An Optimal Controller Synthesis for Longitudinal Control of Platoons with Communication Scenarios in Urban Environments and Highways

Anuj Abraham,[1] Nagacharan Teja, [2] Soumya Dasgupta, [2] Apratim Choudhury, [2] Justin Dauwels[2]
[1] Agency for Science Technology and Research (A*STAR), Singapore
[2] Nanyang Technological University (NTU), Singapore

With the introduction of autonomous vehicles, interest in platooning of Heavy Goods Vehicle (HGV) is gradually on the rise. Platooning of HGVs has several benefits such as increase in fuel efficiency, reduction of congestion on roads and lower costs incurred in operating a fleet. Therefore, several research are trying to address this problem by developing vehicle platooning algorithms which will allow HGVs to drive on highways in tight platoon formation. This paper proposes a Proportional Integral Derivative (PID) controller based on the combination of Constant Distance (CD) and Constant Headway Time (CHT) policies to operate an HGV platoon in the Cooperative Adaptive Cruise control (CACC) mode. In addition to CACC, the controller is tested and verified for carrying out splitting and merging maneuvers. An ARI protocol (Appeal, Reply, and Implementation) has been proposed as the communication paradigm for the execution of a splitting and merging maneuvers. The design of the protocols is carried out to make it easier for implementing any complex platoon formation or dissolution. Furthermore, the controller performance is analyzed in the presence of Vehicle-to-Vehicle (V2V) communication constraints among the platoon vehicles. Results on Packet Delivery Ratio (PDR) among platoon vehicles have been obtained for traffic scenarios with and without the influence of surrounding traffic on V2V communications. The proposed research is validated with the help of an integrated simulation environment comprising of MATLAB, VISSIM and the Network Simulator (NS3), the controller performance is analyzed for both urban arterial and highway traffic scenarios. The simulator capabilities are demonstrated by testing platooning under different traffic conditions. The contribution of this paper is principally towards the design of a platoon controller that allows a long HGV platoon to execute safety-critical maneuvers such as split and merge under communication constraints. The results show that the controller can maintain the desired constant distance and time gap. Finally, the error minimization parameters such as the Integral Absolute Error (IAE), the Integral Square Error (ISE) and the Mean Square Error (MSE) are compared with an existing CACC algorithm. It is observed that the worst case MSE in speed for the proposed controller is reduced to 246.996 from 353.91. Similarly, worst case MSE in intervehicular distance is reduced to 2.02 from 3.513.

Keywords: look-ahead platooning; PID controller; network simulator; VISSIM; MATLAB; Vehicle-to-Vehicle

1: Introduction

Developments in the transportation sector have improved our lives through multiple folds by easing connectivity. However, traffic volume in urban centres is growing due to increased use of personal vehicles and freight transport vehicles. This uncontrolled growth of traffic volume has led to numerous complications such as congested cities, road accidents and higher fuel consumption. To combat the issue of higher fuel consumption, research related to personal vehicles is concentrated on finding alternative fuels. For freight transport vehicles, many studies have proposed vehicle platooning techniques. With the advancements of autonomous vehicles and Vehicle-to-Vehicle (V2V) communication, the infrastructure for platooning is readily available. Platoon refers to a group of vehicles that are moving at the same speed in a pattern and are connected wirelessly. The most common pattern is a straight line with vehicles moving one behind the other in the same lane. The first vehicle is manually driven to set the pace, and the remaining semi-autonomous vehicles adjust their speed to match the first vehicle. A significant proportion of air-drag is reduced by making the vehicles follow at a close-range which leads to a reduction in fuel consumption. Throughout the world, freight transport consumes a million tons of fuel every year. Hence, even a modest decrease in fuel consumption makes a significant difference on a broader scale. Additionally, another benefit of platooning is that it results in increased roadway capacity [1].

The challenge in platooning is to develop a capable controller that can keep the vehicles at a close-range, track the speed changes of the first vehicle and avoid collisions among the platoon members. Several researchers have investigated platooning during the last decade [2]. Most of the earlier work on platoon controller design entails the use and development of an Adaptive Cruise Control (ACC) strategy [3]. In an ACC system, a controlled vehicle obtains speed and position of the immediate neighbouring vehicles utilizing radar communication and calculates its control input. Due to the inherent time-delays in radar communication, it is unreliable in emergencies. To overcome the shortcomings of ACC strategy, researchers proposed an advanced version of ACC, called Cooperative ACC (CACC). CACC strategy uses wireless communication standards such as 5.9GHz Dedicated Short-Range Communications (DSRC) or 5G to exchange data among the platoon members [4]. The use of wireless standards allows a wide range of data sharing such as GPS position, IMU data and the control actions like throttle or brake. Access to more data helps in implementing advanced control strategies. The work done in this paper mainly comprises of development of the CACC strategy using Proportional Integral Derivative (PID) controller.

For HGVs to benefit from platooning, the members need to move in a close range. The clearance between the platoon members can be designed based on two policies, i.e., constant distance policy and constant time gap policy. In constant distance policy, the gap between the platoon members is a constant value decided during the design of the controller. In constant time gap policy, the gap is proportional to the speed of the platoon. In this paper, a combination of both the policies is used for designing the PID controller. When the platoon is on the move, the intervehicular gap between the vehicles is maintained using constant time gap policy. However, if the platoon were to approach a traffic signal, the speed of the platoon and gap between the platoon members decrease to 0 meter. Therefore, to avoid collisions, a minimum gap ($\mathbf{GAP_{SAFE}}$) between the platoon members is enforced by the addition of constant distance policy in conjunction with constant time gap policy.

Vehicle-to-Everything (V2X) communication is a crucial requirement for designing platoon controllers. V2V and Vehicle-to-Infrastructure (V2I) communication are generally used for platoon implementation. However, for deploying V2I a huge initial investment is required [5]. Hence, in this paper the platoon controller is implemented based on V2V communication. To facilitate communication, devices are installed on vehicles. These are called as On-Board Units (OBUs). OBUs transmit their own vehicle state information and collect the state information of vehicles around them. Similarly, those installed on traffic infrastructure are called Road-Side Units (RSUs) and the RSUs transmit data depending on the infrastructure at which they are installed and collect data on traffic conditions. To ensure acceptable quality of service in V2X communication, the wireless standard must support high frequency and low latency data exchange. IEEE 1609 WAVE (Wireless Access for Vehicular Environments) and IEEE 802.11p standards are particularly designed to support the requirements of vehicular networks. As demonstrated in [6], the performance of the networks utilizing these standards is suitable even for vehicular environments of high mobility. In 2019, ISO 20035 standard is published with a focus on supporting the CACC strategy for platooning. It provides a set of guidelines for testing V2X communication.

In the case of HGV platooning, each platoon member determines its control action based on the data from the vehicle that is immediately ahead of it and the first vehicle of the platoon. WAVE based V2V communication is used for facilitating this data exchange between the platoon members. To simulate the effects of V2V communication there are two main approaches, namely the network-centric approach and the application-centric approach. In network-centric approach the analysis of network simulation results is carried out offline. It can be used when there is no need to modify a vehicle's behaviour based on communication results. On the other hand, the application-centric approach is when the outcome of the communication exchange among platoon members define the next state of the vehicle. In this paper, application-centric approach is suitable since platoon members must adjust their behaviour upon receiving the information from the other members of the platoon.

Platoon controller design is validated by carrying out simulations. Traffic, wireless communication, and platoon controller are necessary to be simulated for appropriate replication of platooning scenario.

Network Simulator (NS3) is used to simulate the V2V interactions between the platoon vehicles. IEEE 802.11p based MAC layer and PHY layer are available in NS3. The settings for the various parameters are selected based on the recommendations of the standards. Additionally, NS3 has appropriate models to represent propagation losses and mobility of the nodes, which are essential to model the communication among vehicles. To model the platoon dynamics and that of the surrounding traffic, the microscopic traffic simulator VISSIM has been chosen. The possibility to model a variety of traffic scenarios and the diverse range of data that can be obtained from the simulations, make VISSIM a strong candidate for traffic simulations [7]. Simulation of Urban MObility (SUMO) tool is an open source alternative for VISSIM but it does not support left hand driving. In this paper, simulations are carried out for Singapore road conditions where traffic is left hand driving. Finally, MATLAB is used to develop the logic for platoon controller. Upon inter-connecting all the three software packages, a control algorithm implemented in MATLAB can make use of the traffic data and the communication results to determine appropriate control inputs for each platoon member. The simulation environment is explained in greater detail [8]. The contribution of this paper is focussed towards the design of a platoon controller that allows a long HGV platoon to execute safety-critical maneuvers such as split and merge under communication constraints. To test the controller, an accurate V2V modelling was carried out using the specified simulation environment to inject realistic noise in packet delivery as a result of the platoon travelling in a high-speed traffic environment.

The rest of the paper is organized as follows: Section 2 presents the literature survey of the recent work carried out in platooning. Section 3 deals with platoon modelling for any number of trucks. Section 4 describes the platoon maneuvers such as split and merge protocol is realized using the control algorithm. Section 5 illustrates the simulation setup and the architecture used to interconnect the software to achieve integrated simulation architecture. Section 5 also details the results of the simulations. Finally, section 6 comprises of conclusion and future scope of the work.

2: Recent studies

In the last decade, the concept of platooning has received considerable attention from many researchers due to the plethora of advantages it has to offer. Researchers mainly focused on improving safety, reduction of travel time and improving efficiency. Projects such as the CHAUFFEUR project [9], the SARTRE project [10] and the California PATH project [11] investigated platoon controllers using the ACC system. The European Commission’s CHAUFFEUR I and II are one of the earliest projects on platooning. They developed an electronic tow-bar system to couple the trucks. This project did not advance as the concept of tow-bar coupling is practically infeasible. The renowned California PATH project is one of the major milestones for platooning [11][12]. This project focused on the automated movement of trucks, passenger cars and buses on a dedicated lane of the highways. Once they move out of the dedicated lane, drivers can control the vehicles manually. The transition of control between the automated driver and the manual driver is handled by controllers residing in the lead vehicle of platoon or on the RSUs. One of the major drawbacks of this project is that the RSU deployment throughout the highway requires a big investment. This project continues to remain in development with current work concentrated on the development of a CACC system.

Studies on developed platooning techniques are seen with an assumption that the platoons originate from one base station, travel all the way together to another destination station [13]. This assumption restricts the functionality and does not serve the general use case. Often, the vehicles originate from and terminate at different stations. Whereas, in our work platoon vehicles need not start from and end up at the same base stations. Vehicles can merge or split dynamically in the middle of the road. The concept ARI protocols (Appeal, Reply, and Implementation) are proposed, so that scope of study need not stick to the assumptions seen in the literature. In a highway scenario, a vehicle can travel together and split to reach their respective destinations with the developed ARI protocols. Also, researchers investigated the impact of platoon spacing policy on fuel efficiency. Similar studies were carried out on traffic flow characteristics [14]. It has to be noted that a small number of controllers are developed to keep the platoon fundamentally string stable [15].

The minimum distance that is required for the platoon to move smoothly without collision is investigated [16]. The authors describe a framework for analyzing the safety aspects of HGV platooning. The experiments are conducted on two SCANIA trucks using a real-time onboard unit to communicate with each other. The results show that 1.2 meters to 2 meters are to be maintained for platooning to work safely and seamlessly. Researchers studied vehicle platooning and its role in fuel usage reduction [16]. A system model for the HGV platoon is developed and the fuel-consumption behaviour of the platoon is studied when the platoons traversed an up-hill or a down-hill terrain on Swedish Freeways. Although the algorithm is effective in controlling the follower vehicles, it exponentially increases the computational cost of programming in the state-space.

A prediction-based platoon controller using Model Predictive Control (MPC) using V2V communication is developed [17]. The performance of the controller is analyzed for various levels of latency and message reliability. It is found that 0-100ms latency and 70-90% reliability is sufficient to efficiently operate the platoon. A similar study analyzed the prediction-based controller for different latency and reliability [18]. The traffic congestion levels also play a role in the performance of the controller since communication is affected due to many nodes. The Transmit Rate Control (TRC) is a part of the IEEE 802.11p standard proposed by ETSI for Europe. TRC regulates the message transmission rate whenever the traffic congestion is high. The TRC has an adverse effect on the platooning application because it depends on the high message rate [19]. At higher congestion levels, platoon performance is deteriorated. Furthermore, these authors established that flexible platooning for an urban traffic scenario, which helps in reducing congestion levels. A CACC control design for platooning with longitudinal and lateral control are presented in [20]. Along with simulations, the controller is implemented on a mobile robot platform to study the behaviour.

Some of the studies have investigated V2X communication standards for platooning scenarios. A comparison of two V2V technologies for highway platooning were presented in [21]. They simulated the movement of a truck platoon with varying levels of traffic congestion. It is found that 3GPP Cellular V2X (C-V2X) allows for shorter intervehicular distances between the platoon members than the IEEE 802.11p when the traffic congestion is high. The evaluation of the ITS-G5A standard is carried out in [22] and they investigated the autonomous driving scenario with a platoon merging scenario. The vehicles move autonomously and merge to form a platoon [22]. The performance of the ITS-G5A standard is however, found to be inadequate for the platoon merging scenario. A detailed evaluation of the C-V2X standard based on 3GPP for the platooning application is carried out in [23].

3: Platoon modelling

This section of the paper describes the model of the platoon used for controller synthesis.

3.1: Introduction

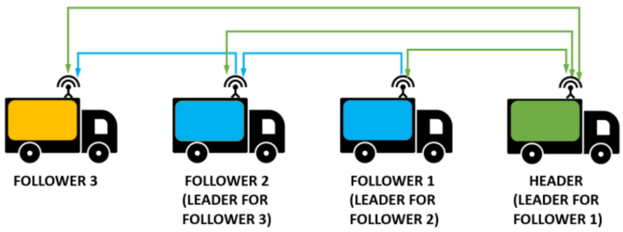
Platooning of vehicles is generally implemented using two policies, the Constant Distance (CD) policy and the Constant Headway Time (CHT) policy. CD policy tries to maintain a constant intervehicular distance between the platoons irrespective of the vehicle's velocity profile. CHT policy maintains a time gap between the individual vehicles. Both the policies have their own advantages and disadvantages. At a higher speed, an emergency can cause the platoon vehicles to fail. Hence, sufficient clearance between the platoon members is essential. The CHT policy ensures that there is sufficient clearance for emergency braking scenarios by increasing the intervehicular distance at a higher speed. However, this paper tries to combine both CD and CHT policies to optimally apply both principles. The controller developed in this paper allows the platoon members to maintain a time gap of 0.3s as per the CHT topology. The time gap corresponds to an intervehicular distance that is directly proportional to the speed of the platoon. Hence, the intervehicular distance becomes 0 meters when the platoon is about to stop. Therefore, to overcome this shortcoming, the CD policy is made to kick in to ensure that the gap does not reduce to 0 meters by maintaining a constant clearance $\mathbf{GAP_{SAFE}}$ between the platoon members. The combination of the two policies ensures the safe operation of a platoon.

3.2: Nomenclature and problem description

The platoon vehicles are addressed with different names depending on the position of the vehicle. Figure 1(a) shows a platoon of three HGVs that are connected with V2V communication. The green vehicle is the *header* of the platoon. A certified driver drives the header HGV. The destination, speed and the lane are at driver's discretion. The remaining HGVs highlighted in yellow are anointed as *followers*. They follow the header and are not allowed to take any decisions like joining or leaving the platoon without the permission of the header. The green arrows indicate the information exchange between header and all the followers which are necessary to implement general CACC strategy.

In Figure 1(b), a four HGV platoon is shown for the developed CACC methodology. The header of the platoon acts as leader for follower 1. The follower 1 acts as leader for follower 2. The follower 2 acts as leader for follower 3. As there is no vehicle after follower 3, it does not act as leader to any vehicle. In CACC strategy, every follower vehicle requires a double feedback to determine the control action. The first feedback is obtained from the header and the second feedback is obtained from the leader. Blue arrows indicate the additional feedback provided by the leaders to their next followers. It must be noted that leader vehicle only provides the feedback, hence it is indicated with a single headed arrow originating from the leader to follower. The data exchange arrows are indicated from the controller design perspective. Through V2V communication, all vehicles exchange data with all the other vehicles. The terminology described in Figure 1(b) is extendable to any length of the platoon.

a



b

Figure 1. ***(a)*** *A 3 HGV platoon indicating the Header and Followers,* ***(b)*** *Leader and Header of a follower vehicle in 4 HGV platoon.*

3.3: Modelling of the platoon

The mathematical modelling for a platoon of vehicles is explained in this section. The platoon is considered to be analogous to a mass-spring-damper system [24], which can be represented as,

$$m_n \ddot{x}_n + b_n \dot{x}_n = u_n. \tag{1}$$

where index n denotes n^{th} vehicle of the platoon, m_n is the mass of the vehicle, b_n is the damping constant, x_n is the longitudinal position and u_n is the input information.

To implement a platoon controller with CD and CHT policy, this paper utilizes the PID controller, which can be formulated as,

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{d}{dt} e(t). \tag{2}$$

where k_p, k_i and k_d are the proportional, integral and derivative gains of the system.

The corresponding transfer function from the error signal $e(t)$ to the input signal $u(t)$ is represented as,

$$G(s) = \frac{U(s)}{E(s)} = k_p + \frac{k_i}{s} + k_d s = \frac{k_d s^2 + k_p s + k_i}{s}. \quad (3)$$

For this control problem, the spacing error (constant time gap and constant distance) between the vehicles is considered as error signal. This is a pragmatic approach for longitudinal control of vehicle platooning [25]. The spacing error between the follower and the leader is given by ε_{fl}. The spacing error between the follower and the header is given by ε_{fh}. The spacing errors are calculated as follows,

$$\begin{aligned} \varepsilon_{fl} &= x_l - x_f - hd_{fl} - (hw_{fl} \cdot v_f) = dx_{fl} - hd_{fl} - (hw_{fl} \cdot v_f) \\ \varepsilon_{fh} &= x_h - x_f - hd_{fh} - (hw_{fh} \cdot v_f) = dx_{fh} - hd_{fh} - (hw_{fh} \cdot v_f). \end{aligned} \quad (4)$$

where x_l , x_f and x_h respectively represent the GPS positions of the leader, the follower and the header, hd_{fl} and hw_{fl} represent the desired constant distance and headway time between the leader and the follower respectively. Similarly, hd_{fh} and hw_{fh} represent the desired constant distance and headway time between the header and the follower respectively.

For a set of n vehicles, the constant distance and headway time between the header and the follower can be calculated as follows,

$$\begin{aligned} hd_{fh} &= (n-1) \times hd_{fl} \\ hw_{fh} &= (n-1) \times hw_{fl}. \end{aligned} \quad (5)$$

Using the concept mentioned in [24], the force required for moving a platoon of vehicles can be written as,

$$m\dot{u} = F_x - mg\sin\theta - f_r mg\cos\theta - \frac{1}{2}C_{air}(u+u_w)^2. \quad (6)$$

where, $C_{air} = \rho A_f C_d$ is a constant, F_x is the tractive force of the vehicles in the platoon, C_d is the drag co-efficient of the vehicle, A_f is the frontal area of the vehicle, u_w is the wind velocity, θ is the angle of inclination, u is the vehicle forward velocity, m is the mass of the vehicle and g is the acceleration due to gravity. The wind velocity is positive for a headwind and negative for a tailwind. The drag co-efficient for the vehicle ranges from about 0.2 to 1.5.

The control law is formulated with the variables that are described as follows: dx_{fl} represents the distance between any leader and a follower vehicle, dx_{fh} represents the distance between the header vehicle and n^{th} vehicle of the platoon. v_f, v_h and v_l are the velocities of the n^{th} follower, header and leader respectively. x_f, x_h and x_l are the positions of n^{th} follower, header and leader respectively. a_l and a_f denote the acceleration of the leader and the follower vehicle respectively. hd_{fh} and hd_{fl} represent the headway distance between the header and follower and the distance between the leader and follower respectively. The headway time between the leader and the follower and the header and the follower are represented by hw_{fl} and hw_{fh} respectively. Using the variables described, the acceleration of the vehicle with the PID control law can be written as,

$$a_f = \left[\frac{(a_h + a_l)k_d + (v_h - v_f)k_p + (v_l - v_f)k_p + k_i(x_h - x_f - hd_{fh} - (hw_{fh} \cdot v_f)) + k_i(x_l - x_f - hd_{fl} - (hw_{fl} \cdot v_f))}{(C_{air}.u^0 + 2k_d)} \right]. \quad (7)$$

3.4: PID tuning using optimization technique

The Particle Swarm Optimization (PSO) algorithm is an effective searching technique for tuning optimal PID controller parameters (such as k_p, k_i and k_d representing the proportional, integral and derivative gain) which are mathematically described in [26]. The PSO algorithm is a computational approach that optimizes a predefined problem by iteratively attempting to improve a candidate solution. Firstly, the PSO algorithm searches the optimum solution by initializing some random particles in the solution space. Each particle involves two sets of aspects, namely the velocity and position. The velocity and position of the particles are updated based on the Eq.8 and Eq.9 respectively.

$$v_p^{j+1} = wv_p^j + c_1 r_1 \left(b_p^j - y_p^j \right) + + c_2 r_2 \left(g_p^j - y_p^j \right). \quad (8)$$

$$y_p^{j+1} = y_p^j + v_p^{j+1}. \quad (9)$$

where,

y_p^j and y_p^{j+1} are the current and future searching point,

v_p^j and v_p^{j+1} denotes the current and future velocities,

b_p^j and g_p^j are the velocities based upon the personal best and global best,

w is the inertia weight factor.

The random numbers r_1 and r_2 are generated between 0 and 1. Cognitive learning rate and global learning rate are represented by c_1 and c_2 respectively. The steps involved in PSO algorithm are shown in Figure 2. The initial values of the PSO parameters are chosen as listed in Table 1. The sum of cognitive learning rate (c_1) and global learning rate (c_2) are assigned to be a constant value which is greater than 4, (i.e. $c_1 + c_2 = \varphi > 4$). The total number of iterations during the search is equal to N multiplied by the number of swarm steps. The objective function $J_{\min}$ for the optimization algorithm is the total error spacing minimization ε (Integral Square Error (ISE)) as defined by,

$$J_{\min} = \int \varepsilon^2 dt = \int \left(\varepsilon_{fl} + \varepsilon_{fh}\right)^2 dt. \tag{10}$$

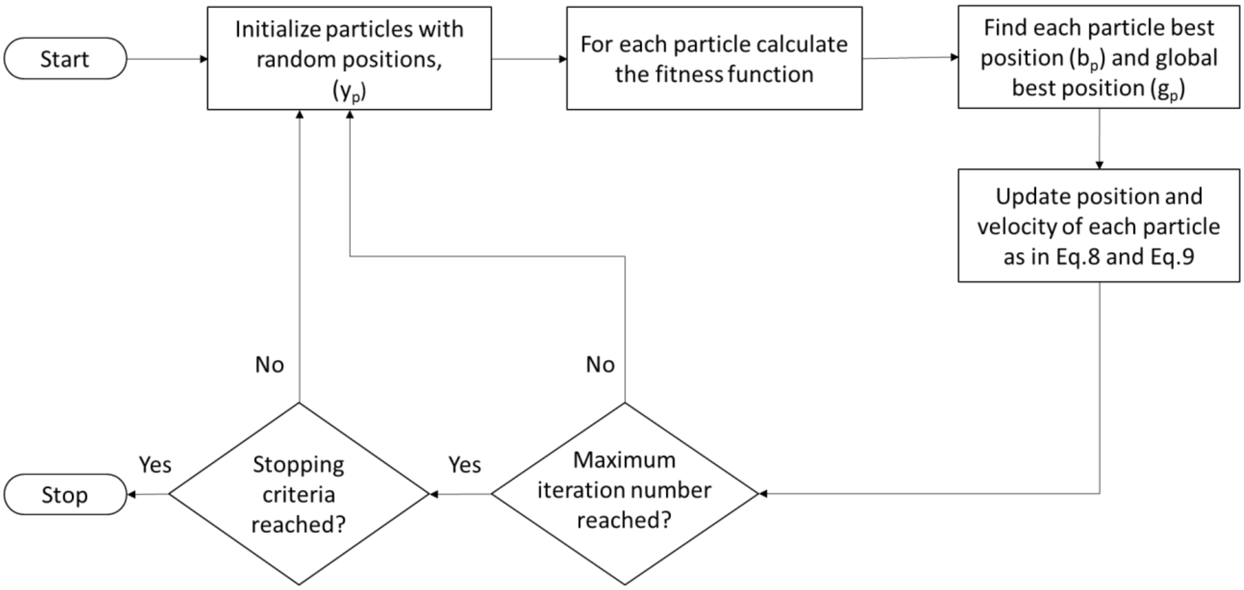


Figure 2. *Steps in PSO algorithm.*

The optimization problem given in Eq.10 is solved using the initialized parameters listed in Table 1, together with min-max range (search space) of the controller tuning parameters defined by k_p =[1, 5000], k_i =[1, 2000], k_d = [1, 5000]. The optimal PID controller parameters computed by PSO algorithm are k_p = 2050, k_i = 900,

k_d = 2040.

Table 1. PSO parameters.

Parameters	Value
Dimension of the search (D)	3
Total number of swarm (N)	50
Number of swarm steps	50
Cognitive learning rate (c_1)	2.3
Global learning rate (c_2)	2.3
Inertia weight factor (w)	0.8
Number of variables to be tuned	3

4: Platoon maneuvers

The platoon controller obtained in the previous section is suitable for platoon operation. However, the formation and dissolution of the platoon are also essential aspects of platoon navigation. The basic maneuvers a platoon is expected to perform splitting, merging and lane change [27]. Every maneuver requires a coordinated protocol for exchange of data among the vehicles through V2X communication. There are two ways of implementing the communication. Some of the earlier studies have recommended the use of V2I communication. However, it is inefficient to install RSUs throughout the highway. Additionally, they pose safety concerns due to communication drops in tricky situations such as hilly regions or tunnels. Another way of communication is with V2V communication using OBUs. Merging and splitting maneuvers based on V2V communication are described in this paper as shown in Figure 3.

Figure 3. *The ARI protocol for platoon maneuvers.*

There are three phases, the *Appeal* phase, the *Reply* phase and the *Implementation* phase. A vehicle makes an appeal to the header and provides the relevant request information. It can be either split or merge request. If there is no acknowledgment received, the appeal is sent again in the next time instant. If the reply is affirmative, the vehicle can carry out the maneuver. If rejected, the vehicle can choose to either repeat the appeal or wait for a certain time depending on the situation. Sample protocols for merge and split maneuvers are illustrated in Figure 4(a) and Figure 4(b) respectively.

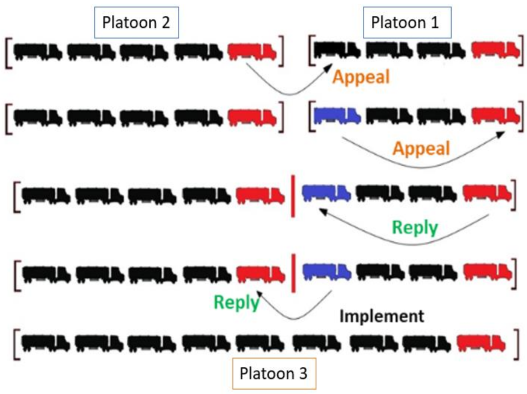


Figure 4(a). *Merge protocol of the platoons.*

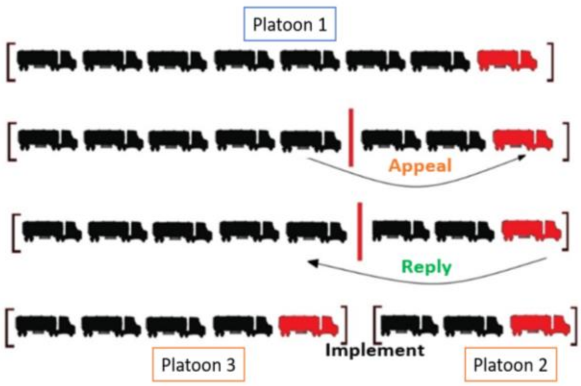


Figure 4(b). *Split protocol of the platoons.*

4.1: The Merge scenario

In the merge scenario illustrated in Figure 4(a), there are two platoons (Platoon 1 and Platoon 2) whose headers are indicated in red and are heading towards the same destination. Hence, they can merge to form a single platoon. The header of Platoon 2 raises the merge request as $\mathbf{Appeal_{Merge}}$ which reaches the last follower vehicle of Platoon 1, indicated in purple. In addition to the merge request, the HGV identification details and their current states such as speed, location, destination and any other relevant information are also shared. Upon receiving the request, the purple HGV forwards it to the header of Platoon 1. In this scenario, it is assumed that the driver accepts the request. The approval from the driver is transmitted as $\mathbf{Reply_{Merge}}$ to the purple HGV, which is further forwarded to the header of Platoon 2. The reply includes identification details and the states of the HGVs of Platoon 1. Once the affirmative request reaches the header of Platoon 2, the $\mathbf{Implementation_{Merge}}$ phase of the maneuver commences. The header of Platoon 2 informs its followers about the merging maneuver and provides the details of the new header. All the vehicles of Platoon 2 are then added to the list of followers of Platoon 1. Therefore, HGVs of Platoon 2 accelerate and merge with HGVs of Platoon 1 to form Platoon 3 as shown in Figure 4(a).

$\mathbf{GAP_{MAX}}$ is the communication range of the OBU. The last follower of Platoon 2 must be within the distance $\mathbf{GAP_{MAX}}$ of the header of Platoon 1. This is essential to ensure that the header of Platoon 1 has stable contact with all the vehicles of Platoon 2. Otherwise, the platoon controller may not operate effectively. The purple vehicle is used in the information exchange since it is closer to the headers of Platoon 1 and Platoon 2. This assures a maximum probability for the signal to propagate without failure. Although this puts an additional step in the communication, it ensures reliable data exchange. There can be several ways of realizing the protocol. Analysis of different protocols is beyond the scope of this paper.

4.2: The Split scenario

After travelling as a platoon for certain time, some of the platoon members may have to head towards different destinations. Hence, the vehicles can split and choose to form a new platoon. As illustrated in Figure 4(b), the red HGV shows the split protocol. The red HGV in the platoon raises the request $\mathbf{Appeal_{Split}}$ to the header of Platoon 1. In this scenario, it is assumed that all the followers after the red HGV are traveling to the same destination and are willing to accept the red HGV as their new header. Upon receiving the request, the driver takes the decision whether to approve or reject it. Here, it is assumed that the request is approved and packaged into a $\mathbf{Reply_{Split}}$ message and transmitted to the red HGV. As the request is approved, the red HGV ceases to exist as a follower and assumes the role of the header of Platoon 3. The Platoon 3 is immediately allowed to carry out independent decisions like lane, direction and speed.

The merge and split protocols described in this section are independent of platoon length and vehicle type. Sometimes, a single vehicle can also initiate and execute the protocol. Hence, any transaction can be realized by executing a proper combination of split and merge requests.

5: Integrated simulation architecture and Results

In order to study the effect of V2X technology on various traffic scenarios, there does not exist any self-supporting simulation tool. However, it is possible to integrate a combination of simulation software. One of the widely used open-source traffic simulator is SUMO [5]. However, it does not support left hand driving traffic simulations which are essential to test applications for Singapore road networks. Hence, this paper uses one of the most versatile microscopic simulator namely VISSIM, for the simulation of traffic in Singapore. VISSIM offers a resolution as small as 50ms and supports real-time data exchange when coupled with other simulators. To simulate V2X communication between the vehicles, NS3 is used while MATLAB is utilized for coordinating and synchronizing the simulations between VISSIM and NS3.

The integrated software architecture was developed in a previous research endeavour described by [28] and the same block diagram were used in this work for the simulator integration. MATLAB and VISSIM communicate with each other using VISSIM's Component Object Model (COM) interface. Both the software is installed on Windows OS but NS3 is developed for Linux. Hence, a Linux virtual machine is setup on Windows for running NS3. TCP/IP socket API is used to establish information exchange between NS3 and MATLAB. The controller application is coded in MATLAB. The position and velocity of platoon vehicles are obtained from VISSIM using COM object at every simulation step. Using this data, MATLAB computes control action in terms of speed. At the same time instant, MATLAB sends the vehicle data to NS3 to perform communication simulations and gets the results from NS3. The results include the information regarding the packet delivery status from header to the followers. Using this information, MATLAB provides speed input to the vehicles in VISSIM through COM object only when the packet status is successful. More details regarding the simulation functionality are described in [28].

All the platoon applications are tested on two sections chosen from the Singapore road network as shown in Figure 5(a) and Figure 5(b). The layouts are created in VISSIM with appropriate traffic volume data obtained from the Land Transport Authority (LTA), Singapore.

(1) Road Network 1: Alexandra road of Singapore is selected to simulate freeway scenarios. As shown in the Figure 5(a), this section is a straight stretch of 2km with no other connecting roads. This simple layout is preferred to carry out preliminary tests of the controller.

(2) Road Network 2: To simulate urban conditions, Yuhua SMC is an appropriate choice. There are multiple intersections with several arterial roads and traffic signals as shown in Figure 5(b). The circles highlight the traffic signals along the road network. After testing the controller in a freeway scenario, road network 2 helps in urban traffic challenges to stress-test the controller.

Figure 5(a). *Map of road network 1, i.e. Alexandra road.*

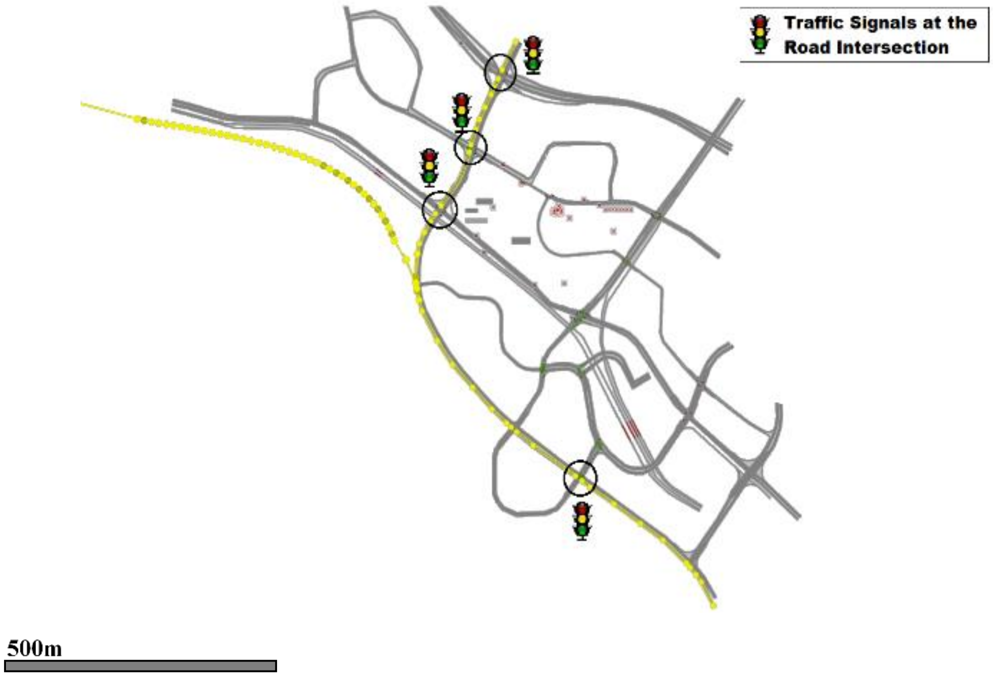
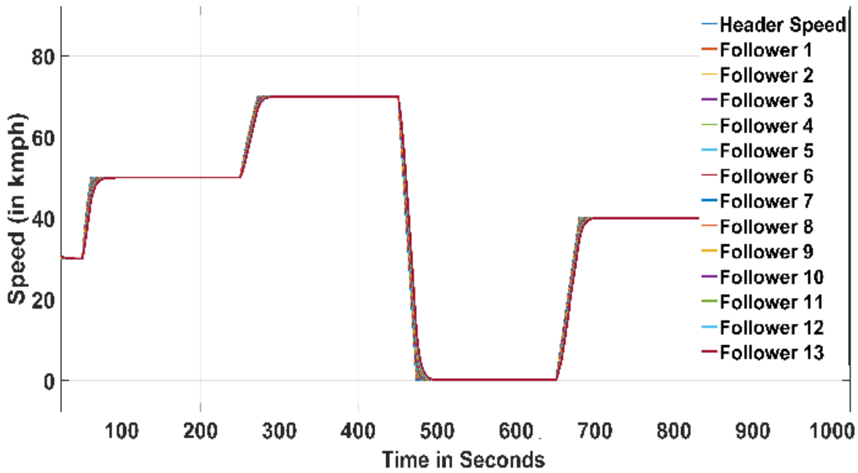


Figure 5(b): *Map of road network 2, i.e. Yuhua SMC.*

5.1: Platoon simulations

In the first phase, the CACC controller behaviour is studied by carrying out simulations on road network 1. An ideal communication setup is used to evaluate the controller thoroughly before introducing the real-world constraints. In the warm up phase of the simulation, fourteen HGVs are added to the road network 1, travelling at a speed of 30kmph on the same lane. After a certain time, the first HGV is assigned as the header and all the remaining HGVs merge to form a 14-HGV platoon. Once the platoon reaches a steady state at 30kmph, the warm-up phase of the simulation completes.



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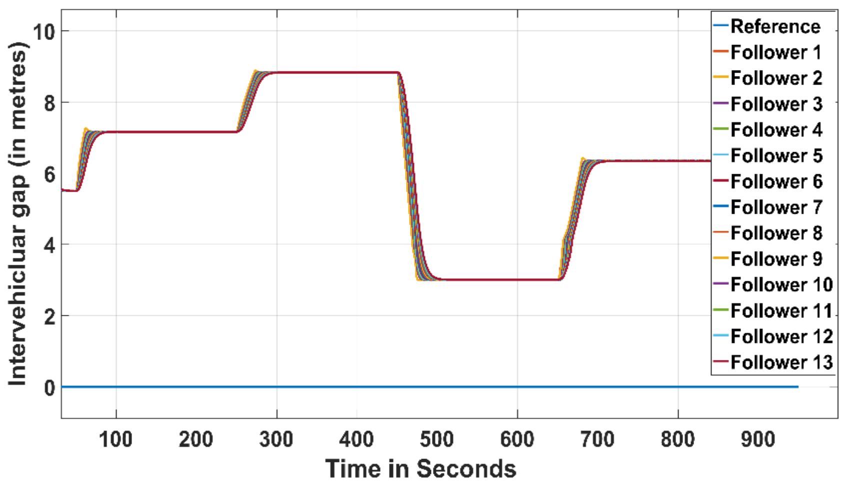


b

Figure. 6. ***(a)*** *Speed profile of the vehicle for road network 1,*
(b) *Intervehicular distance profile of the vehicle for road network 1.*

The speed profile and the intervehicular distance of the 14-HGV platoon are shown in Figure 6(a) and Figure 6(b) respectively. At the steady state speed of 30kmph, the header of the platoon is made to accelerate and reach a speed of 50kmph. It can be observed that the followers accelerate accordingly and reach 50kmph. Furthermore, similar trends are observed when the header of the platoon accelerates to 70kmph. After some time, the traffic signal turns into red causing the header HGV to stop. From Figure 6(b), it is evident that the platoon HGVs decelerate accordingly to stop at the signal and maintain an intervehicular distance of $\mathbf{GAP_{SAFE}}$. Once the traffic signal turns green, the header accelerates to 40kmph and the followers match the header's speed. It can be observed in the Figure 6(b) that the intervehicular distance varies with the speed of the platoon. For different values of speed, Table 2 shows the intervehicular distances according to the CD and CHT policies. The shorter settling times and the tracking capabilities show that the performance of the controller meets expectations.

Table 2. Speeds and Intervehicular distance for desired time and distance gap.

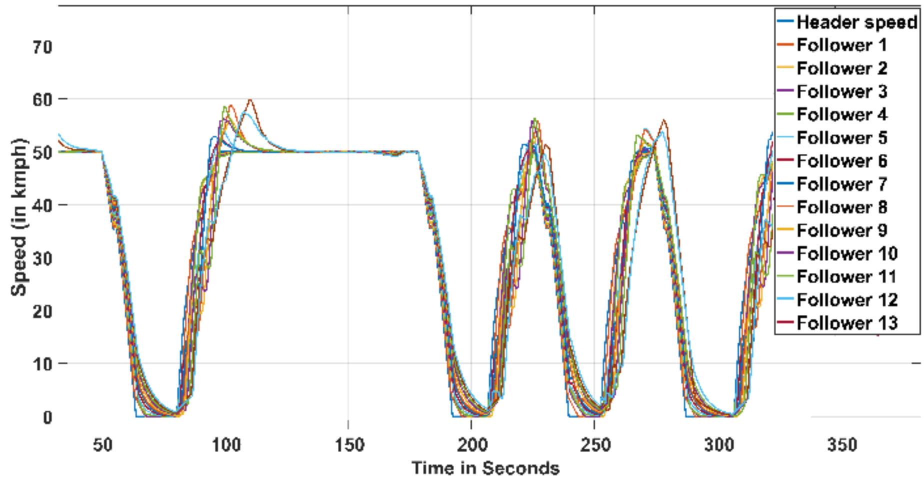
Speed (in kmph)	Desired Intervehicular distance, $GAP_{DESIRED}$ (in meters)
0	3.00
30	5.50
35	5.92
40	6.30
45	6.75
50	7.10
70	8.80

Similar results are seen when the controller is tested for a 14-HGV platoon in road network 2. The surrounding traffic and multiple intersections pose a different challenge to the controller. The positions of HGVs are acquired from VISSIM as Cartesian coordinates and the intervehicular distance is computed as Euclidean distance.

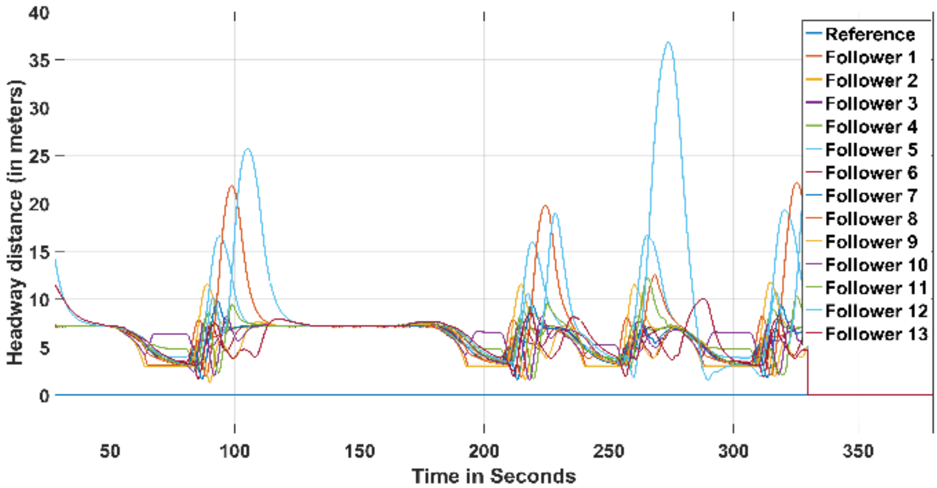
Hence, for a straight line road like the road network 1, the controller maintains intervehicular distance as mentioned in the Table 2. For curved roads, the Euclidean distance will be smaller than the desired intervehicular distance. Based on the results, it is observed that Euclidean distance is sufficient for the simulation scenarios investigated in this paper. However, in a real-world scenario curvature of the road must be accounted for computing the intervehicular distance.

Once the controller performance is evaluated with ideal communication setup, practical communication constraints are introduced into the simulations through NS3. Every HGV of the platoon is assigned a node in NS3 to simulate mobility and communication among platoon HGVs. Since the simulations involve just the platoon application, entire channel duration of 0.1s (10Hz message frequency) is allocated to control channel window. The OBU parameters are set according to the DSRC WAVE protocol [4]. The transmitter power level is set to 23dBm and the message data rate is set to 6Mbps. In addition to platoon vehicles, surrounding traffic within the vicinity of the platoon is equipped with V2V to determine the impact of interference. These non-platoon surrounding vehicles are programmed to broadcast packets at random time instants to add load on the channel. This is similar to realistic traffic scenario when V2X technology becomes mainstream.

In road network 2, there are four intersections with traffic signals that are programmed to turn red by the time platoon reaches the intersection. Once the signal turns green, the platoon accelerates to reach the desired speed of 50kmph. Figure 7(a) indicates the speed profile of the platoon. It can be seen that the speed of the platoon drops to 0kmph at four instances due to the four intersections in road network 2 as shown in Figure 5(b).



a



b

Figure 7. ***(a)*** *Speed profile of 14-vehicle platoon under communication constraint for road network 2,* ***(b)*** *Intervehicular distance profile of 14-vehicle platoon under communication constraint for road network 2.*

From Figure 7(b), it can be seen that the HGVs that are far from the header take more time to converge towards the desired intervehicular distance. Often platooning for HGVs is implemented for highway scenarios where the platoon can cruise for several hundreds of kms to maximize fuel saving as well as improve the traffic flow. The intersection scenarios were demonstrated in the paper because they pose challenges to the controller in scenarios like starting the platoon from 0kmph or bringing a platoon to 0kmph. After settling to the desired set-point, platoon exhibits stable behaviour. From these observations, it is safe to conclude that the controller can keep the platoon safe in a real-world traffic scenario with real-world communication setup. Although the higher intervehicular gap is valid, our investigation did not focus on the platooning applications for the city-like networks.

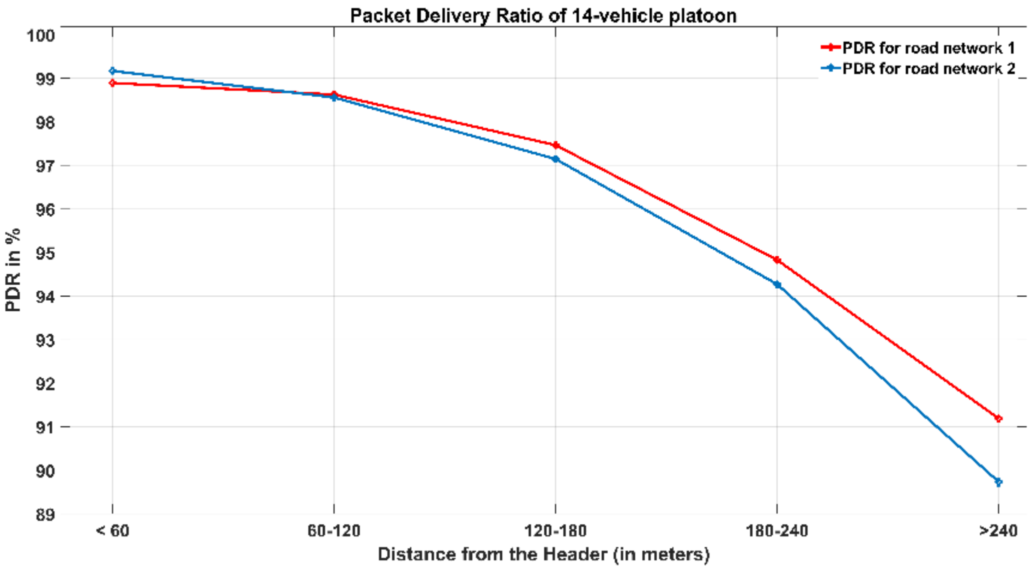
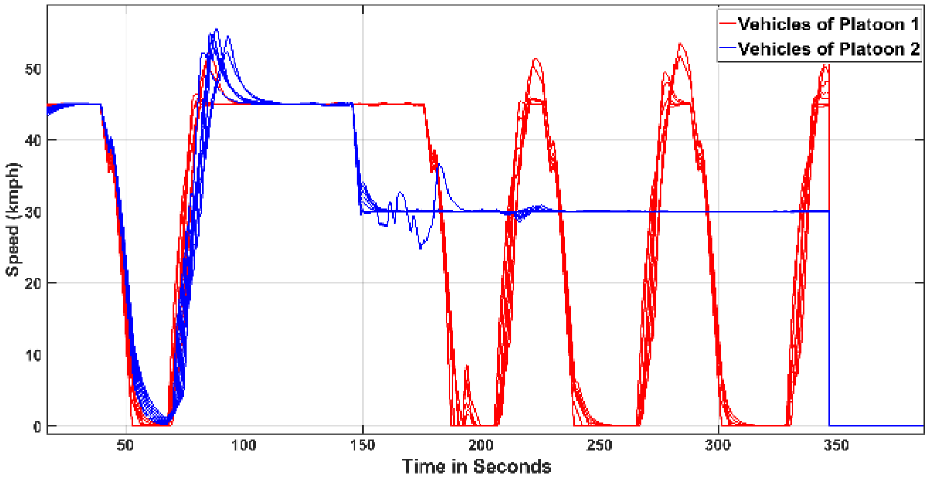


Fig. 8. *PDR for road network 1 and 2.*

Packet Delivery Ratio (PDR) is a good indicator of network performance. For a platoon, PDR is defined as the ratio of the number of packets broadcasted by the header to the number of packets that are received successfully by the follower. The packet delivery ratio of the header for road networks 1 and 2 is shown in Figure 8. PDR is calculated for an individual follower and the graph is generated by combining the PDR of vehicles that are within a particular distance from the header. At 50kmph, the distance between the header and last follower of the platoon is more than 250m. It can be seen that the PDR drops below 95% at distance greater than 180m. It indicates that the last four followers see more packet drops which justifies the time taken by those vehicles to settle to the desired speed and intervehicular distance whenever the header accelerates or decelerates. The effect is visible in the speed profile shown in Figure 7(a) and the intervehicular distance profile shown in Figure 7(b). As observed in Figure 7(a) near the 100s mark, the speed of platoon HGVs overshoot while accelerating from 0kmph to 50kmph.

Furthermore, the splitting and merging maneuvers are simulated according to the ARI protocol described in section 4. Initially, the protocols are tested with ideal communication constraints in road network 1 and road network 2. Once they are validated to perform as desired, realistic communication parameters are step up for the simulations along with the surrounding vehicles interference. In this paper, the splitting and merging protocols for road network 1 are validated but the results are not discussed here to avoid redundancy. Simulations for road network 2 with realistic communication setup are discussed here.

The splitting maneuver is simulated for a 14-HGV platoon travelling at 45kmph in road network 2. Immediately after the first intersection in road network 2, there is a lengthy section of the road which provides enough time for the maneuver to take place. Figure 9(a) shows the speed profile of the platoon before and after splitting. It can be observed that the splitting happens after the platoon crosses the first traffic signal. The 14-HGV platoon is split into Platoon 1 of seven HGVs and Platoon 2 of the remaining seven HGVs. Platoon 1 continues to move at 45kmph and Platoon 2 speed is reduced to 35kmph. Figure 9(b) shows the intervehicular distance of the platoons. Since Platoon 2 is moving at a slower speed, the gap between the platoons continue to increase for demonstrating the effectiveness of the protocol. In the real world, Platoon 2 is allowed to move at a higher speed and overtake Platoon 1. Since Platoon 2 is lagging behind the Platoon 1, it managed to reach the traffic signals whenever they turned green. Hence, the speed of Platoon 2 stayed at 35kmph for the rest of the simulation. This study demonstrates the capabilities of the splitting protocol.



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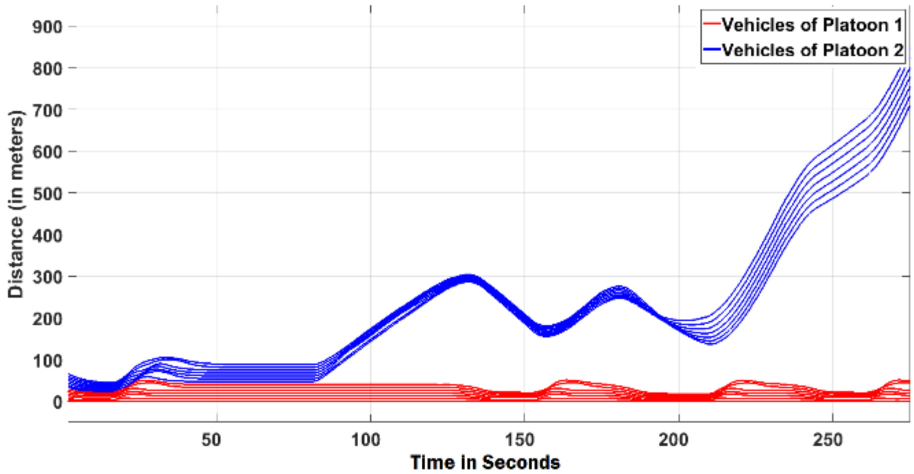

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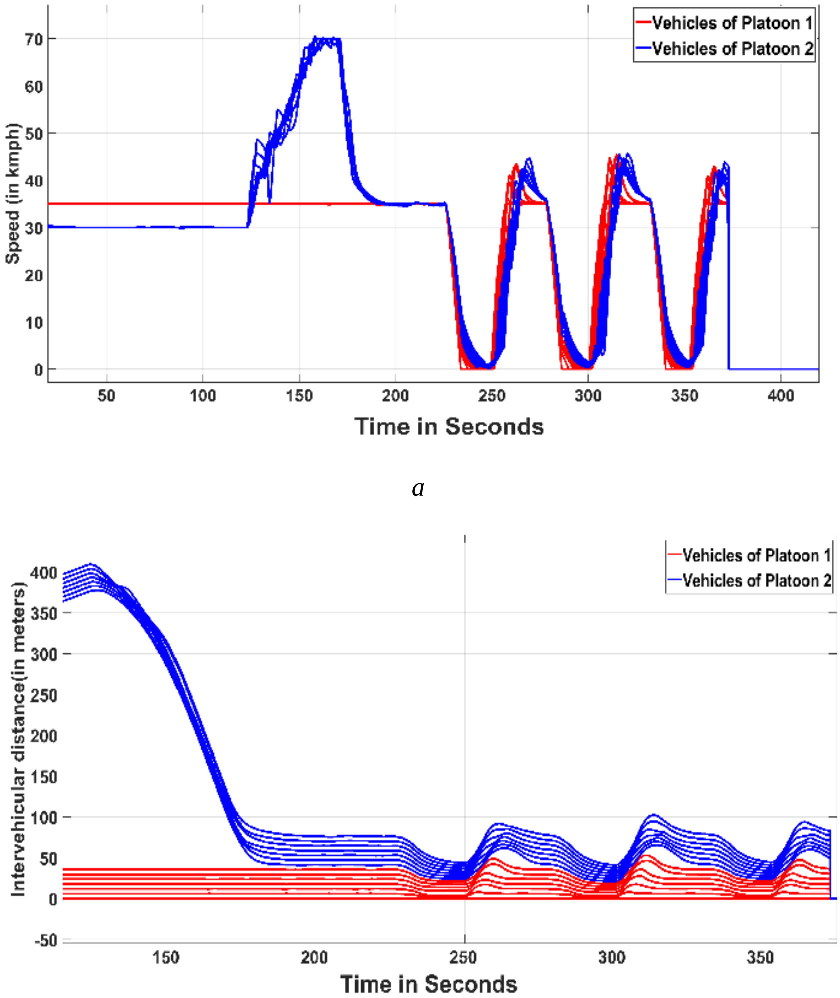
Figure 9. (a) *Speed profile of the platoon while realizing a split maneuver,*
(b) *Intervehicular distance profile of the platoons while realizing a split*

In the second set of simulations, two 7-HGV platoons are made to merge to form a 14-HGV platoon. Platoon 1 moves at 35kmph and Platoon 2 moves at 30kmph as shown in Figure 10(a). Immediately after the first traffic signal is crossed, the merging protocol is commenced. The HGVs of Platoon 2 begin to act as followers of Platoon 1 and start to accelerate to catch up with the Platoon 1. The PID controller that is proposed in this paper tries to merge the platoons as early as possible by accelerating the HGVs beyond their physical limits. However, Singapore road regulations do not allow HGVs to go over 70kmph. Hence, additional measures are added in the simulations to ensure that the speed limit is not violated. It is important to note that the design of the controller is not altered to handle the speed limits. During the implementation of merging maneuver, the intervehicular distance between the HGVs decreases as shown in Figure 10(b). Once it reaches the desired value, the followers decelerate to match with the speed of the header. This completes the merging maneuver and the platoon moves at a speed of 35kmph for the rest of the simulation.



a

b

Figure 10. ***(a)*** *Speed profile realizing a merge maneuver,*
(b) *Intervehicular distance profile realizing a merge maneuver.*

Quantization/measurement noise has been introduced in simulations to analyse the performance of the controller. The proposed control algorithm can track the header speed and maintain the desired intervehicular distances in the presence of noisy input and output measurements. The testing is carried out for a noise range [-1, 1]. The measurement noise is added to the speed parameter of the platoon vehicles acting at the input and output section. Figure 11 shows the PDR curves for a 14-vehicle platoon in three scenarios. These are: (i) Platoon communication with no communication interference from surrounding vehicles and no measurement noise, (ii) Platoon communication in the presence of interference from surrounding vehicles and no measurement noise and (iii) Platoon communication in the presence of interference from surrounding vehicles and non-zero measurement noise.

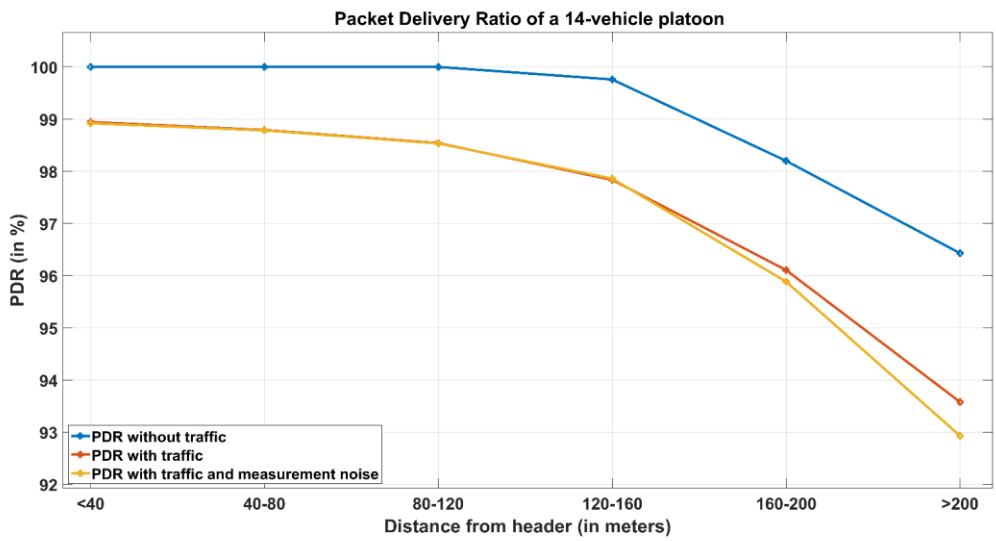


Figure 11. *PDR curves for a 14-vehicle platoon in three scenarios as listed.*

It is observed from Figure 11 that with the introduction of measurement noise causes a dip in PDR in the later vehicles of the platoon. Due to the measurement noise, the farther vehicles in the platoon will take slightly more time to reach the set-point. Hence, more packet drops are observed in the farther vehicles. This is evident in the

Figure 11. As the noise level is increased further, the intervehicular distances deviate from the desired value for the initial vehicles of the platoon.

5.2: Comparison with existing methodologies

This section of the paper compares the results obtained in this paper with the existing platoon control algorithm mentioned by authors in [5]. These researchers developed a CACC controller for HGV platooning which has two different layers, an upper layer controller and a lower layer controller[5]. The lower layer controller generally calculates the throttle and brake commands for the vehicles. The upper layer controller has three different operation modes-the Speed Control (SC) mode, the Gap Control (GC) mode and the Collision Avoidance (CA) mode. The controller in general switches between these individual modes to generate acceleration required for the platoon movement.

The vehicles maintain a $\mathbf{GAP_{SAFE}}$ between them which is determined by the speed and the maximum deceleration ability of the individual vehicles. As soon as the gap between the vehicles become lesser than $\mathbf{GAP_{SAFE}}$ the controller shifts to the collision avoidance mode to avoid crashes. On the other hand, the vehicles use either the speed control mode or the gap control mode in case the instantaneous gap between the vehicles are more than $\mathbf{GAP_{SAFE}}$. While this concept looks fine on paper, it has an inherent fallacy once it is deployed on a real-time system such as platooning. To explain this, let’s consider a situation where a platoon of vehicles is moving on a road, such as the YUHUA SMC section in Singapore. When the distance between the vehicles is more than $\mathbf{GAP_{SAFE}}$, the controller operates with either of the SC mode or the GC mode. In case of an emergency, such as a non-platoon vehicle intercepting the track of the platoon or the platoon needs to stop, the controller needs to shift from one control mode to the other. Vehicles communicating at 10Hz frequency with a $\mathbf{GAP_{MINIMUM}}$ of

1m, would have a higher risk of collision with the obstacle in front as well as with the other vehicles in the rear. Considering instances of packet drops which are unavoidable in V2V communications, the risk of collision increases by manifolds. However, this scenario will not affect the vehicles which are controlled by the controller developed in this paper as there is a single controller handling both the use cases. The controller in Eq.7 uses both policies, i.e., the speed control mode or the gap control mode together and hence the control applications work seamlessly under any speeds further decreasing the chances of collisions.

Following the controllers design, the testing is performed with various set-point inputs. Table 3 shows the performance in speed and spacing errors of platoons split scenario using metrics like IAE, ISE and MSE defined as in Eq.11 – Eq.13:

$$\mathrm{IAE} = \int_0^\infty \left| e(t) \right| \, dt. \tag{11}$$

$$\mathrm{ISE} = \int_0^\infty \left[e(t) \right]^2 \, dt. \tag{12}$$

$$\mathrm{MSE} = \frac{1}{N_t} \int_0^\infty \left[e(t) \right]^2 \, dt. \tag{13}$$

where $e(t)$ is the error signal and N_t is the total simulation time. The performance indices are significantly lower in the proposed PID controller in comparison to existing CACC algorithm for vehicle platooning used in [5]. It is observed from Table 3 that application of the proposed algorithm leads to significant reduction in worst case MSE for both speed and intervehicular distance.

Table 3. Comparison between speed and spacing errors of first and last vehicles in platoon split scenario for proposed PID and CACC algorithms.

Performance Measures	Speed errors			
	Proposed Controller		Controller used in [5]	
	First vehicle	Last vehicle	First vehicle	Last vehicle
IAE	$9.28x10^{1}$	$4.47x10^{3}$	$4.51x10^{3}$	$2.59x10^{4}$
ISE	$8.94x10^{1}$	$8.84x10^{4}$	$2.35x10^{2}$	$1.28x10^{5}$
MSE	0.249	246.996	0.656	353.91
	Spacing errors			
IAE	$8.21x10^{1}$	$5.75x10^{2}$	$3.38x10^{2}$	$9.56x10^{2}$
ISE	$2.43x10^{2}$	$7.23x10^{2}$	$5.86x10^{2}$	$1.26x10^{3}$
MSE	0.677	2.02	1.637	3.513

6: Conclusion and Future scope of the work

The concept of platooning is one of the important research topics within the V2X domain due to the benefits it brings to road transport. This paper addresses the platooning problem by proposing a look ahead platooning method using the PID control. The controller is designed with CD and CHT policies combined to capitalize on the benefits of both. The PID gains are optimally tuned using the PSO technique. Using an integrated simulation framework, the controller is evaluated for traffic conditions in Singapore. Both ideal and realistic V2V communication constraints are considered for simulations. It is observed that the controller performs well in all the scenarios and causes no collisions among the platoon members at steady and transient states. The speed and intervehicular distance profiles of the platoon show that the platoon performance is as per the design.

From the V2V point of view, the results indicate that the IEEE 802.11p standard can support CACC platooning. In our analysis, the time gap is set to 0.3s which is lower than the ISO 20035 standard's recommended minimum time gap of 0.5s. Rest of the parameters are as per the recommendations of ISO 20035 standard. Results indicate that the PID controller operated the platoon safely with a 0.3s time gap. Adding additional sensors such as Lidar and cameras will enhance the safety.

ARI protocols for platoon splitting and merging are proposed to facilitate all the platoon formation and dissolution. Sample splitting and merging scenarios are simulated to study the behaviour of a PID controller. Results indicate that the ARI protocols are effective in carrying out platoon maneuvers reliably. To further analyze the robustness of the controller, quantization noise is introduced. The simulations showed that the drop in PDR due to quantization noise at input and output measurements did not affect the controller's performance. Finally, the performance errors such as the IAE, ISE and the MSE are determined to show that the proposed PID controller is better in terms of error minimization when compared with other controllers from the literature.

For the future work, a small development will be to replace the use of Euclidean distance to account for the curvature of roads. This will help in studying large scale platooning for various complex urban networks throughout the world. Further, the controller design will be extended to support a variety of vehicles for heterogeneous platooning. Additionally, lower-level controllers will be modelled to consider the engine torque effect on platooning. From the V2V perspective, an analysis of the controller under deliberate communication failures will be of interest. Also, the time gap recommendation of the ISO 20035 needs to be analyzed to understand the impact on fuel consumption and traffic flow compared to our choice of 0.3s.

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Glossary of terms, Abbreviations and Acronyms

HGV	Heavy Goods Vehicle
PID	Proportional Integral Derivative controller
CD	Constant Distance
CHT	Constant Headway Time
ACC	Adaptive Cruise control
CACC	Cooperative Adaptive Cruise control
PSO	Particle Swarm Optimization
ARI protocol	Appeal, Reply, and Implementation
V2X	Vehicle-to-Everything
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
DSRC	Dedicated Short-Range Communications
WAVE	Wireless Access for Vehicular Environments
COM	Component Object Model
OBUs	On-Board Units
RSUs	Road-Side Units
PDR	Packet Delivery Ratio
NS3	Network Simulator
SUMO	Simulation of Urban MObility
SC mode	Speed Control mode
GC mode	Gap Control mode
CA mode	Collision Avoidance mode
IAE	Integral Absolute Error
ISE	Integral Square Error
MSE	Mean Square Error