Merging and Splitting Maneuver of Platoons by Means of a PID Controller

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Abstract—With the advent of automated cars in road networks, automobile engineers have now focused on platooning of Heavy Duty Vehicles (HDVs) on a much broader scale. A platoon is a number of vehicles that are travelling together and electronically connected with a certified driver in leader vehicle of the platoon while the other vehicles follow autonomously. While platooning reduces the number of drivers generally required for standalone vehicles, it also improves fuel efficiency reducing the air-drag between the trails of vehicles. This paper mainly focus on the merging and splitting of n-vehicle platoon using the PID controller algorithm, which is one of the most used algorithms in process industries. The PID controller has been proposed using VISSIM which has been used in conjunction with MATLAB. The results presented show the efficacy of the PID controller algorithm and extends its usability for platoon maneuvers.

Keywords—PID controller, Platooning, Platoon Splitting, Platoon Merging, VISSIM, MATLAB.

I. INTRODUCTION

The increasing dependence on transportation in the recent days has eased our lives in many ways. The continuous accruing need of this dependence has led to different problems in terms of traffic congestion and increasing the volume of emitted harmful compounds. During the past years, there has been an exponential increase in the demand of road based freight transportation. The major reprise to such increased demand has been the concept of heavy duty platooning which can be seen as the concept of railways transcended to a highway road networks between cities and across countries. Platooning enables a number of vehicles to drive within a short, acceptable distance from each other thereby allowing them to act together as one unit. With vehicles moving in a platoon, there has been a steady increase in the traffic flow with reduced human labor. While on one hand, where platoons travelling as a single unit can save a lot of space on freeways so that the highway section can accommodate much more traffic, on the other hand they also reduce fuel consumption by significant air drag reduction. Statistically freight transport in the world consumes millions tons of fuel every year and an even modest decrease in fuel consumption can lead to humongous savings for thousands of vehicles on a much broader scale.

Although the study of platoons has been in vogue for a number of years now [1], most of the methodologies have concentrated on the platoon control of vehicles using the well-known strategies such as the Adaptive Cruise Control (ACC) or its most recent and sophisticated version i.e., Cooperative Adaptive Cruise Control (CACC). Rajamani et.al. in [2] have implemented platooning and has considered it as an extension to a simple Cooperative Control (CC) strategy with introducing the braking system for the followers to imitate. Many research projects as in the literature have been steered to analyze the challenge and take care of the definite benefits of vehicular platooning. While the needs of intermediate end users considering their safety and the operational benefits have been considered by the project PROMOTE-CHAUFFEUR I and II [3], the KONVOI [4] project which firmly looks into the movement of electronically operated trucks in a 5 vehicle platoon. One of the most talked-about research projects under the California Institute of Technology is the PATH project which deals with multiple issues of platooning and mainly addresses the traffic related issues [5]. The ENERGY ITS [6] project evaluated the energy efficiency for automated platoons and concentrated on energy savings which is one of the prime deliverables of recent day research. Another talked about research project has been the SATRTRE project [7]. The crux of the same had been the analysis of mixed traffic in highway situations considering issues of safety, comfort and fuel efficiency. While the most recent project on platooning, i.e., the COMPANION project [8] focus on the creation, operation and coordination of platoons, most of the literature above broadly overlooks platooning from the application point of view. They use the much approved CACC algorithm which the work in this paper choses to improve and apply for platoon manoeuvres such as splitting and merging.

Vehicle platooning has been extensively dealt by Alam et.al [9] [10] [11] although most of their research focus primarily on fuel usage reduction. It is a well-known concept that for heavy duty platooning, if the platoon members move with the least possible distance, the air-drag between the vehicles decrease improving the fuel efficiency [11]. This has been the nub of most of the literature in [9] [11] [12]. In [13], Alam et.al designed a system model for a Heavy Duty Platoon and determined the fuel efficient behavior of the same while traversing an up-hill or a down-hill terrain on Swedish Freeways. While their work entails the use of optimal control strategies, this paper uses the PID controller methodology, which is one of the most commonly used industrial controllers.

In this study, the vehicles in the platoon are CACC capable which incorporates V2V communication between them using the constant distance topology [14]. The paper broadly relates to the platoon management protocols such as the splitting and the merging, which is considered as one of the most elementary maneuvers. In the merge protocol two platoons of different lengths merge to become one single
platoon unit, whereas in the split protocol, one platoon separates at a specific point to form two different Platoons.

The rest of the paper is organized as follows: Section II deals with the modeling of the vehicular platoon system considering \( n \) number of trucks in the platoon. The nomenclature of the header, the leader and the follower vehicle has been clearly indicated with their implications that they have on the controller performance has been mentioned in this section. Section III deals with the platoon maneuvers and how the splitting and merging has been realized in the Singapore road network. Section IV shows the simulation results and curves of the speeds and intervehicular distance of the platoons while the splitting and merging maneuvers happen. Finally, Section V deals with the conclusion and the future scope of work.

II. PLATOON NOMENCLATURE AND MODELLING

a) Terminology: This section depicts the terminology of how the platoon of vehicles has been articulated for the paper and has been used in the rest of the paper henceforth.

![Figure 1: A vehicle Platoon for 3 HDVs.](image)

The figure 1 above shows a case of 3 HDVs travelling in unison, depicting their direction of motion with wireless connection between them. For this case, the first vehicle would be termed as a header, which would be same once the platoon extends for a \( n \) number of vehicles. The header vehicle is driven by a certified driver which determines the speed of movement and hence it is imitated by the other vehicles of the platoon. It can be seen that for the second vehicle, the first vehicle would be considered as the header as well as the leader, while for the third vehicle, the second one would be considered as the leader. The first one would always be the header in any case. Similarly extending this concept for a representative case of \( n \) member platoon, it can be written that for the \( n^\text{th} \) vehicle of a platoon, it would be the follower and the \( n-1^\text{th} \) vehicle would be leader.

b) Modelling of the Platoon and the Controller: This section of the paper focuses on the mathematical modeling of the platoon for longitudinal motion of vehicles. A vehicle platooning system can be considered similar to a mass-spring-damper system [15]. Similar to the mass spring damper system, the platoon of vehicles follow the control law of

\[
m_i \ddot{x}_i + b_i \dot{x}_i = u_i
\]

where the index \( i \) denotes the \( i^\text{th} \) vehicle in the platoon, \( m_i \) is the mass, \( b_i \) is the effect of damping, \( x_i \) is the longitudinal position of the \( i^\text{th} \) vehicle and \( u_i \) is the input information of the same. In this work, the controller has been designed on the basis of the most well-known control algorithm used in process industries, i.e. a Proportional Integral Derivate (PID) control. The main aim of the controller for this scenario would be to stabilize a platoon of length \( n \), such that the follower would be tracking the leader vehicle in a longitudinal fashion. The crux of the control would be to keep a safe inter-vehicular distance and to maintain a relatively constant speed with the least use of brakes while in motion and applying them as fast as possible in case of an emergency. Ideally in such cases, the step response of the platooning system would normally be an over-damped one. The primary idea behind this has been the fact that if the system is under-damped, it would take more time for the followers to react to the control commands fed to it and might lead to catastrophes while the vehicles are travelling at high speeds. It has also to be borne in mind that the rise time and the settling time of the response should be as less as possible so that while the vehicles are in motion, the platoon operates as a single unit and that is why PID controllers have been chosen for this work. PID controllers are also the most easily implementable ones. The PID gains are designed based on the tracking error and all the gains of the system are balanced to attain a trade-off between the acceptable system responses mentioned above.

A conventional PID controller can be formulated as

\[
u(t) = k_p e(t) + k_i \int_0^t e(t) dt + k_d \frac{d}{dt} e(t)
\]

where \( k_p, k_i \) and \( k_d \) represents the proportional, integral and derivative gain of the system. The corresponding transfer function from the error signal \( e(t) \) to the input signal can be written as

\[
u(s) = \frac{U(S)}{B(S)} = k_p + \frac{k_i}{s} + k_d s = \frac{k_p s^2 + k_i s + k_d}{s}
\]

For this control problem, the difference between positions of the leader and the follower has been taken as an error signal for the controller. This is a very pragmatic approach for longitudinal control of vehicle platooning. The controller receives the reference position \( x_{\text{ref}} \) which is the position of the leader \( x_1 \) and the position of the follower \( x_{fi} \) for each of the \( i \) vehicles. The difference of the same is fed to the controller as error signal and the velocity of the system has been calculated at every instance based on the acceleration. The acceleration of the follower vehicle has been calculated for each leader-follower set of vehicles.

Using the concepts mentioned in [7], the force required for moving a platoon of vehicle can be considered as

\[
m u = F_x - mg \sin \theta - f_x mg \cos \theta - \frac{1}{2} C_{\text{aw}} (u + u_{\infty})^2
\]

where the values of parameters and their definitions have been illustrated in Table 1.

<table>
<thead>
<tr>
<th>Parameter Symbols</th>
<th>Definition</th>
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<tbody>
<tr>
<td>( F_x )</td>
<td>Tractive Force</td>
</tr>
<tr>
<td>( C_d )</td>
<td>Drag Coefficient</td>
</tr>
<tr>
<td>( A_f )</td>
<td>Frontal Area of the vehicle</td>
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This is to be noted that $u_w$ is the wind velocity which is positive for a headwind and negative in case of a tailwind. The drag co-efficient ranges from 0.2 to 1.5 for HDVs.

For formulating the PID controller, few variables have been assigned. The variable $dx_p$ represents the distance between the $(i-1)^{th}$ & the $i^{th}$ vehicle of the platoon, where $i^{th}$ is the corresponding follower vehicle in the platoon whose acceleration is to be determined. $x_{i-1}, x_i, x_n$ represents the coordinate positions of the leader, follower and header respectively. The velocity and acceleration of follower vehicle are represented by $v_i, a_i$. $v_i, a_i$ signifies the velocity and acceleration of header vehicle. Considering $dx_{jn}$ as the distance between the header & the $i^{th}$ vehicle in the platoon, the PID controller in (3) can be written as

$$ a_i = \left( a_n + a_p \right) k_p + \left( v_n - v_i \right) k_v + \left( v_i - v_j \right) k_v + k_i \left( x_n - x_i - hd_1 \right) + k_d \left( x_i - x_j - hd_2 \right) $$

The desired distance between the header and the follower vehicle and between the leader and the follower vehicle are denoted as $hd_1$ and $hd_2$ respectively.

The gain variables $k_p, k_v$ and $k_d$ have usual interpretation.

III. PLATOON MANEUVERS

Most of the present-day researchers in [2] [3] [4] have focused on their studies on platooning following the basic assumption that the platoons start from the base station and remain as such throughout the venture. This paper tries to improve this used case scenario circumscribing the most basic platoon management scenarios such as the split and the merge. While in the split scenario where one platoon (with at-least 2 vehicles) breaks up into two smaller platoons and travels to their defined intended locations, two platoons travelling in a same lane merges to become one single platoon in the merge scenario.

Figure 2 vividly depicts the merging scenario of two platoons with 3 and 4 HDVs respectively in them. The leader vehicle of each platoon has been color coded to red while the rest of the platoon members are coded to be black for the sake of clarity.

The merge maneuver is always commenced by the platoon leader of the platoon 2 when the platoons come close to each other within some prescribed distance. The distance is generally judged based on the communication constraint between the vehicles and has not been described here as it is not within the scope of the work. The merging scenario can be realized in three different steps: Appeal, Reply and Implementation (abbreviated as A.R.I) as in the figure 3.

**Appeal Merge**: The leader of the platoon 2 as shown in figure 2 appeals for platoon merging to the leader of the first platoon, i.e. platoon 1. This communication is generally realized wirelessly and is achieved using the Dedicated Short Range Communication (DSRC) which has been standardized in IEEE 802.11. There are several reasons that DSRC has been used, but the most prominent of them has been the fact that DSRC operates at around 5.9 GHz is designed to support various operations and has a high transmission range varying from 100-1000 meters which is highly suitable for data-exchange for vehicles in platoons. It has to be borne in mind that there can be certain cases of the appeal not raised due to communication failure between the HDVs, and in such cases the appeal requests from the platoon which wishes to join the platoon ahead would necessarily be re-raised.

**Reply Merge**: The leader of the platoon 1 either accepts or rejects the appeal based on its current scenario. Reasons for rejection could be such that the platoon 1 could be going through some other complex platoon management scenarios themselves such as lane changing operations of its own or may be due to a communication failure. In such cases, platoon 2 needs to wait until a valid acknowledgement is received.

**Implementation Merge**: Once the acknowledgement has been received and that the merging scenario has been permitted, there could be a proper information interchange between the last vehicle of the platoon 1 and the leader of the platoon 2. The data packet which has the platoon 2’s label addresses are exchanged between the vehicles of platoon 1 and vice-versa. The speed of the platoon 1 and platoon 2 are been matched and
the control action starts considering the distance between the leader of the platoon 2 and the last follower of platoon 1 as error signals. This entire protocol takes place in a fraction of seconds depending on the communication interface between the platoons. The control action decreases the intervehicular gaps of the platoons and matches the inter vehicular gap $hd_1$ and $hd_2$ as mentioned in the earlier section. Once the merging scenario has been realized, the control of the entire merged platoon shifts directly to the leader of the platoon 1 and the entire set of platoon of vehicles move as intended.

The split scenario can be similarly realized for the platoons. The only difference has been the implementation section which has been explained below. The AppealSplit and ReplySplit have been omitted in this section for the sake of brevity.

**ImplementationSplit**: As similar to the platoon merging scenario, the split scenario has been realized similarly and can be explained illustrated with the figure 4 below:

![Figure 4: Platoon Split Scenario](image)

From the figure 4 it can be seen that the third vehicle from platoon 1 has put forward a split request. Once the split request from the third vehicle has been acknowledged by the header of the first platoon, the third vehicle is assigned to be the header of platoon 2. The speed of the platoon 2 is reduced and the platoon 2 naturally falls back in distance from platoon 1 realizing the split. Once the platoons are split, the platoon 2 is dealt as a standalone platoon and can move as desired.

**IV. SIMULATION AND RESULTS**

In this section, the platoon maneuver scenario has been realized using MATLAB and VISSIM [16]. VISSIM is a micro-simulator which has the capabilities to replicate and control the trajectories of vehicles in simulation for both right hand and left hand driving scenarios. This is one of the major advantages of using VISSIM over the open source traffic simulator SUMO [17] which allows only left hand traffic driving scenarios. VISSIM even allows the access of vehicular information from infrastructure as well as from other vehicles with simulation time as low as 100ms. With simulation time as low as this, it is generally easy to track the vehicle parameters to the smallest time interval, thus providing control on the entire platoon of HDVs.

The figure 5 shows the Alexandria Road freeway corridor in Singapore as implemented using the “Toggle Background Maps” function in VISSIM which has been used to overlay the section of the road on the maps.

![Figure 5: The road section of Alexandria Road, Singapore](image)

The vehicles have been injected into the network at the exact link and the lane as desired by the user. VISSIM allows certain types of vehicle models, out of which the HDVs were used for the same as the controller has been developed for platooning of trucks in the road network. Considering the challenges of extending the simulation to a much more holistic environment, the controller algorithm uses the “Co-ord” function. The co-ordinate function refers to the exact GPS position of the trucks with respect to the entire map area plotted using VISSIM and hence, the code for the algorithm can be extended to any networks just putting the layover map of desired location. The simulation has been done for a platoon of 14 HDVs moving from a base station to another while moving through the freeway. The speed profile of the HDVs are shown in figure 6 with a total simulation period of 1000 seconds. The controller algorithm used in (5) has been used for a set of 14 vehicle platoon with controller parameters $k_p = 900, k_i = 2250 \text{ and } k_d = 200$.

![Figure 6: Speed profile of the platoon members](image)

Figure 6 shows the speed tracking of the header of the platoon by the rest of the platoon vehicles. While the header starts at a speed of 50 Kmph, it increases speed to 70 Kmph, and again to 90 Kmph. The speed stays at 90 Kmph for a sometime until it reduces to 71 Kmph. Figure 6 shows the close tracking of the platoon followers to the platoon header while the speed profile varies within the simulation proving the efficacy of the controller.

The difference in distance of each vehicle in the platoon from the one in front has been shown in figure 7 below, which is kept to be at a desired distance of 5 meters from each other. A small jagged section of the curve represents the change in speed as evident in figure 6.
The next section illustrates the platoon maneuvers using the same controller.

**i. Merge Maneuver:** For the merge maneuver, a platoon length of 14 HDVs have been considered. The two platoons move at a fixed speed with a small distance between them. The work done in this section follows a small assumption that both the set of platoons has to be at the same speed and within a small prescribed gap between the platoons before the AppealMerge has been raised. This assumption in strictly in-line with the actual traffic scenario as platoon of vehicles ready to merge would already have exchanged their parameters such as speed and acceleration before the merge scenario could be realized. While on a highway when the platoons are ready for a merge, they need to close to each other for the AppealMerge to be raised and accepted. In-case there is any random intervehicular gap between the platoons (other than the allowed gap), the communication would fail and hence the merging maneuver couldn’t be realized. The prescribed distance for the merge hasn’t been described in here as the communication scenario and its limits are not within the scope of the present work. For the simulation scenario, it is considered that both the platoons move at 70 Kmph at first. After a certain time when the header of platoon 2 follows the A.R.I protocol as mentioned above and raises an AppealMerge to join, the header of the platoon 1 accepts the RequestMerge and implements the same for the set of vehicles in the platoon.

**ii. Split Maneuver:** The split maneuver has been realized in a different methodology. While a platoon of 14 vehicles are seen to move in tandem, it has been considered that two platoons split after the 7th vehicle. After the request has been raised and acknowledged, the vehicle 8 is assigned to be the header of platoon 2 as mentioned in section III above. Figure 10 below shows the speeds of all the vehicles in the platoon to be around 70 Kmph before the commencement of the split maneuver. Once the AppealSplit and ReplySplit have been accepted by the header of the 14 vehicle platoon, the ImplementationSplit starts by decreasing the speed of the platoon 2. The decrease in speed can be seen from the above figure where the vehicles speeds wane to 51 Kmph. With the reduced speed, the distance between the platoons increase until the two platoons are dealt as standalone ones. The increase in intervehicular distance between the last vehicle of the platoon 1 and the vehicles of platoon 2 after the split is
also evident from the figure 11. While the position of the platoon 1 has been kept as reference, the ever increasing distance of the other vehicles in platoon 2 clearly depicts that the split maneuver has been properly realized.

![Figure 10: Speed profile of platoon 1 and platoon 2 while splitting](image)

![Figure 11: Intervehicular distance between the last vehicle of platoon 1 and all vehicles of platoon 2](image)

**Conclusion and Future Work**

In this paper, we have considered two platoon maneuvers, i.e., the splitting and the merging. While platoon maneuvers have been attempted by a number of researchers using basic linear control algorithms, this paper proposes a newer PID controller methodology to work out the splitting and merging scenario of platoons. The result section shows the efficacy of the controller not only for platoon movement, but also for platoon maneuvers, the curves illustrates that the platoon of vehicles are string stable. The string stability of the vehicles in a platoon of vehicles guarantees that any disturbance that appears in between the vehicles does not propagate to the end of the stream of the platoon and hence terms the entire system to be stable in terms of coercive movements. In the future work we plan to introduce communication constraints into platooning. Splitting and merging maneuvers with other non-platoon members in the network would be another point of interest as non-platoon members would serve as disturbance for the maneuvers to realize from the communication point of view.

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