of the simulation experiment. Note that some text boxes are described in shorthand, which is illustrated as in Table 3.

After the end of the simulation experiment, clicking the analysis button to get the simulation results, as shown in Figs. 6, 7, 8 and 9. Based on Fig. 6, we can observe that the velocity of all the followers has converged to 20 m/s at t=10s and then keep the movement with this velocity following the leader. Meanwhile, the inter-vehicle gap of all the followers has converged to 25 meters as shown in Fig. 7. Based on the results from Figs. 6 and 7, it show that all the followers have achieved consensus with respect to velocity and inter-vehicle gap.

Fig. 8 shows the acceleration profile of truck platoon. We can observe that the maximum acceleration and deceleration of the following truck are about 2.1 m/s^2 and -0.7 m/s^2. Then, the acceleration of all the followers converge gradually to zero and keep it, which implies that truck platoon has reached a stable state. The spacing error also converges to zero at t=10s, as shown in Fig. 9. It represents that all the followers have reached the desired inter-vehicle gap.

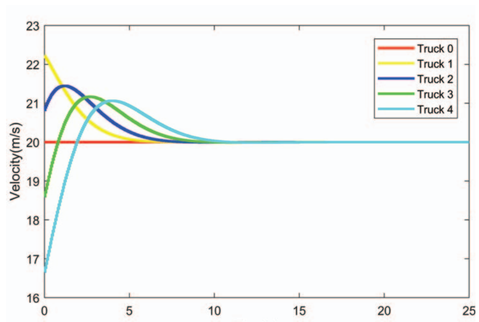

Fig 6. Velocity profile.

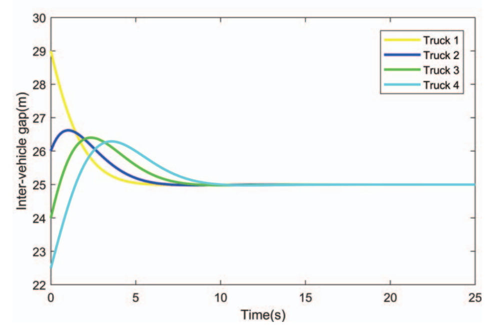

Fig 7. Inter-vehicle gap profile.

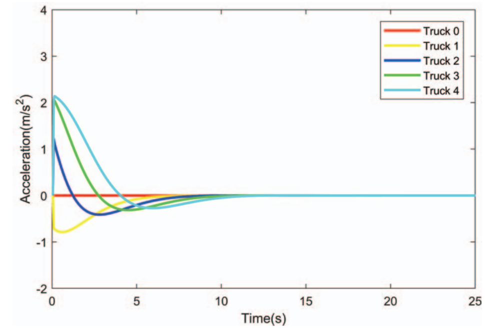

Fig 8. Acceleration profile.

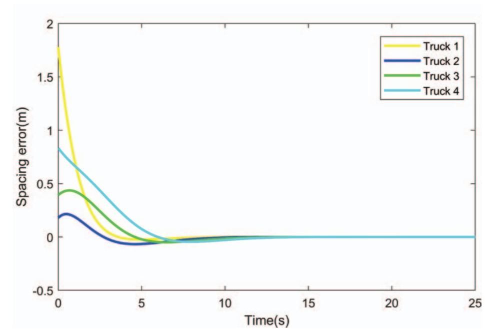

Fig 9. Spacing error profile.

From the simulation results, all the followers have reached the desired velocity (20 m/s) and desired inter-vehicle gap (25 meters) after a brief adjustment and without occur unreasonable negative velocity, negative inter-vehicle gap, achieving consensus with respect to velocity and inter-vehicle gap. It is verified that the favorable performance of the platoon controller designed in this study.

6 CONCLUSION

In this study, first, we illustrate a general development framework of connected truck platoon control based on PreScan. Second, considering the benefits of acceleration feedforward control and car-following behavior, this study designs a new distributed longitudinal controller for a truck platoon. Lastly, this study conducts truck platoon control experiments in PreScan. The results in terms of velocity, acceleration, and spacing error profiles show that all the following trucks achieve consensus with respect to velocity and inter-vehicle gap without unreasonable negative velocity and negative inter-vehicle gap, which demonstrates the effectiveness of the platoon controller designed in this study.

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