Longitudinal Control of a Platoon of Road Vehicles Equipped with Adaptive Cruise Control System

ZEESHAN ALI MEMON*, SALEH JUMANI*, AND JAVED LARIK**

RECEIVED ON 20.02.2012 ACCEPTED ON 21.06.2012

ABSTRACT

Automotive vehicle following systems are essential for the design of automated highway system. The problem associated with the automatic vehicle following system is the string stability of the platoon of vehicles, i.e. the problem of uniform velocity and spacing errors propagation. Different control algorithm for the longitudinal control of a platoon are discussed based on different spacing policies, communication link among the vehicles of a platoon, and the performance of a platoon have been analysed in the presence of disturbance (noise) and parametric uncertainties. This paper presented the PID (Proportional Integral Derivative) feedback control algorithm for the longitudinal control of a platoon in the presence of noise signal and investigates the performance of platoon under the influence of sudden acceleration and braking in severe conditions. This model has been applied on 6 vehicles moving in a platoon. The platoon has been analysed to retain the uniform velocity and safe spacing among the vehicles. The limitations of PID control algorithm have been discussed and the alternate methods have been suggested. Model simulations, in comparison with the literature, are also presented.

Key Words: **Longitudinal Control, Vehicle Following, String Stability, PID Control.**

1. INTRODUCTION

Control problems arising from the automatic vehicle following system have been receiving increasing attention, due to requirements for high safety and traffic capacity. Decreasing inter-vehicular spacing is the major way to increase highway capacity. There are several approaches that can be used to increase the traffic flow. Among them, platooning is one of these approaches that has acquired much attention in last two decades. A platoon (automatic vehicle following system) can be defined as a group of vehicles travelling together with relatively small spacing to improve the capacity and to minimize the relative velocity of the vehicles in case of emergency. The stable behaviour of a platoon can be achieved if the individual vehicle stability and string stability of the platoon are ensured. In the literature, most of the researchers have discussed the steady state operation of a platoon based on different spacing policies, communication link between the lead vehicle and the following vehicles, in the presence of parametric uncertainties and the control system accuracy in the presence of noise signal in the measurement. Some researchers have designed the adaptive controller for automatic vehicle following system. Among them, only a few researchers analysed the behaviour of platoon under

* Assistant Professor, and ** Lecturer,
Department of Mechanical Engineering, Mehran University of Engineering & Technology Jamshoro.

the severe extreme condition, e.g. how the platoon will behave if the lead vehicle encounters an accident or if any of the following vehicle have the similar situation (tyre burst). The problem associated with such a situation is the control of the braking force with a maximum possible deceleration so it should not cause a collision of the vehicles in the platoon.

The purpose of this study is to investigate the performance a platoon with different control strategies under different spacing policies, communication link among the vehicles, performance of a platoon in the presence of disturbance and large acceleration/deceleration variations so it could be decided that which control strategy should be adapted for further research.

The control strategies adapted in the literature are:

(1) Constant spacing control strategies [4].

(2) Variable spacing control strategies (constant headway) [10-12, 8].

(3) Hybrid strategies [8].

(4) Global communication among the vehicles [17].

(5) Local communication among the vehicles [10,12].

(6) Platoon performance in the presence of noise signal [9,18].

(7) Platoon performance when large accelerations are applied [16].

(8) Platoon performance when large decelerations are applied [18].

(9) Effect of parametric uncertainties on the platoon performance [7,17].

The advantage of this study is to investigate the behaviour of the following vehicles if a large acceleration or deceleration is applied to lead vehicle due to accident or any other reason. How quickly and safely the following vehicle should decelerate to come in rest position avoiding the collision and then continue the operation?

There are mainly two types of controllers for a platoon; longitudinal control, which deals with the spacing regulation without considering the steering, and the lateral control, which controls the steering of the vehicle to keep it in lane. This study focuses only on longitudinal control of the platoon of vehicles, i.e. the vehicles are moving in a straight line.

In the literature, Peppard [1] designed a model for the string stability of relative-motion based on the PID feedback control algorithm for an individual vehicle which uses the velocity error of that vehicle from a specified value and its distance error to the vehicle ahead and vehicle behind it and a constant spacing policy has been adapted. Peppard [1] did not consider the measurement error propagation towards to the tail of the platoon instead, Peppard [1] investigated the relative-motion stability of the platoon and his model disregarded the actuation and sensing lags of the system operations. One drawback of the PID controller is, if the controlled model is nonlinear and if the initial condition changes then it will be necessary to retune the controller gains in order to keep the desired performance. As the technology advanced in the platoon dynamics control systems, PID controllers were modified and replaced by advanced controllers. The widely used controllers in the literature are adaptive controllers, sliding mode controllers, predictive controllers, switching mode controllers, transitional controllers and so on. An adaptive controller is a controller with adjustable parameters and a mechanism for adjusting parameters [2]. Swaroop, et. al. [3] presented a mathematical definition for string stability where string stability requires the uniform boundedness on the system states if the initial conditions are uniformly bounded. They have also introduced the l_p-string stability and produced the satisfactory results for l_2-string stability which is a weaker property than string stability. Swaroop, et. al. [4] have also debated on performances of a platoon based on different spacing strategies and the information available for the controlled vehicle. They have presented different control algorithms using the constant and variable spacing control strategies with the information of reference vehicle, lead vehicle and preceding vehicle to the controlled vehicle. Based on all the above discussion Swaroop, et. al. [4] designed a decentralized controller which is based on constant spacing policy and uses the information of vehicles in front of the controlled vehicle for vehicle following control algorithm. They discussed the limitation and problems associated with other control strategies. The control strategies they discussed are; the autonomous control, semi-autonomous control, controller with the information of the reference vehicle only, controller with the information of lead vehicle and preceding vehicle, semi-autonomous control with vehicle ID knowledge, controller with information of only "*r*" immediately preceding vehicles, mini-platoon control strategy, mini-platoon control with lead vehicle information. They argued that the control algorithms which do not use the lead vehicle information result in the weak string stability. Also these controllers are not robust to signal processing lags and actuator lags and suggested that, it is necessary to have single reference (lead) vehicle information for constant spacing vehicle following systems. However, the reference (lead) vehicle information can be obtained at the cost of communication load which results in time delays.

Huang, et. al. [5] introduced a control theorem for merging and splitting of the vehicle platoon with other platoon based on safe velocity profile. They have used the relative distance, relative velocity and relative acceleration between the platoons and the same approach is used in this study for a member vehicle of the platoon. Kato, et al. [6] have proposed the model which uses the current speed of the preceding vehicle as an input for the following vehicle. They use the longitudinal velocity as the control input; tracking the maximum acceleration and deceleration coupled with road geometry and adapt the real-time data transmission characteristics for the inter-vehicle communication control.

Yi, et. al. [7] designed an impedance control system which uses serial chain of spring-damper to generate the link between the vehicles. The lead vehicle's information propagates to the following vehicles through the elasticity of the spring-damper. The spring-damper is a force control strategy to minimize the effects of forces exerted from uncertain environment. Although their model is stable in the presence of noise and parametric uncertainties but it lacks the situation when high acceleration and deceleration are applied to any one of the platoon vehicle. Girard, et al., [8] have tested ACC (Adaptive Cruise Control) and CACC (Cooperative Adaptive Cruise Control) systems using real-time, embedded, hybrid control software while tracking the speed profile and vehicle following applications for passenger vehicles. Girard, et al., [8] designed the controller as a function of spacing error, derivative of error and/or integral of errors. Martinez, et. al. [9] proposed a non-linear model with simple feedback loop to compensate the un-modelled dynamics and external disturbances and uses the acceleration signal of the lead vehicle to maintain the safe distance among vehicles.

Different performance criterions for a platoon of vehicle have been discussed in literature. Many researchers have designed a control law based on sliding mode technique [8,10-12]. In the literature, much effort has been made on developing various platoon-stable control schemes based on different spacing policies. Canudas, et. al. [13] have discussed linear control strategies, based on inter-vehicle spacing policy, for the string stability of the platoon of vehicles. They analysed that for unidirectional operation, a platoon will be string unstable if constant spacing policy is used and designed a stable controller with speed-dependent inter-vehicle spacing which ensures the string stability of the platoon of vehicles. [10] has presented a decentralized adaptive control algorithm for a platoon of vehicles which is based on constant spacing policy. For the constant spacing policy the desired inter-vehicle distance is independent of the velocity of the controlled vehicle.

Rajamani [11] argues that the constant spacing policy is unsuitable for autonomous control applications and defines the inter-vehicle spacing as shown in Fig. 1:

$$\varepsilon_i = x_i - x_i-1 + l_i-1 \qquad (1)$$

Where x_i and x_{i-1} are the distances of the ith vehicle (under observation) and the preceding vehicle (the leader vehicle) from the reference point and l_{i-1} is the length of the preceding vehicle. is the distance between the two consecutive vehicles. It is clear from Equation (1) that every following vehicle in the platoon used the information of its preceding vehicle. This inter-vehicle distance is likely to change when lead vehicle accelerates of decelerates and it is compared with the desired distance to generate an error signal which is termed as spacing error. Where under the constant spacing policy, the spacing error of the i^{th} vehicle is then defined as:

$$\delta_i = x_i - x_{i-1} + L_{des} \qquad (2)$$

Where L_{des} is the desired constant value of inter-vehicle spacing and includes the preceding vehicle length l_{i-1}. With only the preceding vehicle information available for the controlled vehicle and using the constant spacing

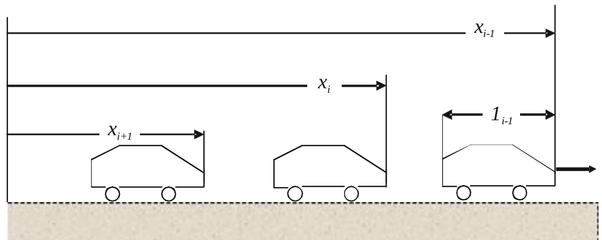


FIG. 1. STRING OF ADAPTIVE CRUISE CONTROL VEHICLES

policy, it is impossible to attain the string stability of a platoon as discussed by Rajamani [11]. The desired inter-vehicle spacing (L_{des}) should not be constant.

Most of the researchers [8-9,11-12,14-16] have used the speed-dependent inter-vehicle spacing policy (constant headway policy), where the desired inter-vehicle spacing (L_{des}) is not constant but varies linearly with velocity, which guarantees the string stability of a platoon of vehicles. Martinez, et. al. [9] proposed that for constant headway policy, the velocities of the vehicles during braking manoeuvre must be equal. For constant headway policy the desired inter-vehicle spacing (L_{des}) varies with velocity and is defined as:

$$L_{des} = l_{i-1} + h\dot{x}_i \qquad (3)$$

Where h is the constant headway time, h>0.

For the constant headway policy, the spacing error is then defined as:

$$\delta_i = \varepsilon_i + h\dot{x}_i \qquad (4)$$

where $\varepsilon_i = x_i - x_{i-1} + l_{i-1}$ as defined earlier in Equation (1).

Communication link from a lead vehicle to each individual vehicle is needed for platoons with constant spacing policy or speed-dependent inter-vehicle spacing policy (constant headway policy). Global communication network, wirelessly linking the vehicles, uses the highway infrastructure to transmit the lead vehicle information to the following vehicles at the cost of introducing and maintaining continuous inter-vehicle communication [17]. On the contrary, local/decentralized communication network links the predecessor and follower vehicles if the speed-dependent spacing policy or constant spacing policy is adapted, where the vehicle (under observation) uses the relative information of the lead vehicle's position, velocity and acceleration [7,10,12,14] based on feedback linearization. Global communication link, due to setting the link between the lead vehicle and the following vehicle through the highway infrastructure, can be avoided by using the local communication network. Global communication network causes the noise in the measurement and inaccuracies in the performance of the platoon and increases the cost of the operation.

In the literature, research work has been focused on the effects of parametric uncertainties on the performance of the platoon. Shladover [17] has analysed the behaviour of controller in the presence of uncertainties in mass, aerodynamic drag coefficient, and rolling resistance. In addition of that, Shladover [17] has focused on the effects of severe manoeuvres, rapid changes in acceleration and jerks, measurement noise and different vehicle propulsion dynamics (due to less responsive power-train and dynamics of internal combustion engine which include both first-order and transport lags). Shladover [17] suggested that the existing controller should be modified to compensate the effects of the above parametric uncertainties. Swaroop, et. al. [10] has investigated the effect of uncertainties in mass of the vehicle, aerodynamic drag coefficient, rolling resistance, and their combined effect on the performance of a platoon. Their controller design is based on simplified model which does not take account of the states associated with torque converter, manifold air dynamics, slip between the tire and the wheels, and the lag in delivering the desired brake torque. Their analysis shows that the estimated parameters do not converge to their true values because they have neglected the above state variables in their controller model. There is enough room to improve the stability of a platoon under these parametric uncertainties coupled with the above state variables effects in the controller design. Yi, et. al. [7] proposed the impedance control algorithm, which is quite efficient and stable, and shows the robustness and stability of the vehicle platoon performance against the uncertainties in vehicle model parameters and the noise in the measurement signals. Sun et. al. [16] have estimated the parameters for the vehicles which can improve the string stability of the platoon and have discussed the parametric uncertainties due to varying road conditions like weather changes or road gradients. This may seriously affect the performance of the platoon. Their designed controller maintains the desired performance under the influence of parametric uncertainties. Their designed model only simulates the behaviour of platoon for the steady state operation but does not analyse the platoon in the emergency condition. Also, they have designed the controller for fixed parametric values but if the vehicle parameter change, as the mass of the vehicle is variable with the number of passengers, the aerodynamic drag coefficient could be different and the important thing is the severe weather condition like heavy rain. Their model is not suitable for these variable conditions. There is room for designing a controller which can cope with large changes in these parameters. Canudas, et. al. [13] referred the problem of designing safe controllers for the internal dynamics of the platoon as the objective for future work.

This paper presents a control law, based on PID feedback control algorithm, for a constant inter-vehicle spacing of the vehicles of the platoon and investigates the effects of noise signal and sudden acceleration and braking in severe conditions on the performance of the platoon.

The paper is organised as follows. In Section 2 ACC system with its performance limitations are discussed and the stability conditions for individual vehicle stability and string stability of the platoon are discussed. Section 3 presents a simple longitudinal dynamics model for a member vehicle of the platoon and introduces a control law for lead vehicle. Performance of lead vehicle under the influence of noise signal is also shown in this section. Section 4 presents the control law for follower vehicle and investigates the behaviour of 2-vehicle and 6-vehicle platoons in the presence of noise signal and large acceleration and deceleration. Section 5 discusses the simulation results. Section 6 provides the conclusions and Section 7 highlights the directions for future research.

2. ACC SYSTEM AND ITS PERFORMANCE LIMITATIONS

An ACC system is the modified form of a standard cruise control system. A cruise control system is used for the speed control of a vehicle when the driver sets the vehicle at desired speed and vehicle travel under the cruise control system. As the brake is applied the cruise control is disconnected and control comes back in the driver control. An ACC vehicle is equipped with radar or any other sensor to measure the distance from the preceding vehicle. When there is no preceding vehicle, ACC vehicle moves with the user set speed and when it detects a preceding vehicle, ACC vehicle follows the preceding vehicle while tracking the velocity trajectory of preceding vehicle and maintaining a safe distance from preceding vehicle. ACC vehicle does not require any wireless communication from other vehicles on the highway, it just reads the information of the relative displacement, relative velocity and relative acceleration of the preceding vehicle through the sensor or radar. ACC is an autonomous system.

ACC vehicle has two modes of steady state operation.

(1) Speed control

(2) Vehicle following control (space control)

In the speed control mode, much like a cruise control system, ACC vehicle travels at user set speed. In the vehicle following mode, ACC vehicle maintains a desired spacing from the preceding vehicle. ACC control the throttle and brake to maintain that desired distance. This section mainly discusses the vehicle following mode of the ACC system and the need for transition trajectories for the smooth transition from speed control mode to vehicle following mode and vice-versa. The vehicle following mode must meet the two important performance criterions. The performance criterions are the individual vehicle stability and the string stability of the platoon.

2.1 Individual Vehicle Stability

Individual vehicle stability is the ability of any member vehicle in the platoon to track any bounded acceleration and velocity profile of its predecessor with bounded spacing and velocity errors [11].

2.2 String Stability

String stability of a string of vehicles refers to a property in which spacing errors are guaranteed not to amplify as they propagate towards the tail of the string [10,11,15,16]. It is desired that the errors in spacing and velocity must not amplify upstream from one vehicle to another, i.e. spacing error between second and third vehicle should not propagate to other member vehicles and so on. String stability ensures that spacing error decreases as they propagate downstream through the platoon [12]. When the preceding vehicle accelerates or decelerates then the spacing error would become non-zero, it is essential then to know that how the spacing error would propagate from vehicle to vehicle in a string of ACC vehicles that use the same spacing policy and control law. It is important for the string stability that the spacing errors of successive vehicles should be independent of each other [11].

ACC is an autonomous control strategy. When a constant spacing policy is adapted, ACC vehicle satisfies the individual vehicle stability condition but the string stability condition is not satisfied with constant spacing policy. Rajamani [11] has analysed that the constant spacing policy is unsuitable for autonomous control operations. Therefore, a constant time-gap (constant headway) policy should be adapted for ACC systems where the desired inter-vehicle distance is not constant but varies linearly with ACC vehicle velocity.

Consider the situation when the ACC vehicle operates under the speed control mode and it detects a slow or decelerating target vehicle ahead of it. ACC vehicle will accelerate first to get to the desired distance and by the time ACC vehicle will acquire the high acceleration while the target vehicle is decelerating. As the ACC vehicle reaches the desired distance quickly and decides to decelerate when the actual distance is less than the desired distance. At this moment, even the maximum braking force is applied, it will be difficult to avoid the collision. Therefore, a transitional trajectory [11] must be designed for the steady state following distance during the transition from speed control mode to vehicle following mode and vice-versa.

The main reasons for the transition trajectory are:

(1) To avoid/prevent collision.

(2) The brake and engine actuators have limited allowable forces and they saturate.

(3) Whether a new detected vehicle should always be the target vehicle for ACC vehicle or not.

When a new vehicle is encountered, then the ACC vehicle has to decide:

(1) The ACC vehicle should use the speed control mode.

(2) The ACC vehicle should use the vehicle following mode.

(3) The ACC vehicle should brake as hard as possible to prevent collision.

For the transitional controller design, a range-rang rate can be used to make the above decisions [11]. The manoeuvres controlled by transitional controller do not affect the string stability of the platoon. They only control the lead vehicle, the rest of the platoon follow the same control law to maintain the string stability.

3. A SIMPLE MODEL OF A MEMBER-VEHICLE OF THE PLATOON

A platoon, consists of 6 vehicles, has been considered in this study. All the vehicles are controlled in the sense that their longitudinal speeds and longitudinal positions are determined by the controller. It is assumed that all the vehicles of the platoon are identical for the simplicity. A longitudinal dynamics model [11]. Fig. 2 can be adapted to a give sufficiently accurate representation of the longitudinal dynamics of a member vehicle in the platoon.

$$m\ddot{x} = F_x - F_{aero} - mfg - mg\sin(\vartheta_F) \quad (5)$$

where M is mass of the vehicle (kg) , x is displacement (m), F_x is traction force (N), F_{aero} is aerodynamic force (N) = $1/2\rho A_f C_d V^2$, V is vehicle longitudinal velocity (m/s), C_d is aerodynamic drag coefficient (Ns^2/m^2), f is rolling resistance coefficient, A_f is frontal area of the vehicle (m^2), ρ is mass density of air (kg/m^3), and ϑ_F is slope angle (degrees) = 0^o

The analysis will be carried out on the first vehicle, the so-called 'leader vehicle', and then will be extended for the whole platoon of 6 vehicles. In this paper a simple PID feedback control algorithm has been used for the lead

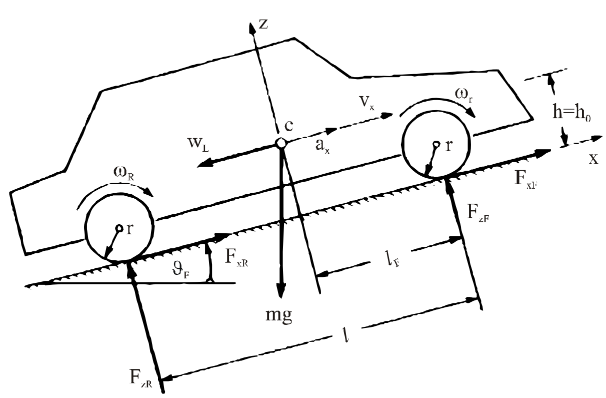


FIG. 2. VEHICLE SUBJECTED TO LONGITUDINAL FORCES AND MOVING ON AN INCLINED ROAD

vehicle, where the only feedback signal is the actual velocity of the lead vehicle. The block diagram for feedback control system is shown in Fig. 3.

The control signal is F_x, the traction force at the contact point between the tire and the ground.

$$F_x = K_p(V_d - V) + K_i\int_0^t (V_d - V)d\tau + K_d\frac{d(V_d - V)}{dt} \quad (6)$$

where V_d=*5 m/s* is the desired velocity of the lead vehicle and K_p=*3000* is the proportional gain, K_i=*800* in the integral gain and K_d=*500* is the derivative gain.

For the design of any controller, it is important to know about the transient and steady state behaviour of the system. The control strategy, PID controller, used for lead vehicle, in Fig. 4 (a-b), shows that the transient behaviour of the lead vehicle dies away quickly with a little oscillation and the lead vehicle attains the steady state position within a short time. This shows the stability in the designed controller.

The simulation is carried out when the lead vehicle is subjected to the noise signal. The possible causes for the noise are gust of air, noise in the measurement signal, uncertainty in the traction force due to time delays, weather condition, actuation lags, sensing lags or any other disturbance. In this study the source of noise is the disturbance in the input force and it is assumed to be 300 N between 25-27 seconds and 400 N between 45-47 seconds as shown in Fig. 5. The controller is quite stable for the lead vehicle in the presence of the noise signal. The desired velocity for the lead vehicle is 5m/s. The

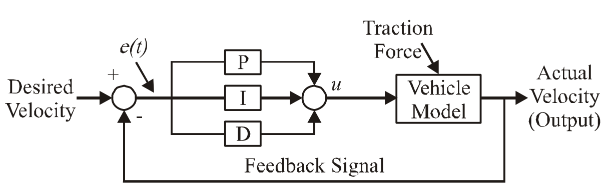


FIG. 3. BLOCK DIAGRAM FOR THE PID FEEDBACK CONTROL SYSTEM

mass of all the vehicles is 1200 kg, aerodynamic drag coefficient is 0.3 and the coefficient of rolling resistance is 0.01.

4. EFFECT OF NOISE SIGNAL AND ACCELERATION VARIATION ON THE PERFORMANCE OF PLATOON

This section discusses the performance of 2-vehicle and 6-vehicle platoon under the influence of noise signal and large acceleration and deceleration. A numerical simulation has been conducted for the designed controller.

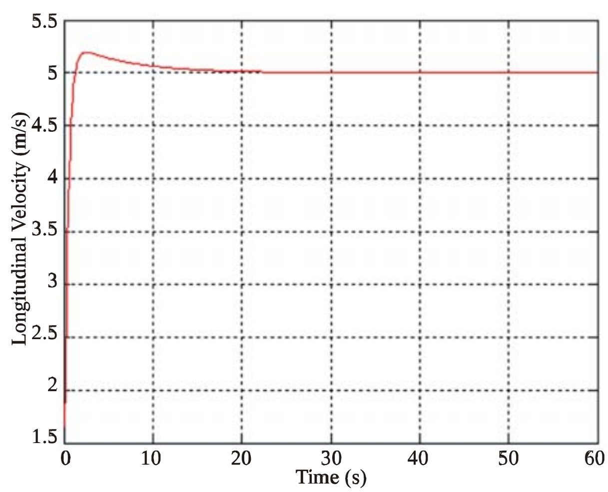


FIG. 4(a). VELOCITY OF THE LEAD VEHICLE

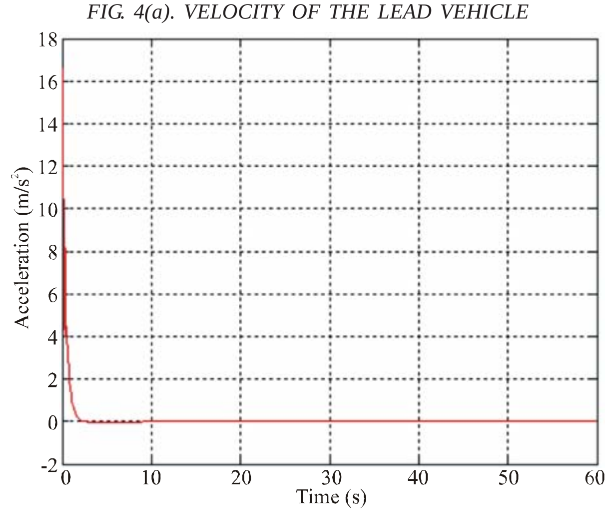


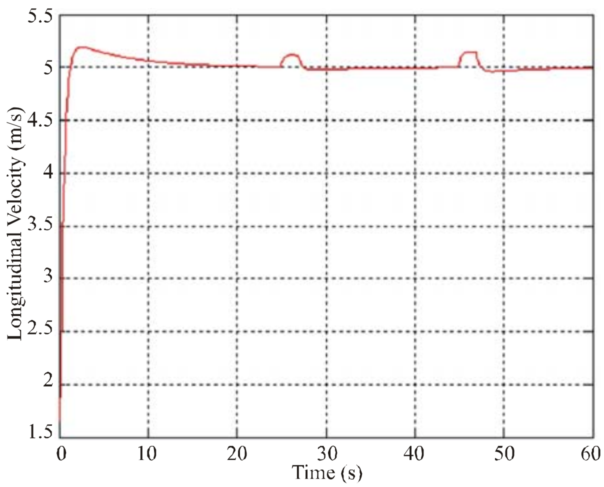
FIG. 4(b). ACCELERATION OF THE LEAD VEHICLE WITHOUT NOISE

This paper uses the position error feedback, velocity error feedback and acceleration error feedback of the preceding vehicle with the following vehicle. The control law for the follower vehicle is given by:

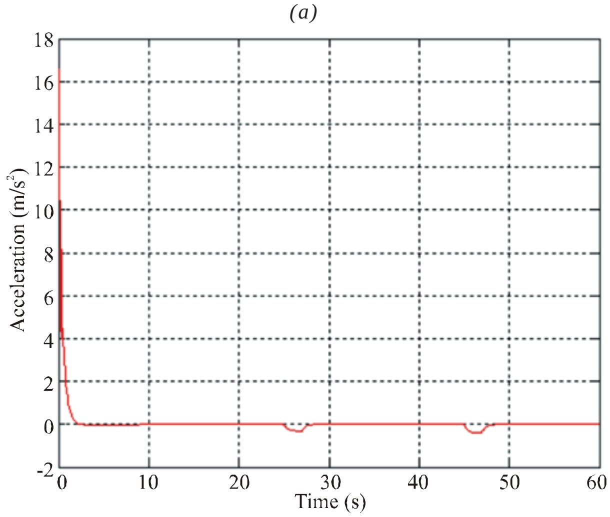
$$u_i = K_1(x_{i-1} - x_i - l_{i-1} - x_{des}) + K_2(\dot{x}_{i-1} - \dot{x}_i) + K_3(\ddot{x}_{i-1} - \ddot{x}_i) \quad (7)$$

where $K_1=400$, $K_2=5000$, and $K_3=200$ are the controller gains, x_{i-1} and x_i are the actual positions of the lead vehicle and the follower vehicle, and $x_{des}=12$ m is the desired relative position between the successive vehicles in the platoon. The designed control law for each following vehicle uses the differences between the state of its predecessor vehicle and the state of that vehicle as the error signal to generate the desired traction force.

The control law for lead vehicle, in Equation (6), and the control law for the follower vehicle, in Equation (7), are different. But the performance of both vehicles is similar in a way that the transient behaviour of the second vehicle vanishes within the same time as for the lead vehicle and they maintain the steady state behaviour for the whole operation, as shown in Fig. 6(b). The interesting behaviour of follower vehicle is, it overshoots for the first few seconds more than the lead vehicle as shown in Fig. 6(b). The same control law, in Equation (7), is used for all follower vehicles.



(a)



(b)

FIG. 5. VELOCITY AND ACCELERATION OF THE LEAD VEHICLE WITH FIXED NOISE

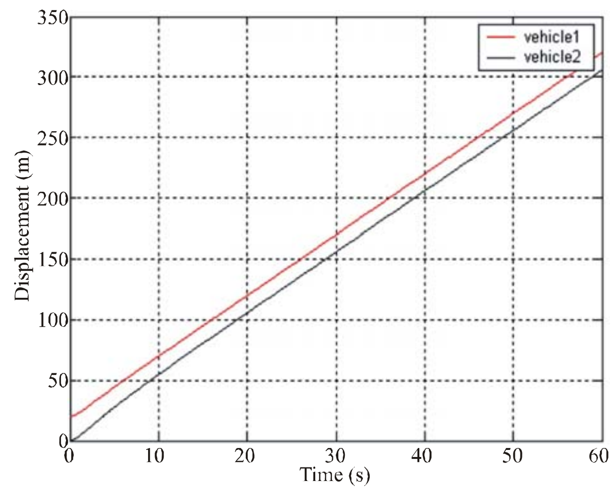


FIG. 6(a). DISPLACEMENT OF THE TWO VEHICLES

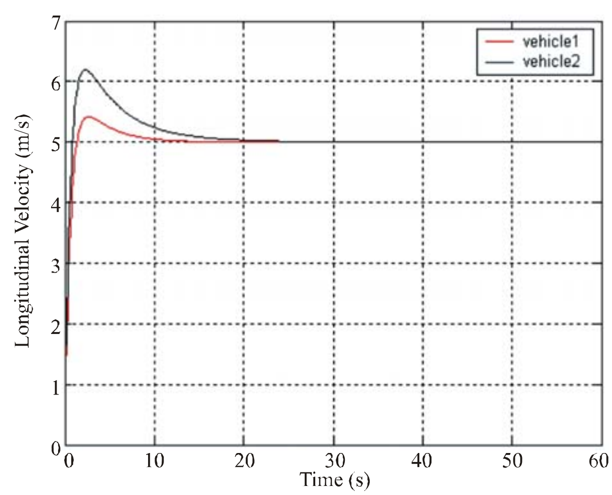


FIG. 6(b). LONGITUDINAL VELOCITIES OF THE TWO VEHICLES

In Fig. 7 both lead and following vehicles, are subjected to noise signal, same magnitude as in Fig. 5, between 25-27 sec and 45-47 sec respectively. It is clear from the Fig. 7 that when lead vehicle is disturbed this affects both vehicles and when the following vehicle is disturbed it does not affect the lead vehicle. This means that the lead vehicle is independent of the following vehicle. Further analysis is carried out in next simulations on six vehicles with fixed noise signal, random noise signal and large acceleration and deceleration.

The six vehicles platoon has been analyzed under different situations. Figs. 8-17 show different case studies for six vehicle platoon and very interesting behaviour of the platoon under the influence of noise, acceleration, and deceleration.

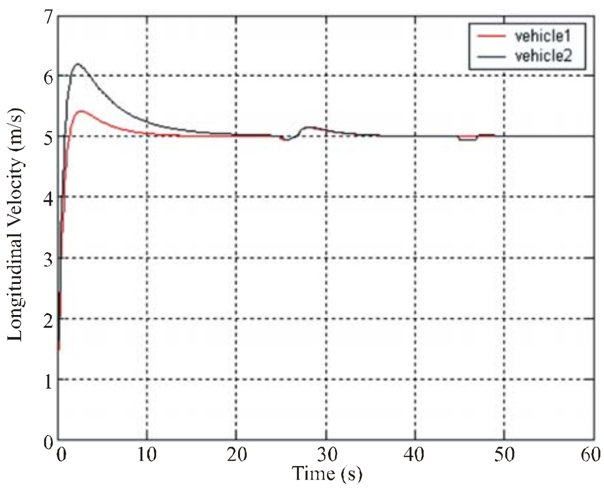


FIG. 7(a). LONGITUDINAL VELOCITIES OF THE TWO VEHICLES

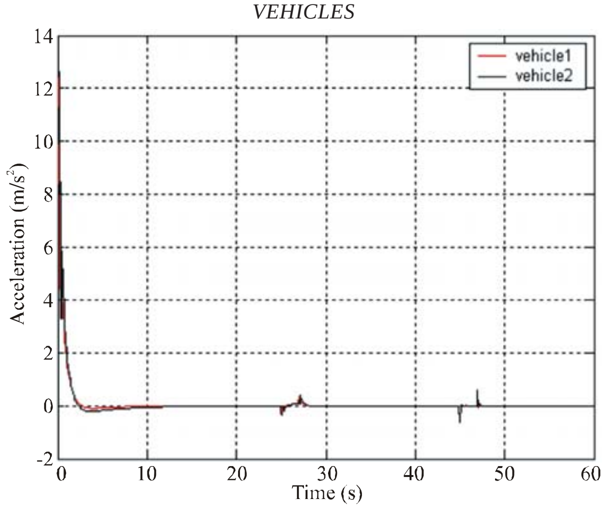


FIG. 7(b). ACCELERATION OF THE TWO VEHICLES, WITH NOISE SIGNAL

Fig. 8 shows the simulation of the six vehicles. The desired velocity for the platoon is 5 m/s and the initial conditions for the vehicles of platoon are, X1=100 , X2=80, X3=60, X4=40, X5=20, and X6=0 m. All the vehicles are 20 m apart. Fig. 8(a) shows that the vehicles are coming closer to maintain the desired distance within the first ten seconds. Fig. 8(b) shows whole platoon acquires the desired velocity within the first 30 seconds; this is due to high acceleration in the first four seconds. The comparison of Fig. 6(b) and Fig. 8(b) shows that each time when a new vehicle is added to the platoon, it accelerates more than the previous vehicle and then decelerates to get the desired velocity.

Fig. 9 shows the effect of fixed noise signal on performance of platoon. The fixed noise means that the fixed amount of noise signal has been introduced at different time steps. As it can be seen from the Fig. 9 the first noise signal was given to lead vehicle at t=25-27 sec, the second noise signal was given to third vehicle at t=45-50 sec and the third noise signal was again given to the lead vehicle at t=70-75 sec. It is clear from the Fig. 9 that first and third noise signals affect the whole platoon as the lead vehicle was disturbed while the second noise signal only disturbs the third vehicle and the whole platoon following the third vehicle. The designed controller shows from the Fig. 9 that it settles down quickly when the noise disturbances were removed.

When the desired velocity of the lead vehicle is 50m/s, which is very high as compared to 5m/s, the platoon shows very high accelerations and large spacing among the vehicles as shown in Fig. 10(b-c). The controller maintains the desired speed of 50m/s and shows similar velocity behaviour as it was with 5m/s as shown in Fig. 10(a). This shows the stability of the proposed controller against the variable desired velocities.

The behaviour of the platoon has been simulated with different initial conditions for the vehicles as shown in the Fig. 11. X1=100, X2=76, X3=62m, X4=40, X5=18 and X6=0m. Under these changes, the platoon shows the stability and coming back to the desired velocity level as shown in Fig. 11(a). All the vehicles take almost the same time to reach the steady state position when compared with uniform initial inter-vehicle distances. This shows the robustness of the proposed controller against these changes. Fig. 11(a) (non-uniform initial inter-vehicle distances) is compared with Fig. 8(b) (uniform initial inter-vehicle distances), it can be seen that vehicle 2 accelerates more in Fig. 11(a) as compared to Fig. 8(b) because vehicle 2 is more distant from vehicle 1, X1-X2=24m. Fig. 12. shows the performance of platoon when lead vehicle is subjected to random noise. In the presence of random noise, the transient and steady-state behaviours of the platoon are hardly affected and the platoon is trying to maintain the desired velocity during the steady-state operation

Fig. 13 shows a very interesting behaviour of the platoon when the brake is applied on the third vehicle for the time span of 35-40 seconds. The brake affects the whole platoon following the third vehicle but it does not affect the first two vehicles. Fig. 13(a) shows that the velocity of the remaining four vehicles is reduced during the same time span and the vehicles decelerate first during the brake and when the brake is removed vehicles accelerate quickly to acquire the required velocity as shown in Fig. 13(b). The spacing among the vehicles increases when the brake is applied but it settles down when the brake is removed as shown in Fig. 13(c). This shows quite stable behaviour of the platoon.

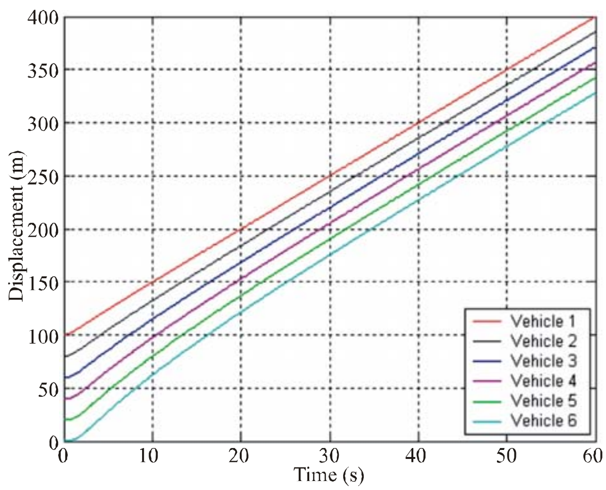


FIG. 8(a). INTER-VEHICLE DISTANCES OF 6 VEHICLES

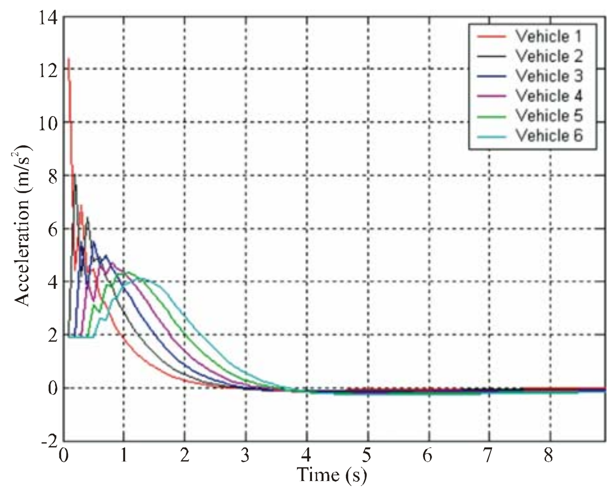


FIG. 8(c). ACCELERATIONS OF 6 VEHICLES

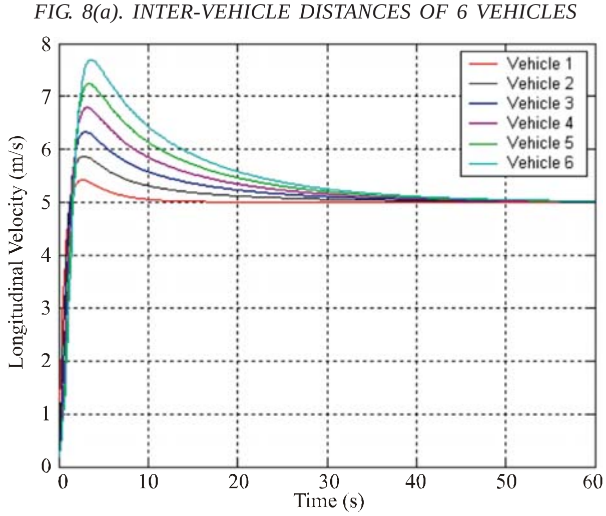


FIG. 8(b). LONGITUDINAL VELOCITIES OF 6 VEHICLES

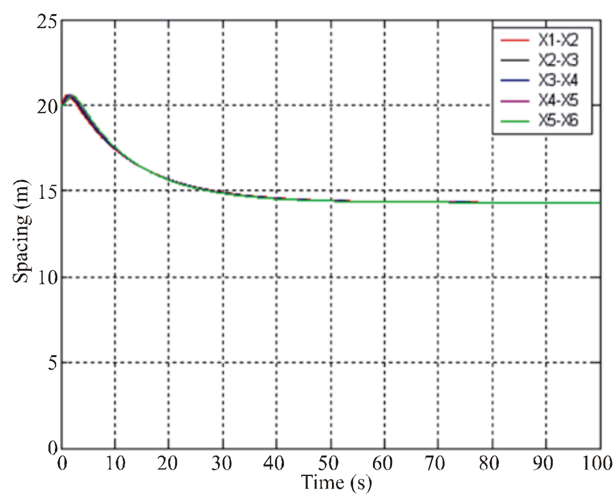


FIG. 8(d). VEHICLES SPACING, WITHOUT NOISE SIGNAL AND UNIFORM SPACING BETWEEN THE VEHICLES

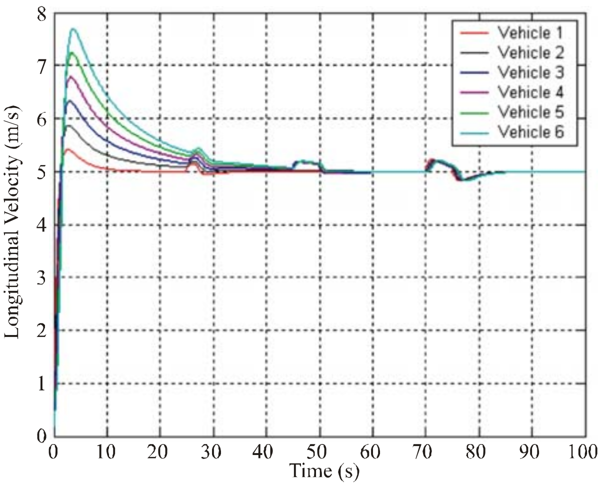


FIG. 9(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

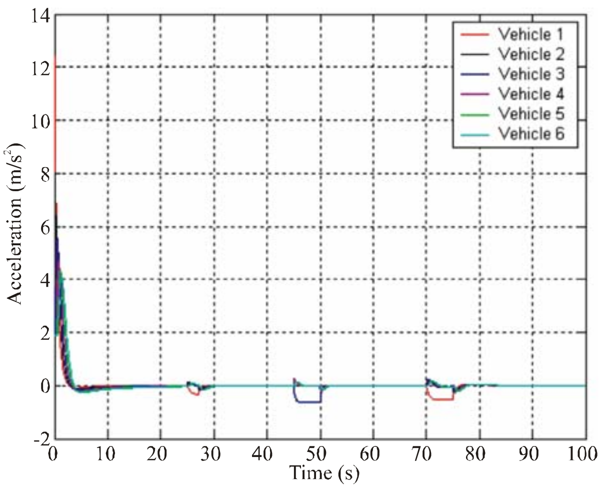


FIG. 9(b). ACCELERATIONS OF 6 VEHICLES

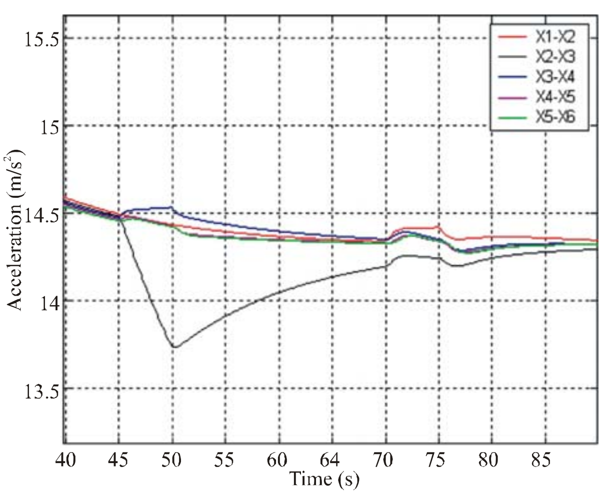


FIG. 9(c). VEHICLES SPACING, WITH FIXED NOISE SIGNAL AND UNIFORM SPACING BETWEEN THE VEHICLES

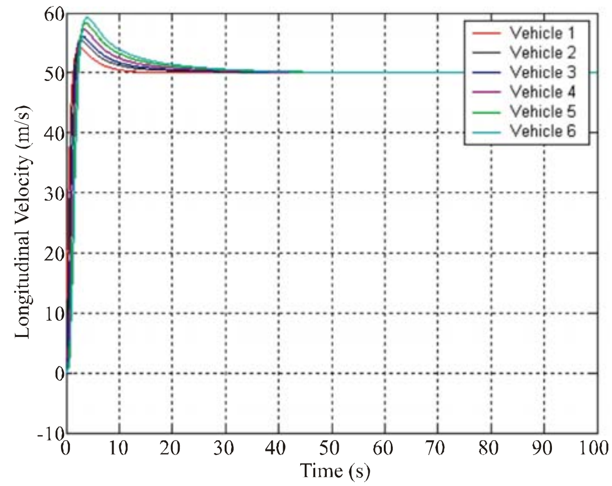


FIG. 10(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

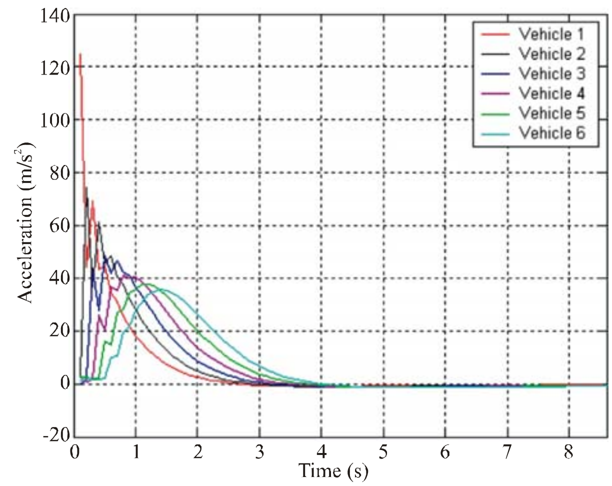


FIG. 10(b). ACCELERATIONS OF 6 VEHICLES

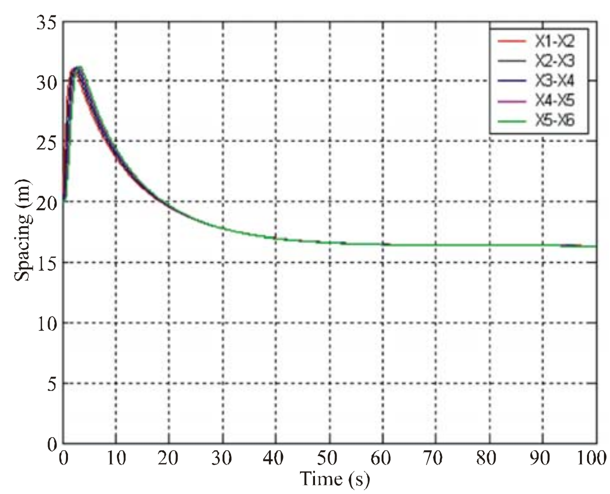


FIG. 10(c). VEHICLES SPACING, AT DESIRED VELOCITY 50m/s AND UNIFORM SPACING BETWEEN THE VEHICLES

One important fact can be seen from the above Fig. 13 that the 4th, 5th, and 6th vehicles do not need the information of the lead vehicle. Each following vehicle uses the information of its preceding vehicle only. Suppose there is large platoon and every following vehicle needs the information of its preceding and lead vehicles then there would be large communication delays of information for the following vehicles in the tail. Therefore, it is worth understanding that any following vehicle should use the information of its preceding vehicle only or the information of its preceding vehicle and its following vehicle or the information of its preceding vehicle and the lead vehicle.

Consider the condition when the platoon is moving at a constant velocity and the lead vehicle suddenly executes an acceleration manoeuvre. The acceleration in the lead vehicle causes the whole platoon to accelerate and the spacing among the vehicles is likely to increase and similar behaviour is shown in Fig. 14(a-c). This acceleration creates a lot of oscillations in the control input command of each vehicle of the platoon. The platoon is coming back to the desired velocity when the acceleration is removed.

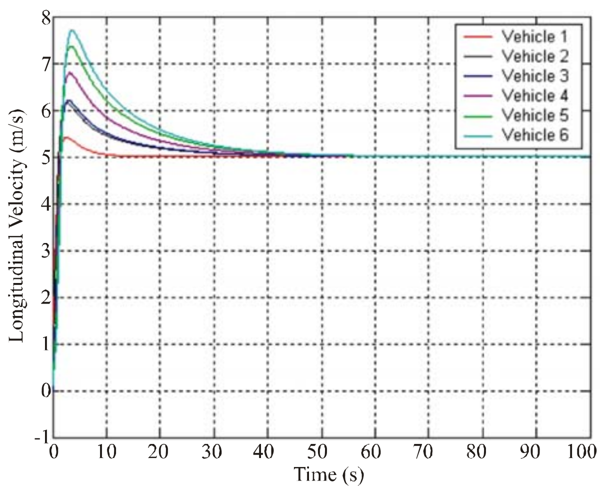


FIG. 11(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

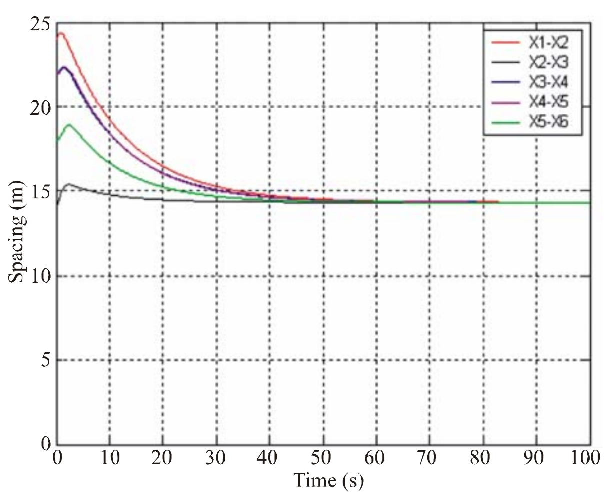


FIG. 11(b). VEHICLES SPACING, NON-UNIFORM SPACING BETWEEN THE VEHICLES

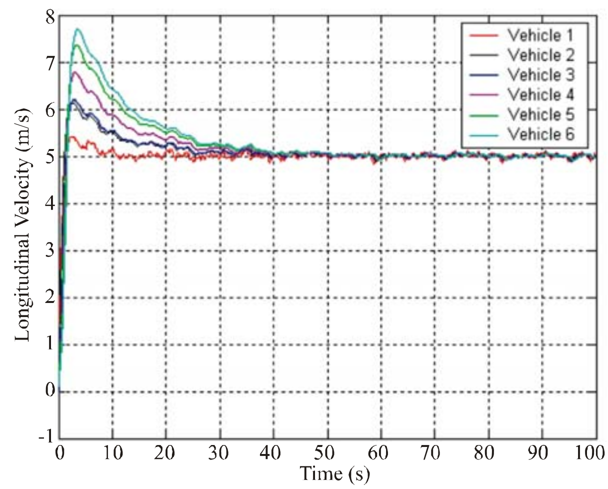


FIG. 12(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

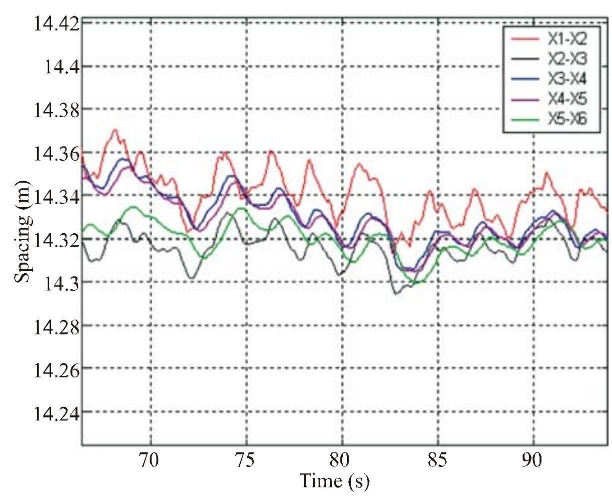


FIG. 12(b). VEHICLES SPACING, WHEN LEAD VEHICLE IS SUBJECTED TO RANDOM NOISE

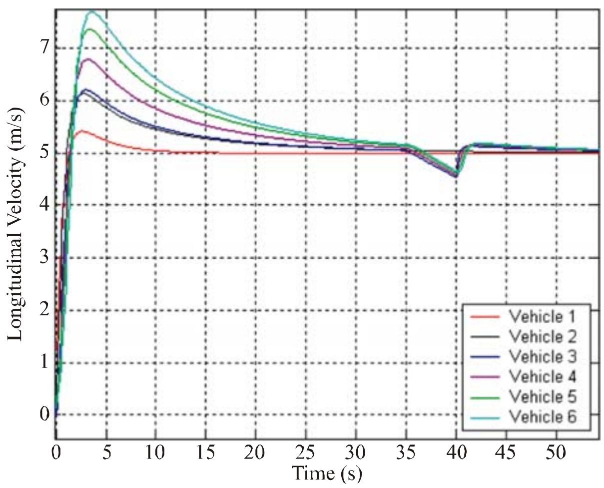


FIG. 13(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

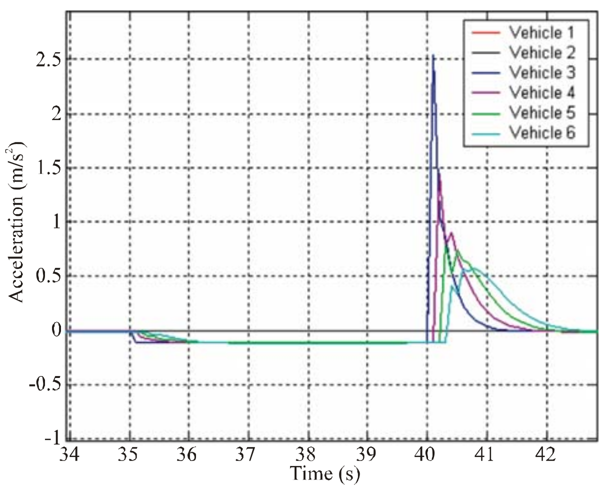


FIG. 13(b). ACCELERATIONS OF 6 VEHICLES

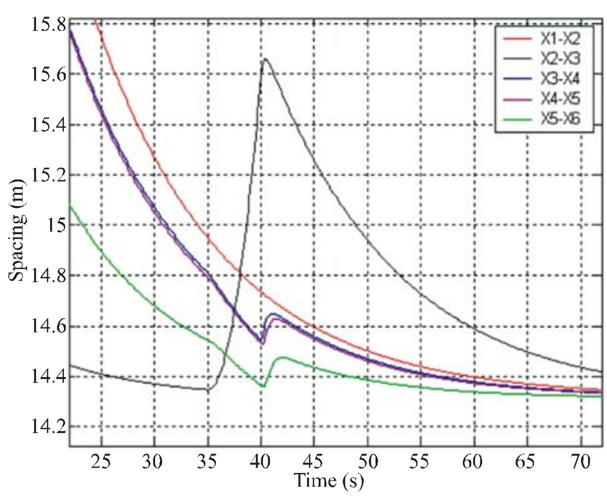


FIG. 13(c). VEHICLES SPACING, AT DESIRED VELOCITY 5m/s AND WHEN THE BRAKE IS APPLIED ON VEHICLE 3 FOR t=35 TO 40 SEC

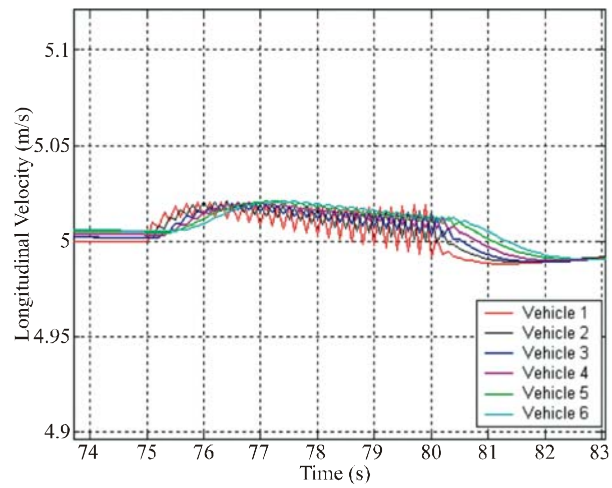


FIG. 14(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

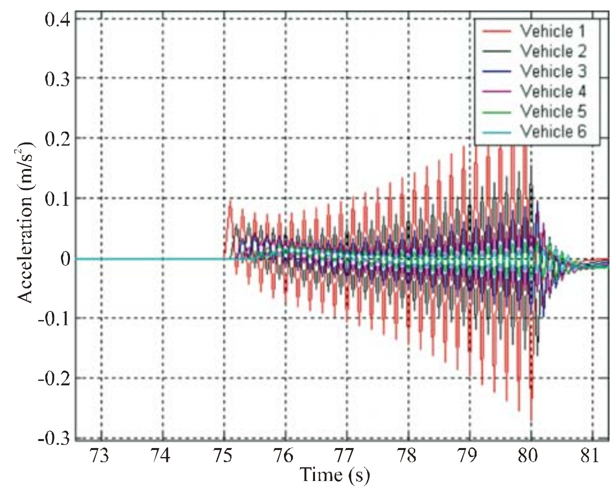


FIG. 14(b). ACCELERATIONS OF 6 VEHICLES

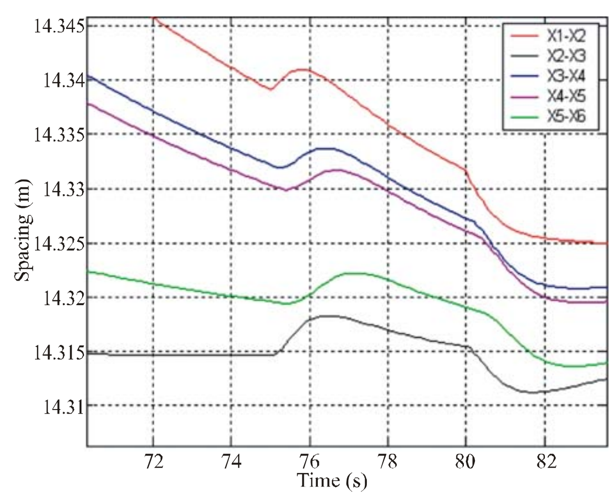


FIG. 14(c). VEHICLES SPACING, AT DESIRED VELOCITY 5m/s AND WHEN THE LEAD VEHICLE IS ACCELERATED

Consider the condition when the platoon in moving at a constant velocity and suddenly the lead vehicle executes a deceleration manoeuvre. The deceleration of the lead vehicle causes the whole platoon to decelerate and the spacing among the vehicles is likely to decrease and similar behaviour is shown in Fig.15(a-c). The platoon is coming back to the desired velocity when the deceleration is removed.

Fig. 16 shows the performance of the platoon when the platoon is moving on a slope with the slope angle of 10 degrees. The velocities of the vehicle and the spacing among the vehicles decrease due to the slope but the acceleration increases to maintain the desired velocity and spacing as shown in Fig. 16(b).

Fig. 17 shows a very important feature of the platoon when the brakes are applied to stop the vehicle. The platoon starts with the initial conditions and acquires the desired velocity of 5 m/s and then at t=60 sec brake is applied on lead vehicle to stop the platoon. The displacement of all vehicles, the velocity of all vehicles, the acceleration of all vehicles, and the spacing of all vehicles can be seen in Fig. 17(a-d) respectively. The velocities reduce quickly within ten seconds of brakes and there is a large deceleration in the vehicles of platoon to reduce the speed, the spacing reduces within the same time when the brake is applied and then comes back to safe level.

For simplicity only six vehicles were considered for the simulation in this study as it is difficult to view the graphs if more vehicles are included in the platoon. Figs. 18-19 shows the simulation of ten vehicles under normal situation which is very similar to Fig. 8.

Initially all the ten vehicles in Fig. 18 are 20 m apart. It can be seen from the Fig. 18 that all the following vehicles are coming closer in the first few seconds to reach the desired inter-vehicle distance; this is the transient response of the platoon and taking very short time to disappear. The platoon is showing very stable behaviour in the steady state condition. The results of the above simulation are

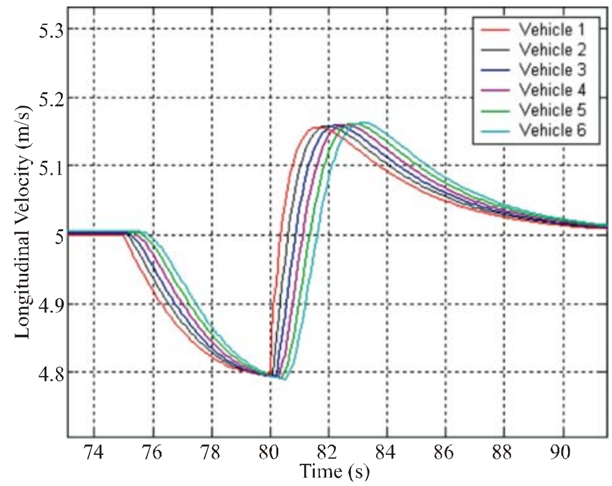


FIG. 15(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

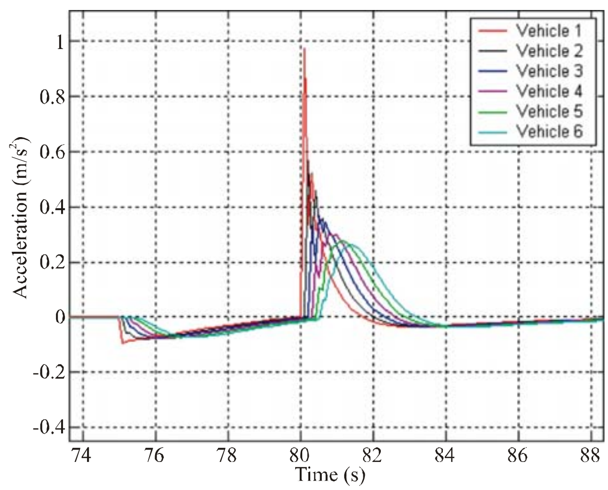


FIG. 15(b). ACCELERATIONS OF 6 VEHICLES

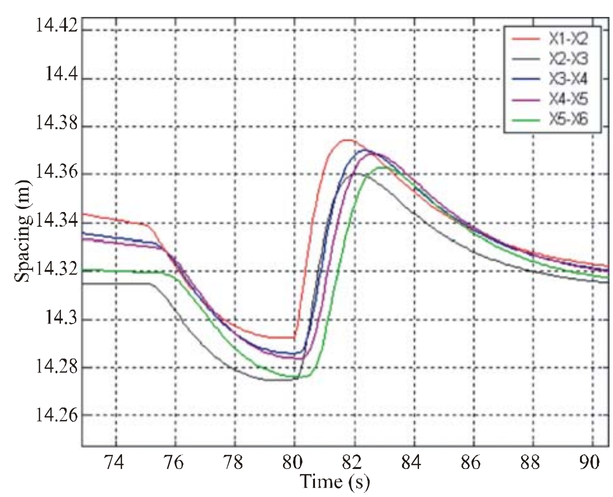


FIG. 15(c). VEHICLES SPACING, AT DESIRED VELOCITY 5m/s AND WHEN THE BRAKE IS APPLIED ON THE LEAD VEHICLE

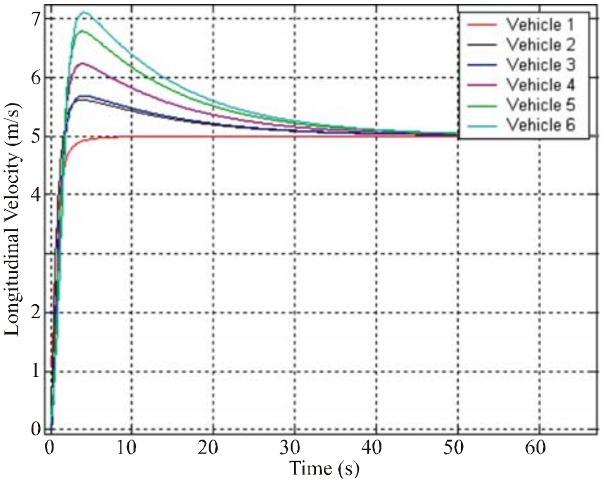


FIG. 16(a). LONGITUDINAL VELOCITIES OF 6 VEHICLES

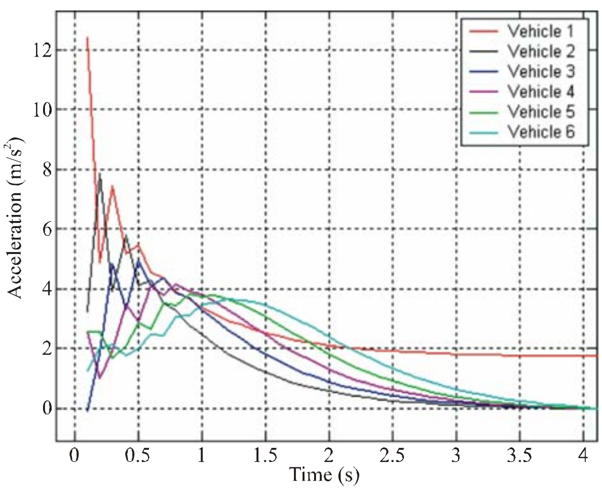


FIG. 16(b). ACCELERATIONS OF 6 VEHICLES

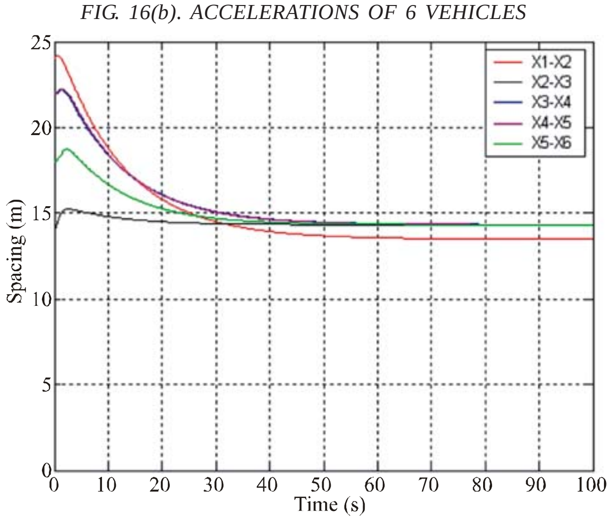


FIG. 16(c). VEHICLES SPACING, AT DESIRED VELOCITY 5m/s AND WHEN THE PLATOON IN MOVING ON A SLOPE WITH THE SLOPE ANGEL OF 10 DEGREES

discussed in comparison with the previous models in the Section 5. The limitations and shortcomings of the proposed PID feedback control algorithm will be observed in Section 6 and the alternate control algorithm will be suggested in the Section 7.

5. SIMULATION RESULT

Simulations are performed for lead vehicle, 2-vehicle and 6-vehicle platoons. Fig. 4 shows the stable PID feedback controller for the lead vehicle. The result shows that the lead vehicle (vehicle 1) achieves the desired velocity with zero steady state error. Fig. 5 shows the effect of noise signal on the lead vehicle (vehicle 1) performance. The

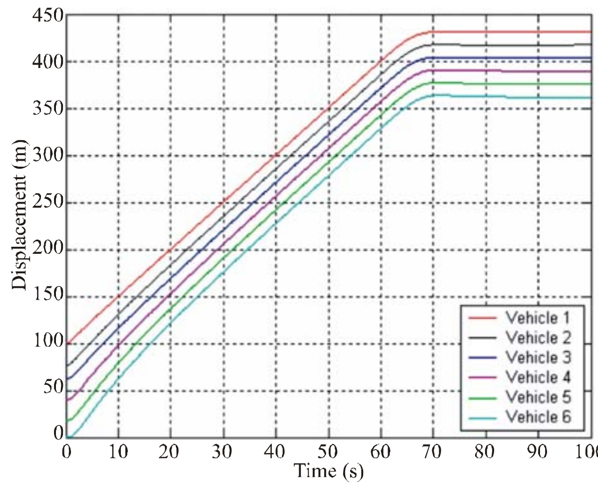


FIG. 17(a). INTER-VEHICLE DISTANCES OF 6 VEHICLES

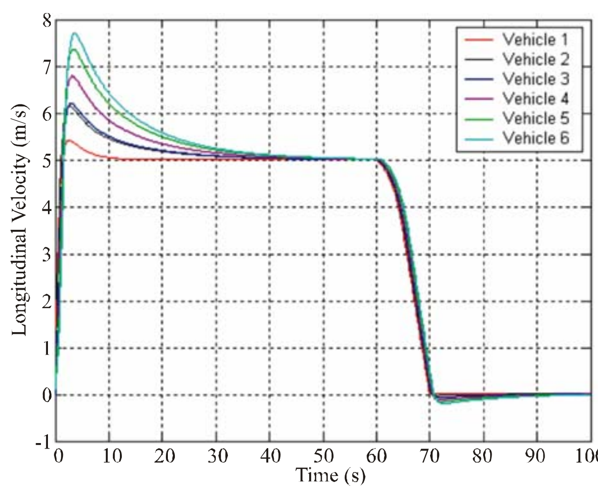


FIG. 17(b). LONGITUDINAL VELOCITIES OF 6 VEHICLES

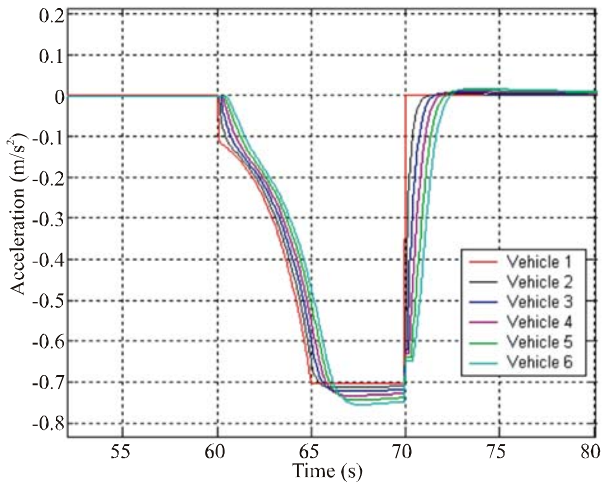


FIG. 17(c). ACCELERATIONS OF 6 VEHICLES

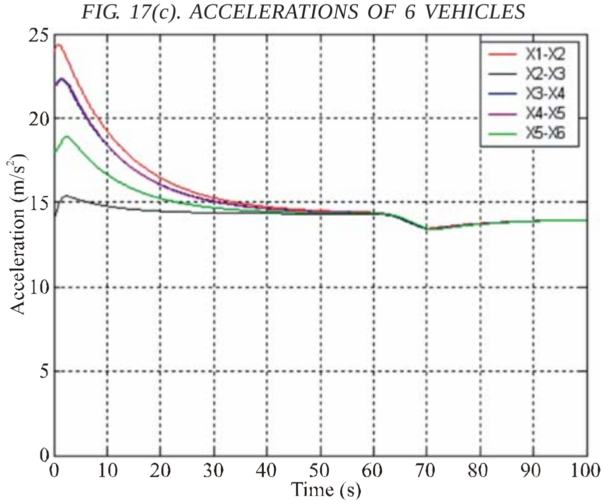


FIG. 17(d). VEHICLES SPACING, WHEN THE BRAKE IS APPLIED ON LEAD VEHICLE AT t=60 SEC TO STOP THE PLATOON

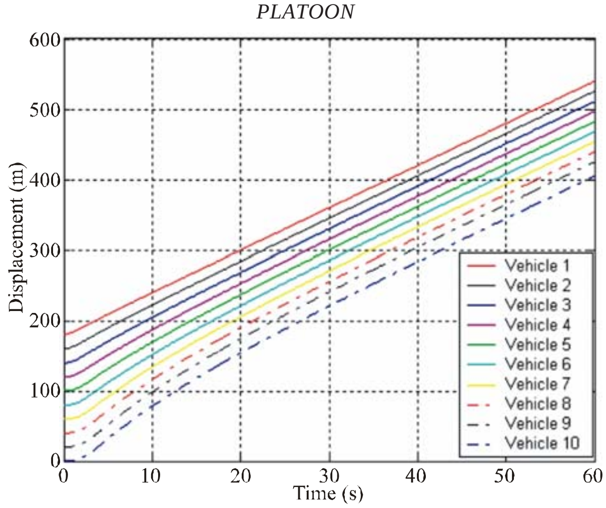


FIG. 18. INTER-VEHICLE DISTANCES OF THE TEN VEHICLES

PID controller shows the stability in the presence of noise signal as lead vehicle (vehicle 1) maintains the bounded steady state position. Fig. 8(b) shows an important feature that the lead vehicle (vehicle 1) accelerates quickly to the velocity of 5.34 m/s for the starting few seconds and decelerates to achieve the desired velocity (5m/s), this causes the wastage of energy and this problem will be sorted out in the further study. As the number of vehicle increases, vehicle 2, vehicle 3, vehicle 4, vehicle 5, and vehicle 6 accelerate to the velocity of 5.9, 6.2, 6.82, 7.17, and 7.6 m/s respectively. Every next vehicle accelerates more than the previous vehicle and decelerates to acquire the desired velocity. This is undesirable behaviour of this model. This behaviour, in Fig. 8(b), can be compared with Shladover [17] model, which shows that the first vehicle is accelerating to the velocity of 2.25m/s and then decelerating to the desired velocity (2 m/s) and all the following vehicles are accelerating to the same velocity of 2.25 m/s and then decelerating to the desired velocity (2 m/s), still there is the unwanted acceleration and deceleration of the vehicles of the platoon. These results of the Shladover [17] model have been improved by Sun, et. al. [16] which shows that all the vehicles are smoothly accelerating to reach the desired velocity of 25 m/s without overshooting.

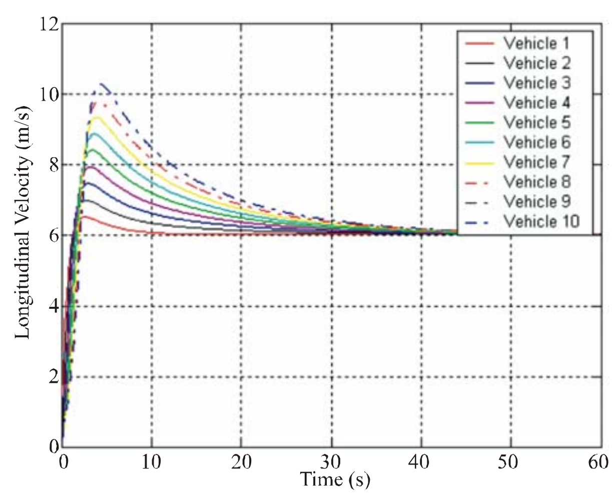


FIG. 19. LONGITUDINAL VELOCITIES OF THE TEN VEHICLES

Once the platoon acquires the steady-state condition then it shows very stable behaviour under the changes in acceleration and deceleration and in the presence of noise signal. The designed controller shows the robustness against the different noise signal, against the large variation in the initial conditions, against large variation in acceleration and deceleration and when the platoon is travelling on a slope and these all can be seen in Section 4 simulations. The behaviour of acceleration of six vehicles, Fig. 8(c), is quite similar to Shladover [17] model but the vehicles should reach the desired velocity smoothly and should not start with the high acceleration. The comparison of Fig. 8(c) with Sun, et. al. [16] shows that the maximum starting acceleration for the proposed model is 12.3 m/s^2 which is practically unsuitable and maximum starting acceleration for the Sun, et al .[16] is 2.5 m/s^2, even the desired velocity (25m/s) in the Sun et al [16] model is much greater than the proposed model desired velocity (5 m/s).

The simulation results of Figs. 14-15, and 17 can be compared with Shladover [17] for the changes in acceleration and deceleration commands and shows quite similar behaviour to Shladover [17] model. But both models are not suitable because they do not consider the actuation lags in their designed controllers.

The simulation result of Fig. 12(b) can be compared with the Figs. 7-5 [11]. The spacing errors in Fig. 12(b) deviates within the range of 14.37-14.27m in the presence of noise signal and Figs. 7-5 [11] shows the deviation of 6.7-6.27m. The platoons performances in both figures are similar but deviation in Fig. 12(b) is small. This is because the magnitude for the considered random noise signal is very small as compared to Figs. 7-5 [11].

The reasons for the above shortcomings in the proposed PID controller are following. The proposed model does not consider the non-linearity in the system. This model uses the constant spacing policy, while for a smooth execution of acceleration manoeuvre constant headway policy should be employed in this model. The essential feature is the control signal, to drive the vehicles to desired safe distance and required velocity, which should be chosen using the sliding mode control method which is used by most of the researchers in the literature. The actual spacing between the vehicles achieved by the proposed controller is 14.3m while the desired spacing between the vehicles is 12m, therefore, the designed model is not capable to keep the desired distance, the reason is; in this model the vehicles are dynamically coupled and the model does not consider the spacing error dynamics, this also can cause the string instability. The consideration of spacing error dynamics is essential to control the vehicles at desired distance. The time delays in the signal processing and actuation signals have been neglected and the controller gains have not been selected by using an appropriate technical method.

The above results also satisfy the results of [1] and shows the limitations of PID controller when compared with Shladover [17] and Sun, et. al. [16]. Due to incapability of the PID controller, to cope with the complicated non-linear models PID controllers should be replaced by more advanced controllers and these advanced controllers are discussed in Section 7.

6. CONCLUSIONS

In this paper, a simple PID feedback control algorithms have been designed for the lead vehicle and the following vehicle. The proposed controller is giving stable behaviour in terms of transient and steady-state behaviour. The performance of the platoon, in the presence of noise signal and large changes in acceleration and deceleration, have also been investigated. The designed PID feedback controller is quite stable once the steady-state behaviour is achieved and shows good agreement with the bounded velocity and bounded spacing error.

As the designed model is based on the constant spacing policy, therefore, it is not suitable for autonomous operation. Because only the relative information of the preceding vehicle have been used for the control law for the following vehicle which is not enough for the string stability when the constant spacing policy is used. For a constant spacing policy, more information is required for the controlled vehicle and this adds more communication load. The results show that there is an undesired behaviour of the acceleration of each individual following vehicle to reach the desired velocity. This is because the time delays in actuation and sensing have been neglected and also this is due to the fact that the design of the controller is based on a simplified model and used the PID control strategy which is very simple and cannot be adapted for the control of a ACC vehicle platoon. The designed control law for each following vehicle uses the differences between the state of its predecessor vehicle and the state of that vehicle as the error signal generates the desired traction force. The only information of the predecessor vehicle for the controlled vehicle is not enough to ensure the string stability of the platoon. The information of the preceding vehicle with the information of the lead vehicle and spacing error dynamics are necessary to be included in the control law for the safe control of the platoon and with ensured string stability. The control law in Equation (7) is used to calculate the differences in states of predecessor vehicle and the controlled vehicle and the same control law is used for all the following vehicles. It has been observed through this study that PID feedback control strategy is not suitable for the longitudinal control of the platoon and should be replaced be advanced controllers, as discussed in Section 5.

7. FUTURE WORK

To improve the controller design, an advanced control strategy is required. The controller should have the capability to cope with the spacing error dynamics and should take into account of the signal processing lags and internal actuation lags. The advanced controllers which can make the model more realistic are Adaptive controller, sliding mode control method, predictive controller, switching mode controller or transitional controller and should be based on constant headway policy to maintain the safe distance among the vehicles of the platoon.

The proposed PID controller should be replaced by introducing the ACC system (autonomous control). The ACC, with sliding mode control method, should use the constant headway policy where the spacing distance is not constant but varies linearly with the velocity of the controlled vehicle. The conditions for string stability should be analysed and guaranteed in the further study. And then the controller should be further modified by introducing the transitional trajectories which helps in smooth switching between the different modes of ACC to avoid collisions while keeping the control on maximum allowable brake force for maximum possible deceleration.

The information available for the following vehicle control law is also very important. The proposed controller design can be improved if the lead vehicle information could be available for all the following vehicles (requires global communication network) in addition with the preceding vehicle information. This can increase the communication load and highway infrastructure is needed to generate the link between the lead vehicle and the following vehicles. The transmission of signals through this medium causes the noise in the measurement and time delays in the operation.

One other strategy discussed in the literature is to use the information of the state of the predecessor vehicle and the follower vehicle for the vehicle under observation. This requires more devices at the rear of the vehicle and increases the communication load, the calculation time, and noise in the measurement signal. Also, for a constant headway policy the controller design using a sliding mode control method would be very complicated for such a strategy.

It has been observed that the lead vehicle information is necessary for all the following vehicles. It is necessary to investigate that whether the information of the preceding vehicle is useful along with the information of the lead vehicle. It should be noted that if the information of both lead and preceding vehicles are used for the following vehicle then it will result in communication delays.

ACKNOWLEDGMENTS

The authors would like to express their sincere thanks to Mehran University of Engineering & Technology, Jamshoro, Pakistan, for giving them an opportunity to pursue this study. The research work/study was supported by Higher Education Commission, Govternment of Pakistan under Faculty Development Scheme.

REFERENCES

[1] Peppard, L.E., "String Stability of Relative-Motion PID Vehicle Control Systems", IEEE Transactions on Automatic Control, Volume 19, No. 5, pp. 579-581, 1974.

[2] Vlacic, L., Parent, M., and Harashima, F., "Intelligent Vehicle Technologies", Oxford, Butterworth-Heinemann, 2001.

[3] Swaroop, D., and Hedrick, J.K., "String Stability of Interconnected Systems", IEEE Transactions on Automatic Control, Volume 41, No. 3, pp. 349-356, 1996.

[3] Swaroop, D., and Hedrick, J.K., "Constant Spacing Strategies of Platooning in Automated Highway Systems", Transactions of the ASME, Volume 121, pp. 462-470, 1999.

[5] Huang, A.C., and Chen, Y.J., "Safe Platoon Control of Automated Highway Systems", Proceedings Institute of Mechancial Engineers Part-I, Volume 215, No. 5, pp. 531-543, 2001.

[6] Kato, S., Tsugawa, S., Tokuda, K., Matsui, T., and Fujii, H., "Vehicle Control Algorithms for Cooperative Driving with Automated Vehicles and Intervehicle Communications", IEEE Transactions on Intelligent Transportation Systems, Volume 3, No. 3, pp. 155-161, 2002.

[7] Yi, S.Y., and Chong, K.T., "Impedance Control for a Vehicle Platoon System", Mechatronics, Volume 15, No. 5, pp. 627-638, 2005.

[8] Girard, A.R., Spry, S., and Hedrick, J.K., "Intelligent Cruise-Control Applications", IEEE Robotics and Automation Magazine, Volume 12, No. 1, pp. 22-28, 2005.

[9] Martinez, J.J., and Canudas de Wit, C., "A Safe Longitudinal Control for Adaptive Cruise Control and Stop-and-Go Scenarios", IEEE Transactions on Control Systems Technology, 15, No. 2, pp. 246-258, 2007.

[10] Swaroop, D., Hedrick, J.K., and Choi, S.B., "Direct Adaptive Longitudinal Control of Vehicle Platoons", IEEE Transactions on Vehicular Technology, Volume 50, No. 1, pp. 150-161, 2001.

[11] Rajamani, R., "Vehicle Dynamics and Control", New York, Springer. 2006.

[12] Ferrara, A., and Vecchio, C., "Collision Avoidance Strategies and Coordinated Control of Passenger Vehicles", Nonlinear Dynamics, Volume 49, pp. 475-492, 2007.

[13] Canudas de Wit, C., and Brogliato, B., "Stability Issues for Vehicle Platooning in Automated Highway Systems". Proceedings of the IEEE International Conference on Control Applicalions, Kohala Coast-Island of Hawai'i, Hawai'i, USA, 1999.

[14] Liang, C.Y., and Peng, H., "Optimal Adaptive Cruise Control with Guaranteed String Stability", Vehicle System Dynamics, Volume 31, pp. 313-330, 1999.

[15] Rajamani, R., and Zhu, C., "Semi-Autonomous Adaptive Cruise Control Systems", IEEE Transactions on Vehicular Technology,Volume 51, No. 5, pp. 1186-1192, 2002.

[16] Sun, M., Lewis, F.L., and Ge, S.S., "Platoon-Stable Adaptive Controller Design", 43rd IEEE Conference on Decision and Control, Atlantis, Paradise Island, Bahamas, 2004.

[17] Shladover, S.E., "Longitudinal Control of Automative Vehicles in Close-Formation Platoons", Journal of Dynamic Systems, Measurement, and Control, Volume 113, pp. 231-241, 1991.

[18] Ali, Z., Popov, A.A., and Charles, G., "Transition Controller for Adaptive Cruise Control System", AVEC 10, 10th International Symposium on Advanced Vehicle Control. Loughborough, UK, 2010.