A New Topology for Homogeneous Vehicular Platoon under Disturbances

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***Abstract*—Vehicle platooning has attracted a lot of interest in research in the last decade as it introduced a solution to many problems in traffic flow, safety, fuel economy, and reducing CO_2 emissions. As the cost reduction is crucial and necessary to the business's sector, in this paper, communication cost reduction is achieved via proposing a new topology called Bidirectional Odd Leader (BDOL). The BDOL topology is advantageous in terms of cost compared to the BDL topology due to the BDOL is a relaxation of the BDL topology. The string stability of the dynamical system with the proposed topology is first proven through numerical comparison with BDL topology. Then, the performance of the proposed topology has been evaluated by intensive computer-based simulation. A homogeneous platoon consisting of eight vehicles is created and tested on a straight and curved track, while keeping a small desired inter-vehicle distance. We evaluated the performance of our topology, and tested the string stability in many scenarios. These scenarios include platoon moving on a straight track with or without disturbance, lastly a velocity disturbance produced by a curved track affecting the platoon is also investigated. The results demonstrate the effectiveness of the proposed topology in achieving the intended objectives.**

***Index Terms*—Vehicle platoon, dynamical system, topology, disturbance, tracking trajectory, Simulation of Urban MObility (SUMO)**

I. Introduction

Intelligent Transport System (ITS) is a various technologies applied to transportation aiming to improve safety, efficiency, and mobility. Vehicle platoon is one of the expected examples of ITS technologies [1]. A vehicle platoon is a group of vehicles that communicate and follow each other leaving a gap between them, i.e. the inter-vehicle distance. Platooning has giant benefits for drivers, environment, and even economic advantages. Since, the majority of traffic accidents are caused by human errors, driving in a platoon is comfortable for the drivers. In connected automated driving, the brake is automatic and as the drivers will follow the leading vehicle, this will allow them to do other tasks or just take a break. Moreover, the vehicles will be close to each other, which leads to a decrease in aerodynamic drag and thus results in fuel savings and less emission of carbon dioxide (CO_2). A platoon is a military unit that runs by a lieutenant and consists of two or more squads. Taking into account the military is a symbol of organization and obedience to the commander's orders, it is an ideal model for a group of vehicles driven by the leading one [2].

In the late 1980s, the first platoon experience was in California, where the PATH program was established [3−5], followed by a number of European projects (e.g. KONVOI, SARTRE, ENSEMBLE, etc.) and the Japanese project Energy ITS [6−12]. Additionally, Peloton Technologies, an American commercial company, seeks to improve both safety and fuel efficiency [10].

Various studies have been conducted to ensure the stability of platoon in the presence of disturbances. For example, Hu *et al*. [13] studied the string stability for heterogeneous connected vehicle platoons in case the leading vehicle is disturbed by exogenous disturbances. In [14], a comparative work was conducted to study the effect of disturbance among different topologies. In [15], the platoon control problem suffering from multiple disturbances and Denial of Service (DoS) attacks has been investigated. The influence of information flow topology on the stability of homogeneous vehicular platoons was studied in [16], where the acceleration/deceleration of the leading vehicle can be considered as disturbances in a platoon. In [1] Jiang *et al*. studied the stability of a vehicle platooning when varying the velocity of the leading vehicle which is again viewed as a disturbance on the platoon. Authors in [17], studied the scalability limitation of a homogenous platoon. In their simulation study they also viewed the acceleration/deceleration as a platoon disturbance.

The vehicular platoon that travels on a straight road has been studied extensively, but on the other hand, there are seldom studies related to the movement of platooning on a curved road. Driving on curved roads has been studied in [18−20].

The concept of string stability is a critical task of platoon control that was broadly studied in the literature. String stability means that the errors that arise when a disturbance occurs are not amplified and fade away through the string of vehicles [21]. In a vehicular platoon, the stability of each vehicle does not mean string stability; additionally, stability or string stability does not guarantee safety versus collisions [22].

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It is noted that most of the published works have ignored the communication cost. However, in applications, the communication cost is of primary interest. One way of reducing the communication cost is by lowering the number of followers that receiving the leader's data broadcasting. In this work, we try to achieve low communication expenses by proposing our Bidirectional Odd Leader (BDOL) topology, whereas continuing to distribute information to all platoon members, the data from the leader is only received by the vehicle with an odd index

The objective of this paper is to study the vehicle platoon behavior under the new topology such that the follower' velocities converge to the velocity of the leader asymptotically and each vehicle can maintain the desired inter-vehicle distance taking into accounts some types of disturbances.

This paper is organized as follows. In Section II, the problem considered in this paper is described. The spacing policy, trajectories, communication network and its relation with graph theory, as well as information flow topology also exist in this section. In Section III, the BDOL topology is proposed. Disturbances affecting the platoon are explained and simulated in Section IV. Section V provides the concluding remarks.

II. Problem Statement

A. Vehicle Longitudinal Dynamic Model

To investigate the behavior of a platoon of vehicles, an appropriate model is necessary.

Denoting by $p_i(t)$, $v_i(t)$, and $a_i(t)$ the *i*th vehicle's position, velocity, and acceleration of vehicle *i*. The state of the vehicle *i* is explained by the vector $\bar{\mathbf{x}}_i(t) = [p_i(t), v_i(t), a_i(t)]^T$. The dynamical system is given by,

$$\frac{d}{dt}\bar{\mathbf{x}}_\mathbf{i}(t) = \mathbf{A}\bar{\mathbf{x}}_\mathbf{i}(t) + \mathbf{B}u_i(t),\ i = 0,1,\cdots,N \qquad (1)$$

where

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\tau \end{bmatrix} \qquad \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 1/\tau \end{bmatrix}$$

$N+1$ is the number of homogeneous vehicles in the platoon. The parameter τ is an inertial time delay and u_i is the control input.

B. Spacing Policy and Trajectories

The spacing strategy is regarded as one of the key elements for the vehicle platoon's formation objective [23]. The inter-vehicle distance which has a decisive effect on the platoon's dynamic behavior is defined by the spacing policy, [24]. Two major different types of spacing policies are Constant Spacing Policy (CSP) and Variable Spacing Policy (VSP). In CSP the inter-vehicle distance is always fixed regardless of the platoon cruising velocity [13]. On the other hand, VSP is a varying as a function of the vehicle's speed. Although the CSP needs the use of lead vehicle information, it is capable of getting string stability in case of high traffic density, while VSP does not need more information from other vehicles. As consequent string stability is guaranteed based on the onboard data. Further the traffic density is low according to the vast inter-vehicle distance [25]. In this work, the constant spacing policy is adopted.

The desired tracking trajectory is generated by the leading vehicle which is considered a command generator, and all following vehicles must synchronize with it, but sometimes information from the leader maybe not accessible to all the follower's vehicles [26].

C. Communication Network

In this section, we use graph representation and notations of the system. A weighted digraph $\mathcal{G} = (\mathcal{V}, \mathcal{E}, \mathcal{A})$ where $\mathcal{V} = \{1, 2, \cdots, N\}$ denotes an index set of *N* nodes, $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ denotes an edge set of paired nodes with (*j*, *i*) representing a directional edge (information link) from node *j* to node *i*. The adjacency matrix $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N \times N}$ denotes a weighted adjacency matrix with $a_{ij} \geq 0$ being the adjacency element (weight) of the edge (*j*, *i*).

Ge *et al*. (2022) mention that "The digraph $\mathcal{G}$ has a spanning tree if there exists at least one node, called the root, such that there is a path from this node to any other node in the graph" [27].

From the point of view of graph theory, it is natural to consider V2V communication network of *N* follower vehicles (nodes) as a weighted digraph since that the information links among them are bidirectional and there is always a link from the leader to each follower.

In addition to the adjacency matrix there are many important matrices associated with the digraph $\mathcal{G}$:

The Laplacian matrix is defined as $\mathcal{L} = \mathcal{D} - \mathcal{A}$, where $\mathcal{D} = \mathrm{diag}\{d_1, d_2, \cdots, d_N\}$ with $d_i = \sum_{j=1}^{N} a_{ij}$.

To describe the communication between the leader and followers a pinning matrix $\mathbf{G} = \mathrm{diag}\{g_{11}, g_{22}, \cdots, g_{NN}\}$, is also defined. Finally, the $\mathcal{H}$ matrix which equal $\mathcal{L} + \mathbf{G}$ is defined.

It is well acknowledged that the eigenvalues of either the adjacency matrix $\mathcal{A}$, the Laplacian $\mathcal{L}$, or the $\mathcal{H}$ matrix essentially represent some global knowledge of the graph (communication network).

D. Information Flow Topology (IFT)

The IFT describes the way how a vehicle exchanges information with its surrounding vehicles [28]. The most common communication topologies are predecessor following (PF), predecessor following leader (PFL), bidirectional (BD), bidirectional leader (BDL). Basically, IFT systems can be of two types; radar-based (BD & BDL) and inter-vehicular communication-based. Before the wide use of inter-vehicle communications in a platoon, communication was limited to the radar-based which a vehicle can exchange information just with its neighbor front and back vehicles [16]. In BD topology, each vehicle exchanges information only with its preceding and following vehicle, hence a linear network topology will be created. We'll concentrate on the BDL topology here because it's relevant to our work.

In BDL topology, if the transmission range is large enough then the leading vehicle sends information to all vehicles as in Fig. 1 (a). Unicast messages are used by the lead vehicle to deliver data to every member of the platoon, while multi-hop communication is used by the members of the platoon to send data to the leading vehicle. When we use the concepts of graph theory, BDL is a single-tree topology in which the leading vehicle is the root and the rest of the vehicles are the leaves [29].

As a result of the many developments in V2V communication, a number of platoon topologies have been designed such as the two-predecessor following and multiple-predecessor following [30] to achieve particular goals.

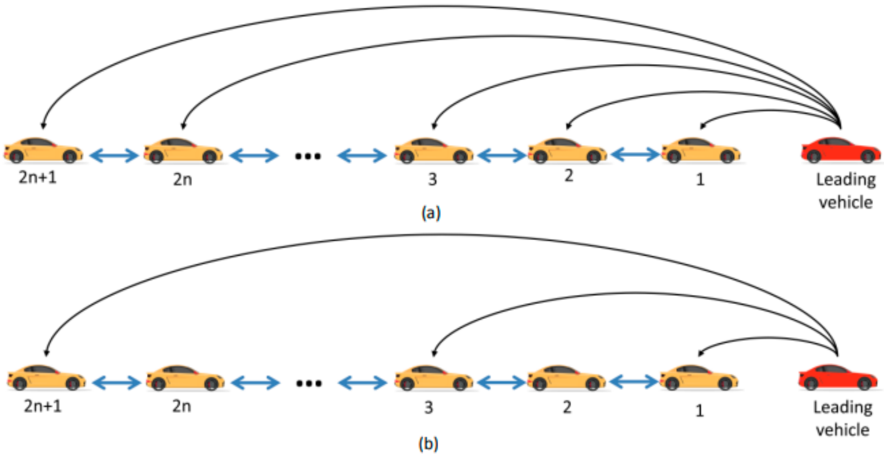


Fig. 1. (a) BDL topology, (b) BDOL topology.

III. The Bidirectional Odd Leader IFT

A. *Proposed Communication Topology (BDOL)*

In this study, a homogenous platoon with one leading vehicle and N followers is considered. We propose a Bidirectional Odd Leader (BDOL) topology of bidirectional type with two radars or LIDAR installed on each vehicle, front and back to detect the status of its adjacent two vehicles (successor and predecessor). The idea is inspired by BDL topology and nevertheless takes into account the cost reduction of the required communications. We consider a topology where the communication between the leading vehicle and the number of followers is reduced. A follower with an odd index can pick up the speed and location status of the leader by wireless communication to keep the cost low. A feature of our topology is that while maintaining receiving information to all platoon members the communication cost was notably reduced by reducing the recipient followers who take information from the leader. We assume that N is an odd number so that the leader information is transmitted to the last one of the platoon. Fig. 1 (a) and Fig. 1 (b) illustrate the BDL and BDOL topologies respectively.

B. *Performance of the Proposed Topology*

In this section, numerical simulation experiment is performed to illustrate the performance of our proposed topology with respect to other topologies. We adopted the prototype model in [14] i.e., (BDL topology). The simulations were run in MATLAB/Simulink for homogenous platoon consisting of four vehicles including one leading vehicle and three followers (i.e $N=3$).

The desired inter-vehicle distance is d=5 m , the inertial time delay $\tau=0.25$ s, the feedback gain matrix **K**=[1.0000, 2.1211, 0.7494], and the coupling gain c=1, while the initial positions for the vehicles $0,1,2,3$ are $45,30,15,0$, respectively, and the initial velocity for each one is set as 20 m/s as in [14].

The Laplacian and pinning matrices for BDL and BDOL are given in Table I. and the control input u_i is represented as:

$$\begin{aligned} &u_0(t)=0 \\ &u_i(t)=c\mathbf{K}e_i(t),\ i=1,2,\ldots,N \end{aligned} \tag{2}$$

where e_i is the cooperative tracking error defined as:

$$e_i=\sum_{j=1}^{N}\left\{a_{ij}\left(x_j-x_i-d_{ij}\right)\right\}+g_{ii}\left(x_0-x_i-d_{i0}\right) \tag{3}$$

TABLE I: The Laplacian and Pinning Matrices for BDL & BDOL

Topology	Laplacian matrix	Pinning matrix
BDL	[1, −1, 0; −1, 2, −1; 0, −1, 1]	[1, 0, 0; 0, 1, 0; 0, 0, 1]
BDOL	[1, −1, 0; −1, 2, −1; 0, −1, 1]	[1, 0, 0; 0, 0, 0; 0, 0, 1]

Fig. 2 shows the result of comparing the performance of each topology. The BDL is represented by the red curve while our BDOL topology is shown as the blue one.

The main goal of the relaxation method is to reduce communication costs. We can see from Fig. 2 that there are no much differences between the blue and the red curves (and even in some intervals and from the computation experience that the above relaxation method works better than BDL topology).

If we let $\epsilon_1, \epsilon_2, \epsilon_3$ denote the deviations between the red and blue curves then we find that of $\epsilon_1 \le 1.107$, ϵ_2 and $\epsilon_3 \le 1.719$. Also we noted that BDOL reaches the steady state faster than the BDL.

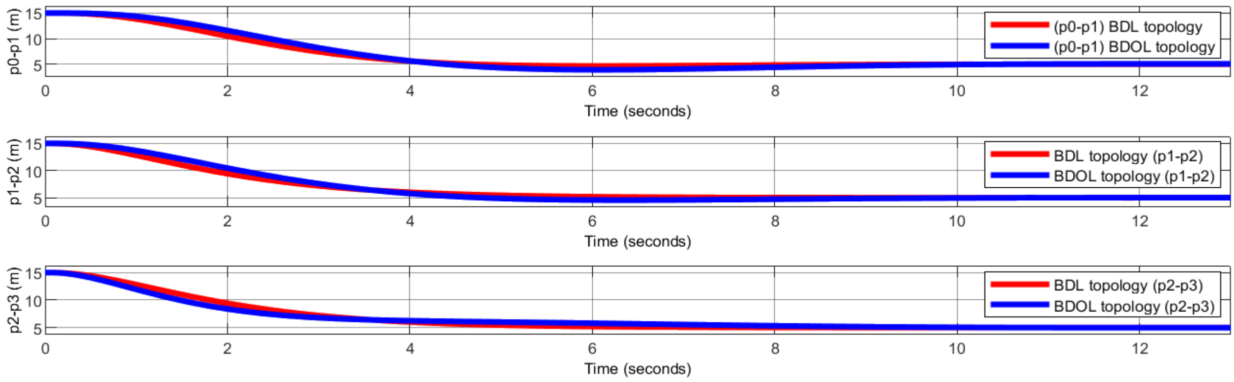


Fig. 2. BDL & BDOL topologies.

IV. Disturnances and Simulation

A disturbance is a signal that tends to adversely affect the value of the output of a system. The topology structure is mostly responsible for determining how disturbances propagate, whereas the design of the feedback gains only has a minor impact [31]. An internal disturbance is one that originates within the system, whereas an external distrbance originates from outside the system [32].

The leader's dynamical system is an autonomous system and is not affected by any follower.

Due to the interrelated nature of the vehicle platoon's coupled system, disturbances affecting one vehicle (especially the leader) may also influence other vehicles and potentially amplify spacing errors downstream, leading to string instability [33]. Nevertheless, any vehicular platoon member has the same chance of confronting external disturbances [34].

The platoon consists of one leading vehicle and seven followers. The lead vehicle index is zero and the rest of the vehicles are ordered from 1 to 7 moving down the platoon. Since the ideal distance between any successive platoon members in a normal platoon is set at 10 m [27], then we assume that the vehicles are homogenous with a desired inter-vehicle distance equal to 10 m. The control input for the seven followers as in Eq. (2). From the Ref. [14], the parameters τ and $\mathbf{K}$ are set as in the previous section. The association matrix $\mathcal{H}$ is:

$$\mathcal{H} = \begin{bmatrix} 2 & -1 & & & & & \\ -1 & 2 & -1 & & & & \\ & -1 & 3 & -1 & & & \\ & & -1 & 2 & -1 & & \\ & & & -1 & 3 & -1 & \\ & & & & -1 & 2 & -1 \\ & & & & & -1 & 2 \end{bmatrix} \quad (4)$$

$\lambda_1 = 0.15, \lambda_2 = 0.58, \lambda_3 = 1.23, \lambda_4 = 2.00, \lambda_5 = 2.76, \lambda_6 = 3.40,$ and $\lambda_7 = 3.80$ are the eigenvalues of the matrix $\mathcal{H}$.

In Ref. [26], the coupling gain c must be chosen to satisfy the condition:

$$c \ge \frac{1}{2 \min_{i=1,2,\ldots,N} \mathrm{Re}(\lambda_i)} \quad (5)$$

where, $\mathrm{Re}(\lambda_i)$ is the real part of the eigenvalue λ_i. Hence, $c \ge 10/3$, we chose it equal to 4.

Furthermore, without loss of generality, we consider the case of homogeneous vehicle, that is, $m_i = m (i = 0,1,\cdots,7)$. The mass m can be chosen any value according to practical applications. The initial velocity for all the platoon is set to be 20 m/s, correspondingly the initial acceleration becomes zero. The initial position for all the platoon vehicles are shown in Table II.

Table II: Initial Position of the Vehicles

Vehicle	0	1	2	3	4	5	6	7
Position	0	−15	−30	−45	−60	−75	−90	−105

A. *Platoon Behavior under Normal Operation*

The platoon was driven on a straight road. The dynamical system of the platoon leader is

$$\frac{d}{dt}\bar{\mathbf{x}}_0(t) = \mathbf{A}\bar{\mathbf{x}}_0(t) + \mathbf{B}u_0(t) \quad (6)$$

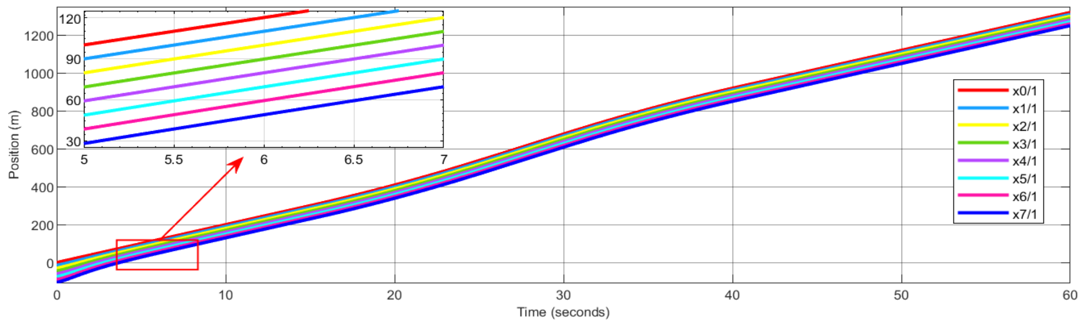
where u_0 is designed as:

$$u_0 = \begin{cases} 0.8 \text{ m/s}^2 & t \in [15,25]\text{s} \\ -0.8 \text{ m/s}^2 & t \in [30,40]\text{s} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

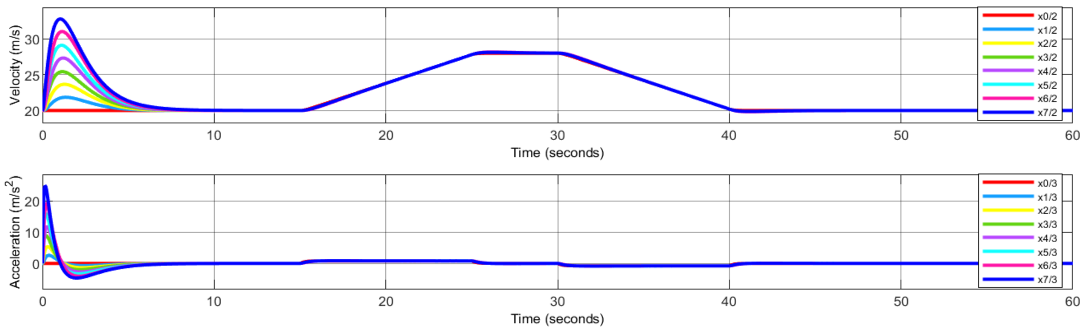
For this case and when applying BDOL topology, the positions of each vehicle in the platoon are shown in Fig. 3 (a), while the velocity and acceleration can be seen in Fig. 3 (b).

In the presence of a known leader control input and in order to achieve the goal of keeping the required distance between every two consecutive vehicles, there must be an increase in speed first, followed by a decrease according to the need to maintain what is required.

From Fig. 3 (b), we find that the leader drives at a constant speed v=20 from the moment t=0 to t=15, after that from t=15 to t=25, accelerating begins until the velocity becomes v=28. Then driving at the same speed until t=30, next slowing down starts so that the speed becomes v=20 at the moment t=40, then continuing at this constant speed, according to the definition of the leader's control unit.



(a)



(b)

Fig. 3. (a) The position of the vehicles in normal operation and (b) the velocity & the acceleration of the vehicles in normal operation

B. Platoon Behavior under Disturbances

Here we assume that the leading vehicle suffers from two different types of disturbances: external or acceleration disturbance. The same parameters as in the section A were used.

1) Sinusoidal Disturbance

The vehicle platoon was driven on a straight road as in the previous section.

The majority of studies on string stability only take into account external disturbances of the leading vehicle which are mostly caused by a gust, rolling resistance, and ground friction [15]. In the presence of some types of disturbances on the lead vehicle, its dynamical system will be:

$$\frac{d}{dt}\bar{\mathbf{x}}_0(t) = \mathbf{A}\bar{\mathbf{x}}_0(t) + \mathbf{B}\left[u_0(t) + \omega_0(t)\right] \tag{8}$$

where $\omega_0(t)$ is an external disturbance. We examine the effect of the disturbance of $\omega_0(t) = a_0 \sin(\omega t + \theta_0)$ [35]. We took the external disturbance that imposes in the leading vehicle as in [27], where:

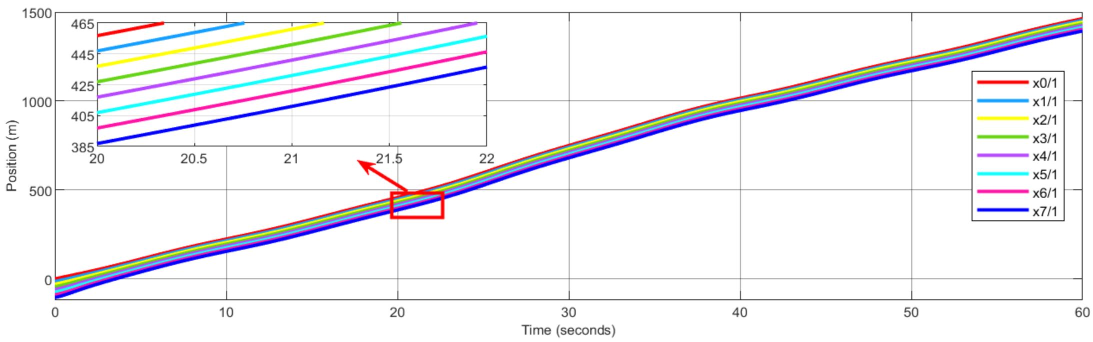
$$\omega_0(t) = 1.5\sin\left(\frac{2\pi}{10}(t-20)\right) \tag{9}$$

The leader's control input u_0 is as defined in Eq. (7).

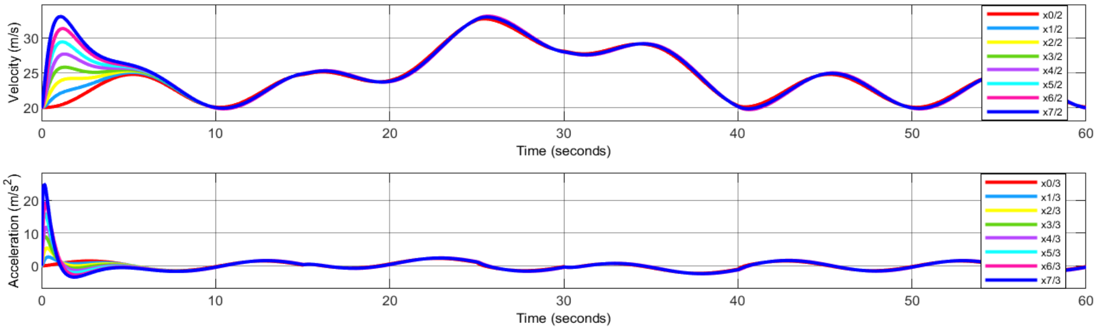
When applying BDOL topology in this case, the results will be:

Fig. 4(a) shows the position of each vehicle in platoon, while Fig. 4(b) shows the velocity, and acceleration.

Fig. 4(b), clearly shows that whereas the leading vehicle is disturbed, the leader increases and decreases the speed in order to maintain the goal. The speed changing will be done according to the sinus curve, followed by all the following vehicles.



(a)



(b)

Fig. 4. (a) The position of the vehicles in case of the sinsoidal disturbance and (b) the velocity & the acceleration of the vehicles in case of the sinsoidal disturbance.

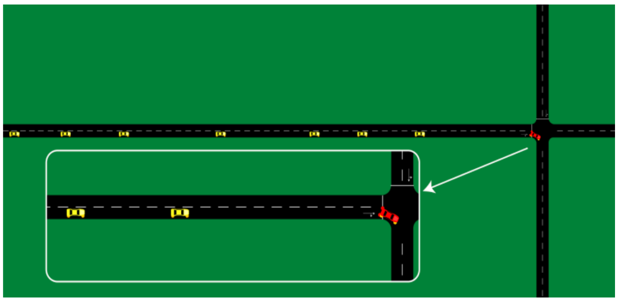


Fig. 5. SUMO simulator a curved road with two lanes.

2) Velocity/Acceleration Disturbance

In a platoon, the variety within the velocity (which leads to acceleration change) of the leading vehicle can be considered as an external disturbances. Such disturbances can be caused by the road's or weather's conditions.

To illustrate this, a curved road with two lanes was initiated in Simulation of Urban MObility (SUMO), a traffic simulation program introduced in 2002, by German Aerospace Center. Since there are intersections, junctions, traffic signals, etc. SUMO requires a description of road networks and traffic demand. There are numerous uses and applications for SUMO in urban traffic management, V2X, vehicle emission simulation, and other types of traffic issues [36−38]. In Fig. 5, the vehicle platoon was driven on that road where the red-colored vehicle is the leader of the platoon and member vehicles of the platoon are shown in yellow color.

The most important disturbances in a platoon are the increase/decrease of the leading vehicle's velocity (or acceleration). In other words, a disturbance means the presence of a source that ensures that the vehicle platoon does not maintain its constant speed.

The leader's dynamical system as in Eq. (6), while his control input u_0 is defined according to it's relation with the velocity (acceleration):

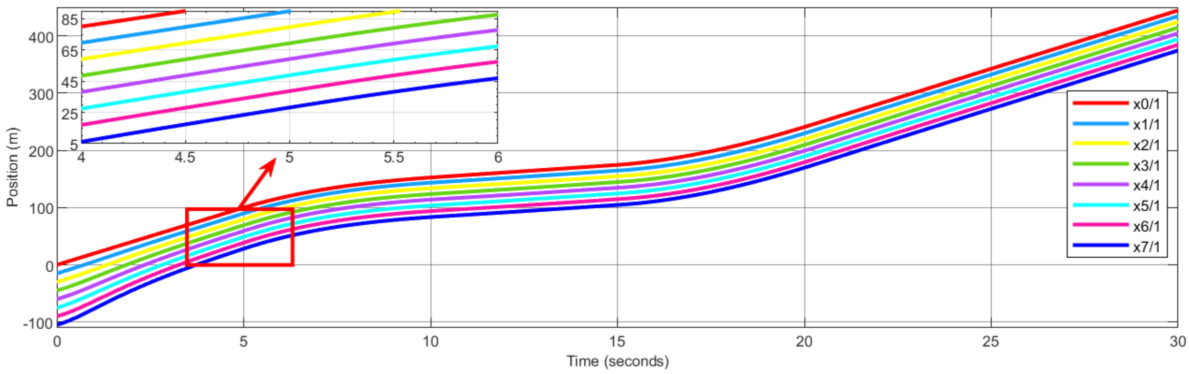
$$u_0 = a_0 + \tau \frac{d}{dt} a_0 \tag{10}$$

Here we define the desired trajectory in the following way:

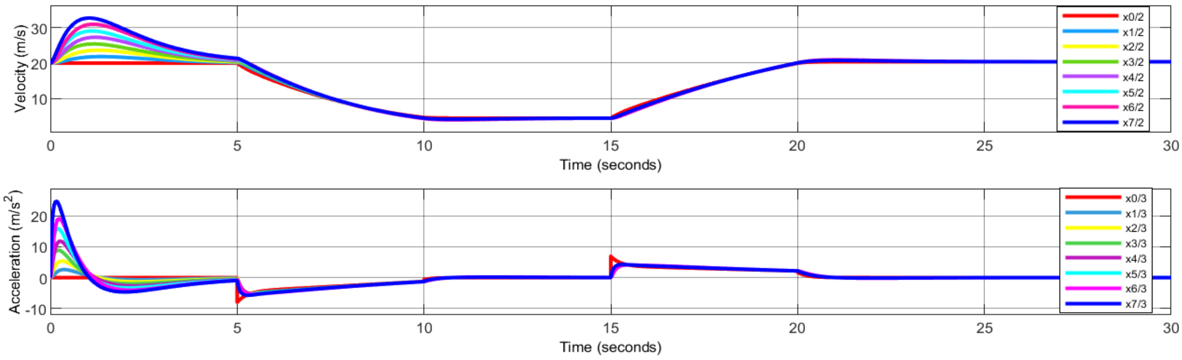
$$v_0(t) = \begin{cases} \frac{1}{3}\left[t^2 - 24t + 155\right], & t \in [5,10] \\ 5, & t \in [10,15] \\ -\frac{1}{6}\left[t^2 - 53t + 540\right], & t \in [15,20] \\ 20, & \text{otherwise} \end{cases} \tag{11}$$

The outcomes of using BDOL topology in this situation are as follows: Fig. 6 (a) displays the positions of each vehicle in the platoon, whereas Fig. 6 (b) displays velocity and acceleration.

From Fig. 6, it is clear that the distance between every two consecutive vehicles is as designed (10m). Because the road is curved, the leader is forced to reduce the velocity to its minimum value v=5 and then has to use this velocity for a while from t=10 s. to t=15 s. For the period t=15 s. to t=20 s. accelerating is necessary to return to the planned velocity v_0=20 m/s.



(a)



(b)

Fig. 6. (a) The position of the vehicles in the case of velocity/acceleration disturbance and (b) the velocity and the acceleration of the vehicles in the case of velocity/acceleration disturbance.

V. Conclusion

Since it is important and required to minimize the communication cost, in this work, a new topology called BDOL for a homogeneous platoon of vehicles was proposed. The BDOL is a relaxation of the BDL topology, where the communication cost is minimized. The reduction in the required number of devices for communication, by limiting broadcasting between the leading vehicle and some followers while maintaining receiving the information to all platoon members. For finding a trade-off between communication cost and the system performance, we evaluated the performance of the BDOL topology, and compare it to BDL topology. In our experiment, the results show that, the BDL and BDOL works almost the same, but on the other hand the communication cost was notably reduced. Later, the performance of the BDOL while using a number of vehicles (N=3, 5, 7) was studied in different scenarios. The scenarios of straight and curved track with or without disturbances are imposed in the leading vehicle. The longitudinal aspect of string stability is concerned with the regulation of distance keeping between two consecutive platoon members.

The string stability of the platoon of vehicles was studied in all the cases and our results showed the effectiveness of the proposed topology. Future research could focus on continuing the work with additional scenarios and greater velocities.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Both authors have analyzed the complete work and prepared the manuscript. Both authors had approved the final copy.

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