Behavior of Vehicle Platoon with Limited Output Information Based on Constant Time Heading

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Abstract. This paper presents synchronization of vehicle platoon with limited-output information based on constant time heading spacing policy. Two control schemes, namely neighborhood controller neighborhood observer and neighborhood controller local observer designed based on constant time heading will be applied into a vehicle platoon. These control schemes are applicable for general topologies as long as spanning tree condition is fulfilled. Both control schemes have identical controller part but different approach in the observer parts. Neighborhood controller neighborhood observer utilizes completely neighborhood information in the observer part, while neighborhood controller local observer only uses the internal information in the observer part. The performance of both controllers will be analyzed numerically, and the results will be compared. Furthermore, the behavior of each follower in various vehicle-to- vehicle topologies in responding to disturbance will be presented and some remarks will be summarized.

Keywords: Vehicle Platoon, Constant Time Heading, Neighborhood Controller, Local Observer.

1 Introduction

Solutions to various problems in the field of transportation require various technological approaches from various sides, including the application of technology in road constructions, traffic sign infrastructures, traffic managements and the vehicles themselves. This paper presents one of the possible solutions in terms of vehicle technology which utilizes collaboration between vehicles, called as a vehicle platoon. Vehicle platoon can be defined as a group of vehicles that collaborate to move like a train by utilizing the information exchanged with a certain topology. With a formation like a train, the vehicle at the front will be set as the leader (like a locomotive) and the remaining vehicles as followers (like carriages). In platoon formation, each vehicle will synchronize the distance between vehicles, velocity and acceleration, which usually depends on the movement of the lead vehicle. It is predicted that vehicle platoon will become one of the features of future vehicles that have many benefits such as increasing road capacity, increasing safety, reducing air pollution and saving fuel.

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Currently vehicle platoon is one of the most active research areas because of their promising potential benefits in the future. This research was conducted from various sides, including controller algorithms related to vehicle dynamics and spacing policy [1, 2], sensors and communication technology [3] with various kinds of problems in each side. The development of control schemes on platoons mostly assumes that the information exchanged is under ideal conditions which generally consists of position, velocity and acceleration, as is the case in [2, 4, 5]. In reality, due to sensor limitations only partial information can be obtained by the vehicle. In this condition, usually full-state information will be estimated from the existing information, as is the case in the control scheme proposed by [6, 7]. Two control schemes in [6] have been studied by Prayitno et. al. in [8] to be applied to a vehicle platoon that apply a constant spacing policy. Where the characteristics of the vehicle platoon on several directed topologies have been presented. Some control schemes, such as [9, 10, 11], are also have possibility to be implemented for vehicle platoon applications with various topologies.

In term of spacing policies, there are several spacing policies that can be applied in platoon applications, including constant spacing policy (CSP) on [2, 5], constant time heading (CTH) on [1], and delay-based spacing (DBS) policy on [12] with various advantages and disadvantages. CSP has the advantage in its ability to maximize road capacity with the distance between vehicles as close as possible but has the potential to cause instability of the string when a disturbance occurs [13]. Meanwhile, CTH has advantages in string stability and increasing safety but the distance between vehicles will widen at high speeds which is contradictory to maximizing road capacity [13]. DBS has the advantage of being more realistic by tracking the same velocity profile in the spatial domain, especially when driving in mountainous areas with up and down road contours [12].

The spacing policy is interesting to observe, especially the behavior of each follower vehicle in various topologies. This information is very important for the controller designer in determining which spacing policy and topology are appropriate for the platoon application. The behavior of CSP in various directed topologies has been studied in [8]. Therefore, this paper modifies the control schemes in [8] to be applied based on constant time heading for synchronization of vehicle platoon. There are two control schemes studied here, namely the neighborhood controller neighborhood observer and the neighborhood controller local observer which will be applied to each follower with various topologies. Both of these control schemes have similarities in the controller but are different from the observer side.

The contribution of this paper is in the formulation of constant time headings that can be applied to vehicle platoon with limited output information under various topologies. Moreover, information about the behavior of each follower vehicle in various applied topologies will be summarized. This information is very useful for understanding the characteristics of constant time heading in vehicle platoon applications.

2 System Description

Homogeneous vehicle platoon that consists of one leader and N-followers usually described by the following dynamics,

$$\begin{cases} \dot{x}_i = Ax_i + Bu_{i,} \\ y_i = Cx_i. \end{cases} \tag{1}$$

Here, the leader is assigned with $i = 0$ and assumed to have constant velocity or the value of $u_0 = 0$. The remaining vehicles are set as followers with $i = \{1,2,\dots,N\}$. Limited output information is represented by the value of matrix C. Full-state information usually consists of position, velocity and acceleration, represented by $x_i = [p_i, v_i, a_i]^T$. The relation of position, velocity and acceleration are explained by matrices A and B as follows,

$$A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\sigma_i} \end{bmatrix} \text{ and } B_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\sigma_i} \end{bmatrix}, \tag{2}$$

where σ_i is the inertial time lags of the powertrain. Homogeneity of vehicles can be represented by the same values of σ_i which usually represent identical vehicles. Smaller value of σ_i will has faster transient response compared to bigger value of σ_i. Therefore, smaller value of σ_i usually owned by passenger vehicles, while bigger value of σ_i usually owned by heavy-duty vehicles [14].
To form a platoon, it is necessary to exchange information between vehicles according to the topology. Internal information in each vehicle is obtained by using on-board sensors and exchanged to their neighbors by using Vehicle-to-Vehicle (V2V) communication technology. For controller design and stability analysis, information flow in the platoon is usually expressed in terms of adjacency matrix and pinning matrix. The adjacency matrix expresses the information flow between followers and denoted by $\mathcal{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$, where the value of $a_{ij} = 1$, if the information is received by vehicle i from vehicle j, otherwise $a_{ij} = 0$. While, the pinning gain represents the leader's information received by followers which denoted by $\mathcal{P} = diag\{\wp_{11}, \wp_{22}, \dots, \wp_{NN}\}$, where the value of $\wp_{ii} = 1$ if the information flow from the leader to follower i, otherwise $\wp_{ii} = 0$. In the vehicle platoon, the V2V topology is required to contain at least a spanning tree condition, with the leader as the root tree. There are six common V2V topologies in the vehicle platoon, namely predecessor following (PF), predecessor following leader (PFL), two-predecessor following (TPF), two-predecessor following leader (TPFL), Bidirectional (BD) and Bidirectional Leader (BDL).

When the platoon formation is achieved, each vehicle will have synchronous inter-vehicle distance, which can either be CSP or CTH. CSP has advantages in maximizing the road capacity and reducing the fuel cost when applied in heavy-duty vehicle with some conditions. While CTH has shown to be able to maintain the stability of the whole platoon and increase the safety. This paper utilizes CTH spacing policy for the platoon synchronization. The challenge in this paper is to formulate the desired distance between vehicle i and lead vehicle which applicable to general topology. The desired distance is formulated as,

$$d_{i,0} = i(h.v_i + \ell), \tag{3}$$

where h is constant time heading and ℓ is the standstill of each vehicle. When the platoon formation is formed, each follower will synchronize the velocity and acceleration to the leader and maintain the desired spacing. It means that in platoon formation, the following condition is achieved,

$$\begin{cases} \lim_{t\to\infty} \|p_i(t) - p_0(t)\| = d_{i,0} \\ \lim_{t\to\infty} \|v_i(t) - v_0(t)\| = 0 \\ \lim_{t\to\infty} \|a_i(t) - a_0(t)\| = 0 \end{cases} . \tag{4}$$

Another challenge is when each vehicle has limited-output information due to limitation of the onboard sensor. Therefore, the objective of this paper is to design distributed controller for each follower with limited-output information for synchronization of vehicle platoon based on constant time heading. Moreover, this paper will discuss the behavior of each follower in each topology when applying CTH.

3 Distributed Controller

In this paper, two control schemes for vehicle platoon with limited output information will be presented, namely Neighborhood Controller Neighborhood Observer (NCNO) and Neighborhood Controller Local Observer (NCLO). This control schemes are adopted from [6] and will be applied for vehicle platoon with CTH spacing policy and the behavior of each follower in each topology will be summarized.

3.1 Neighborhood Controller Neighborhood Observer (NCNO)

Block diagram of NCNO is shown in Fig. 1. It mainly consists of two parts, namely neighborhood observer (NO) and neighborhood controller (NC). NO has responsibility to estimate the full-state information of the vehicle dynamics. While, NC utilizes the internal and neighbors' states estimation for controller design purposes.

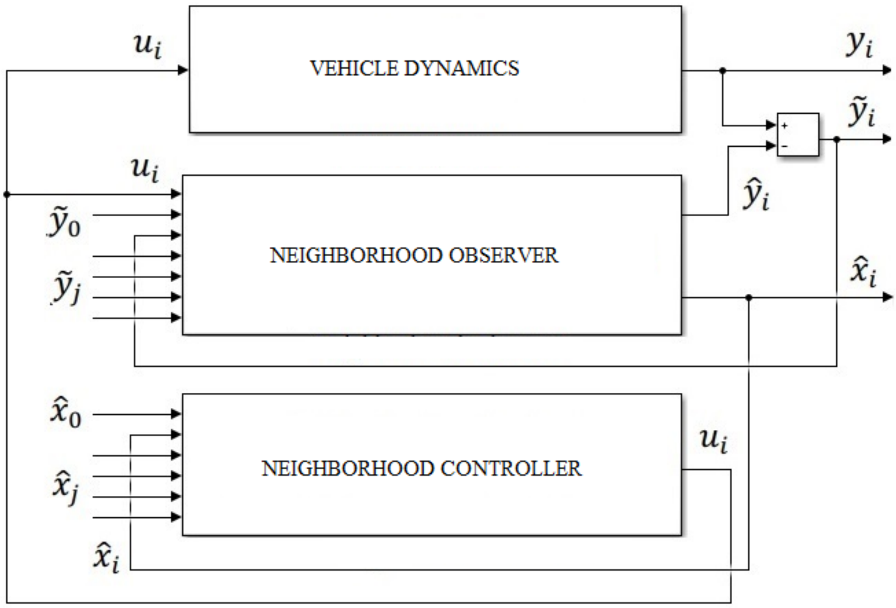

Fig. 1. Block diagram of Neighborhood Controller Neighborhood Observer.

To include CTH spacing policy (3) in the controller design, let define vector $\bar{x}_i = [i(h.v_i + \ell), 0,0]^T$ and $\bar{\hat{x}}_i = [i(h.\hat{v}_i + \ell), 0,0]^T$. Let $\hat{x}_i$ be the state observer, i.e. the full-state estimation of x_i, which obtained by,

$$\dot{\hat{x}}_i = A\hat{x}_i + Bu_i - cF\mu_i, \tag{5}$$

where μ_i is the cooperative output estimation error which calculated by utilizing the internal output estimation error, $\tilde{y}_i = C(x_i + \bar{x}_i) - C(\hat{x}_i + \bar{\hat{x}}_i)$, and neighbors' output estimation error, $\tilde{y}_j = C(x_j + \bar{x}_j) - C(\hat{x}_j + \bar{\hat{x}}_j)$ and $\tilde{y}_0 = Cx_0 - C\hat{x}_0$, as follows,

$$\mu_i = \sum_{j=1}^{N} a_{ij}(\tilde{y}_j - \tilde{y}_i) + g_{ii}(\tilde{y}_0 - \tilde{y}_i). \tag{6}$$

The observer gain, F, can be defined as

$$F = P_2 C^T R^{-1}, \tag{7}$$

where P_2 is the solution of the observer algebraic Riccati equation (ARE), by choosing Q and R positive definite,

$$0 = A^T P_2 + P_2 A + Q - P_2 C^T R^{-1} C P_2, \tag{8}$$

The control signal u_i is designed by utilizing the internal and neighbors' state estimation,

$$u_i = cK\sum_{j=1}^{N}\{a_{ij}((\hat{x}_j + \bar{\tilde{x}}_j) - (\hat{x}_i + \bar{\tilde{x}}_i))\} + g_{ii}((\hat{x}_0) - (\hat{x}_i + \bar{\tilde{x}}_i)). \tag{9}$$

where $c > 0$ is a coupling gain, $K \in \mathbb{R}^{m\times n}$ is the feedback gain matrix chosen as follows,

$$K = R^{-1}B^T P_1, \tag{10}$$

where P_1 is a solution of the algebraic Riccati equation (ARE),

$$0 = A^T P_1 + P_1 A + Q - P_1 B R^{-1} B^T P_1. \tag{11}$$

3.2 Neighborhood Controller Local Observer (NCLO)

NCLO is a simplification of NCNO. Instead of using completely neighbors' output estimation error, NCLO only using the internal output estimation error to estimate the full-state information of each follower. The block diagram of NCLO is shown in Fig. 2. It consists of two main blocks, namely local observer (LO) and neighborhood controller (NC). In here NC is similar with (9), while local observer is designed as

$$\dot{\hat{x}}_i = A\hat{x}_i + Bu_i - cF\tilde{y}_i. \tag{12}$$

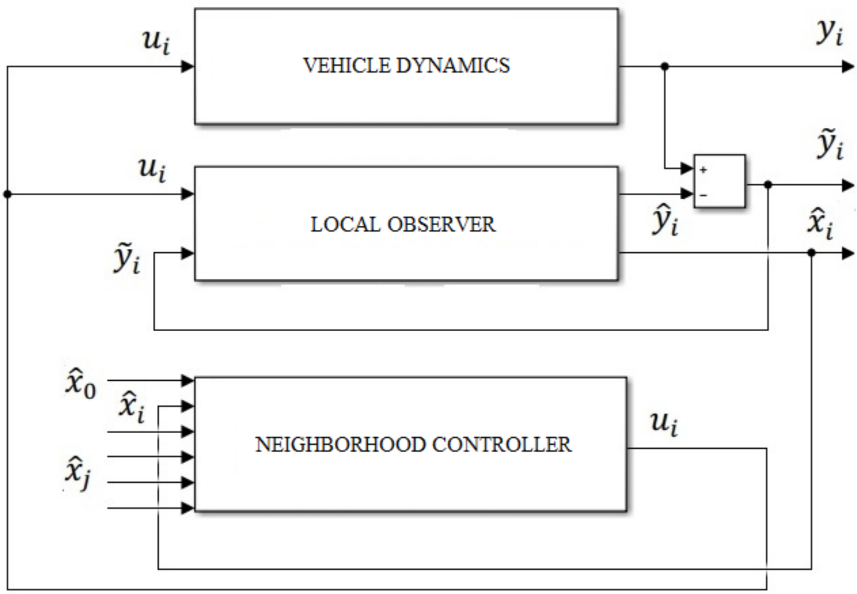

Fig. 2. Block diagram of Neighborhood Controller Local Observer.

4 Numerical Simulation

For numerical simulation, a vehicle platoon consists of 1 leader and 5 followers is used. Vehicles are assumed to be homogeneous with the inertial time lag, $\sigma_i = 0.25$ and only information about position can be obtained. There are two scenarios for the numerical simulation. First, the performance of both control schemes, NCNO and NCLO, when applying CTH spacing policy will be presented. In the first scenario, it is assumed that vehicle platoon applying PF topology and working with coupling gain $c = 0.6$. In the second scenario, the behavior of each follower in many types of V2V topology will be presented. For this purpose, six V2V topologies are studied, namely PF, BD, PFL, BDL, TPF and TPFL, as shown in Fig. 3. To find out the behavior of the followers in responding to disturbances, the lead vehicle is designed to have an input profile as,

$$u_0 = \begin{cases} 0, & 0\,s \le t \le 25\,s \\ 1, & 25\,s < t \le 35\,s \\ 0, & 35\,s < t \le 65\,s \\ -1, & 65\,s < t \le 75\,s \\ 0, & t > 75\,s \end{cases}. \tag{12}$$

For CTH spacing policy, $h = 0.2\,s$ and $\ell = 5\,m$ are selected. By choosing $R = 0.01$ and $Q = I_{3\times3}$, feedback and observer gain matrices are obtained as follow,

$$K = [10.0000 \quad 17.5946 \quad 9.4784]. \tag{13}$$

$$F = [175.9456 \quad 104.7842 \quad 2.5000]^T. \tag{14}$$

Vehicles are set in initial conditions as listed in Table 1.

Table 1. Initial conditions of vehicles.

	Vehicle					
	0	1	2	3	4	5
$p_i(0)$	50	40	30	20	10	0
$v_i(0)$	20	18	18	18	18	18
$a_i(0)$	0	0	0	0	0	0
$\hat{p}_i(0)$	-	40	30	20	10	0
$\hat{v}_i(0)$	-	19	19	19	19	19
$\hat{a}_i(0)$	-	0	0	0	0	0

The performance of NCNO and NCLO when applying CTH under PF topology is shown in Fig. 4. It is seen that both control schemes resulting the similar performance when responding to the disturbance that occurs in the leader's vehicle. It means that instead of using all neighbor's output estimation error information, using internal output estimation error only is enough for estimating the full-state information. It confirms that NCLO scheme simplify NCNO controller algorithm.

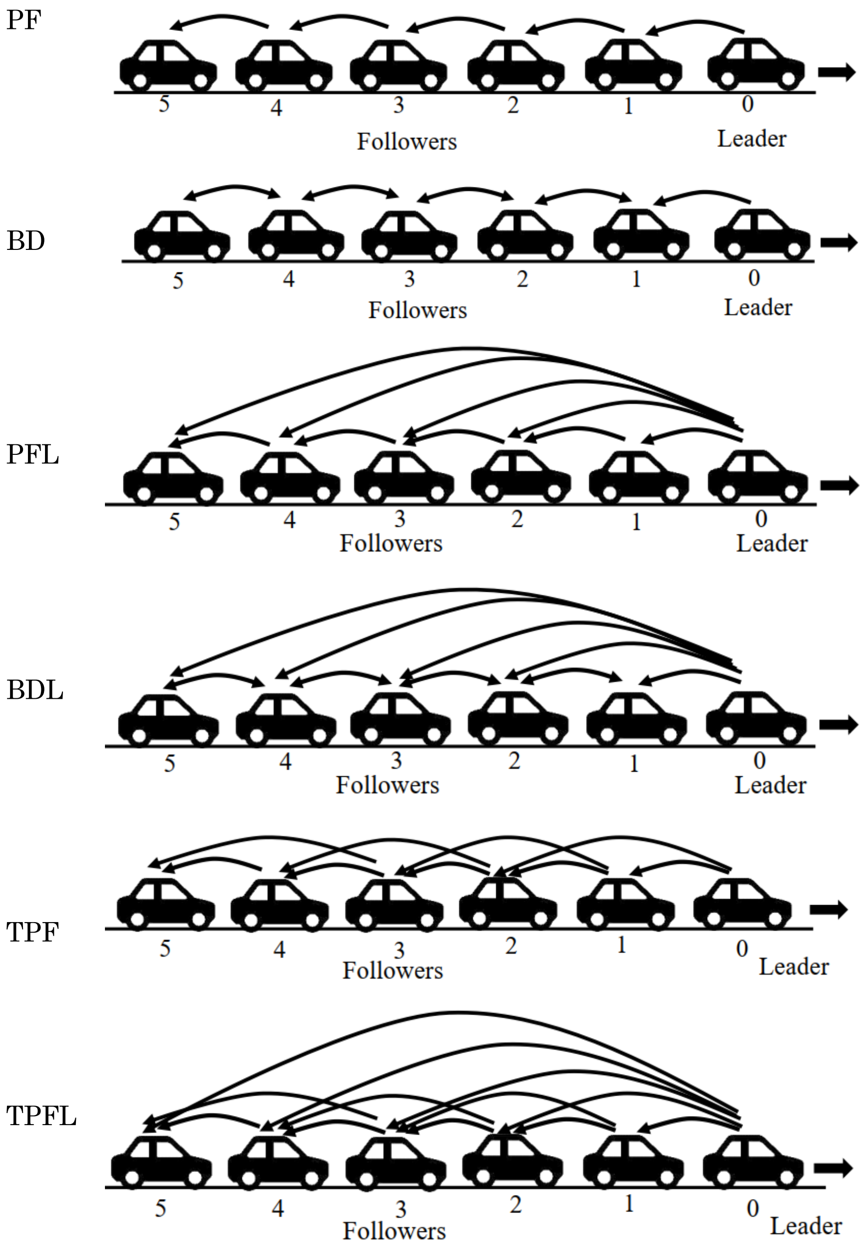

Fig. 3. Six common topologies in vehicle platoon application.

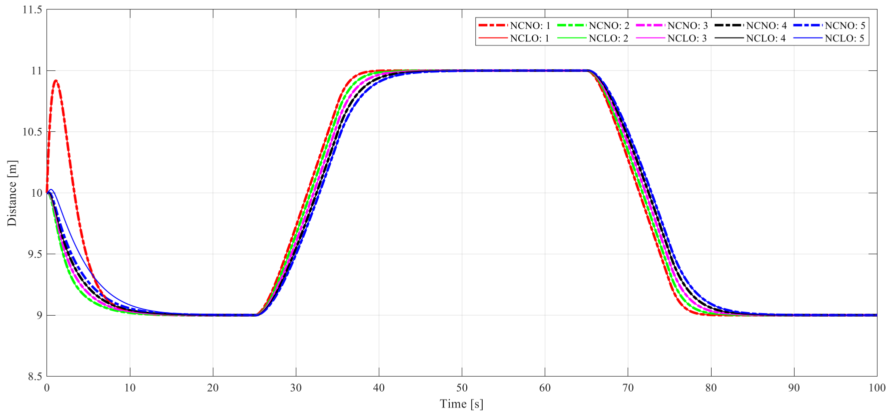

Fig. 4. Performances comparison of NCNO and NCLO.

Due to the satisfactory performance of NCLO, this control scheme will be used to determine the characteristics of the follower in various types of topologies. Simulations were carried out on the 6 topologies mentioned above with the coupling gain values varied from small to large and the response of each follower was observed. For ease of reading, only the four coupling gains are shown in the graph i.e. $c = 0.1$, $c = 0.6$, $c = 10$ and $c = 100$. Simulation results are shown in Fig. 5 to Fig. 9 to represent the behavior of the first follower to the last follower respectively.

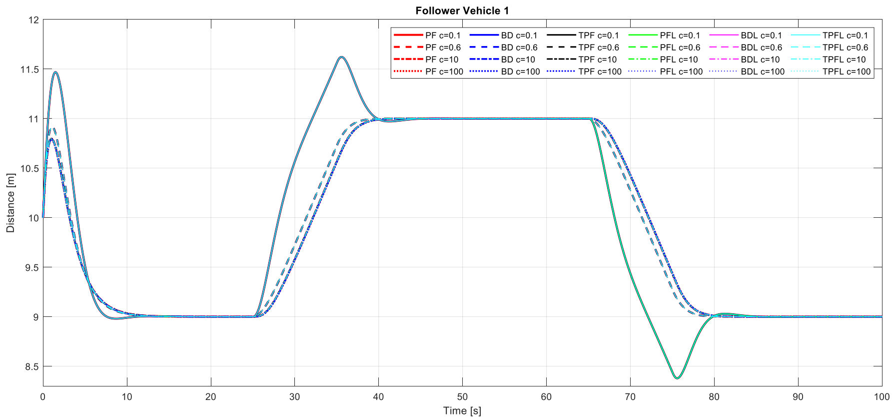

Fig. 5. The first follower's behavior in some V2V topologies.

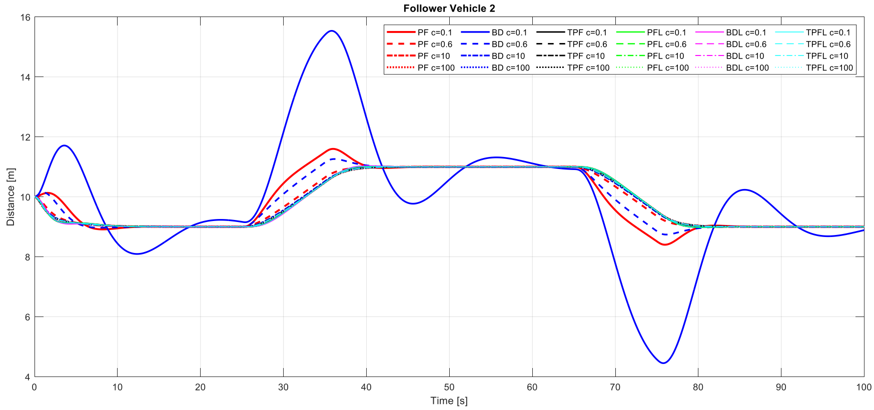

Fig. 6. The second follower's behavior in some V2V topologies.

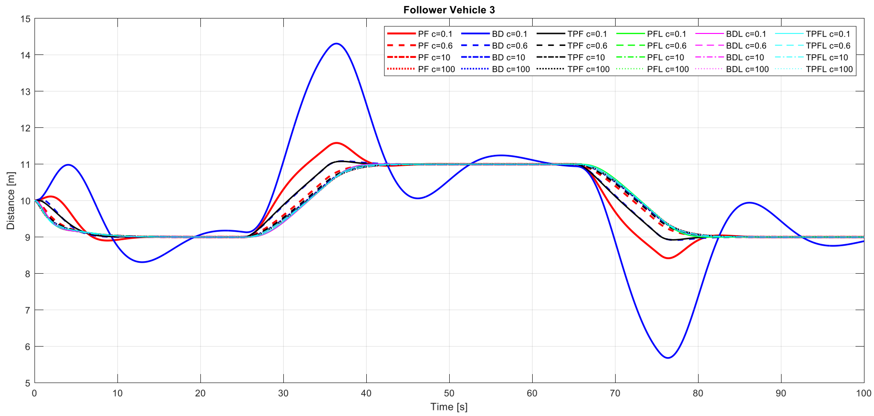

Fig. 7. The third follower's behavior in some V2V topologies.

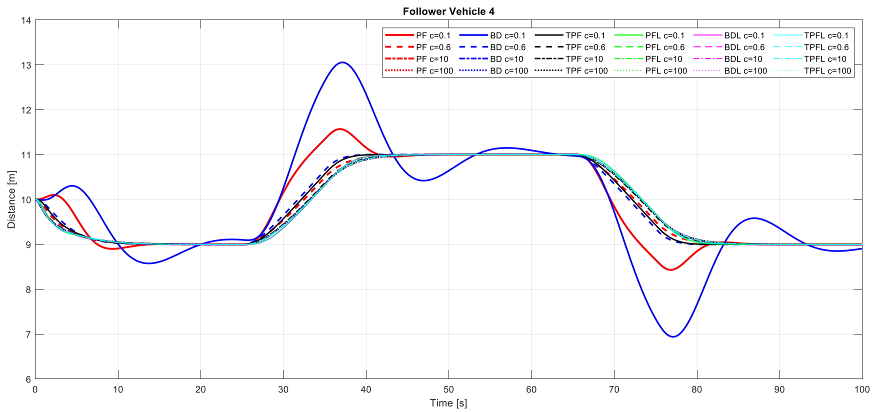

Fig. 8. The fourth follower's behavior in some V2V topologies.

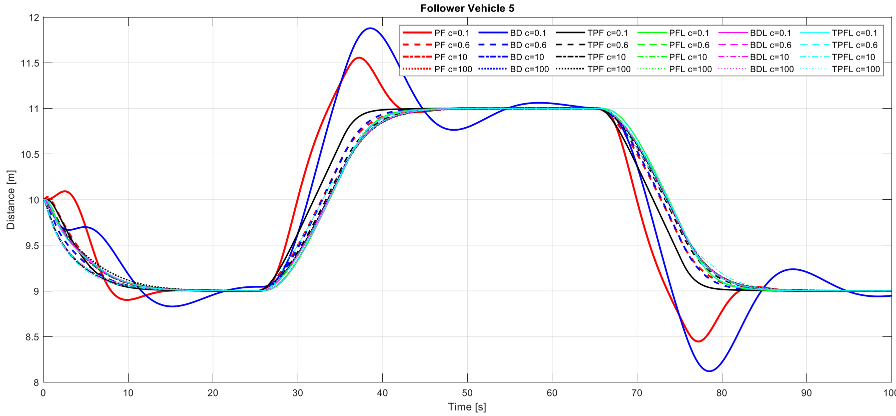

Fig. 9. The fifth follower's behavior in some V2V topologies.

From the simulation results, some remarks can be written here:

- In the first follower it appears that the responses have similar behavior for various topologies for each value of coupling gain. This behavior makes sense because the first follower in all above topologies is only connected to the leader.
- On the remaining followers, vehicles with PFL, TPFL and BDL topologies have relatively the same responses. Meanwhile, vehicles with BD topology have the highest oscillation when disturbance occurs, followed by PF and TPF.
- The greater the coupling gain, the better and the more similar the system responses for all types of topologies.
- With further observations on the control signal, to achieve relatively similar responses for all topologies, it turns out that the control signals required are relatively the same. In BD and PF this can be achieved with a larger coupling gain value compared to TPF, PFL, TPFL and BDL.
- Furthermore, the application of CTH to the NCNO control scheme produces similar characteristics in each follower vehicle.

5 Conclusion

Constant time heading spacing policy has been implemented for two control schemes based on limited-output information, namely NCNO and NCLO. NCNO utilized complete output estimation error from neighbors to obtain the estimated full-state information, while NCLO only used the internal output estimation error. The results showed that NCLO gives similar performance to the NCNO in responding to disturbance. In various topologies, the first follower has similar behavior, while for the remaining followers, vehicles with more complex topologies gave better performance compared to simple topology.

References

1. Harfouch, Y. A., Yuan, S., Baldi, S.: An adaptive switched control approach to heterogeneous platooning with intervehicle communication losses. IEEE Transactions on Control of Network Systems. 5(3), 1434-1444 (2018).
2. Prayitno, A., Nilkhamhang, I.: Distributed Model Reference Control for Cooperative Tracking of Vehicle Platoons Subjected to External Disturbances and Bounded Leader Input. Int. J. Control Autom. Syst. 20, 2067–2080 (2022).
3. Sun, M., Al-Hashimi, A., Li, M., Gerdes, R.: Impacts of Constrained Sensing and Communication Based Attacks on Vehicular Platoons. IEEE Transactions on Vehicular Technology 69(5), 4773-4787 (2020).
4. Prayitno, A., Nilkhamhang, I.: Distributed Model Reference Adaptive Control for Vehicle Platoons with Uncertain Dynamics. Engineering Journal. 25(8), 173-185 (2021).
5. Hu, J., Bhowmick, P., Arvin, F., Lanzon, A., Lennox, B.: Cooperative Control of Heterogeneous Connected Vehicle Platoons: An Adaptive Leader-Following Approach. IEEE Robotics and Automation Letters. 5(2), 977-984 (2020).
6. Lewis, F. L., Zhang, H., Movric, K. H., Das, A.: Cooperative Control of Multi-Agent Systems Optimal and Adaptive Design Approach. Springer-Verlag, London (2014).
7. Prayitno, A., Indrawati, V., Nilkhamhang, I.: Distributed model reference adaptive control based on cooperative observer with optimal control modification for synchronization of heterogeneous vehicle platoon. Mathematical Modelling of Engineering Problems. 9(6), 1565-1573 (2022).
8. Prayitno, A., Indrawati, V., Nilkhamhang, I.: A Comparative Study of Vehicle Platoon with Limited Output Information in Directed Topologies. In: 2023 Third International Symposium on Instrumentation, Control, Artificial Intelligence, and Robotics (ICA-SYMP), pp. 110-113. Bangkok, Thailand (2023).
9. Bayuwindra, A., Lefeber, E., Ploeg, J., Nijmeijer, H.: Extended Look-Ahead Tracking Controller with Orientation-Error Observer for Vehicle Platooning. In IEEE Transactions on Intelligent Transportation Systems, 21(11), 4808-4821 (2020).
10. Shojaei, K., Chatraei, A.: Robust platoon control of underactuated autonomous underwater vehicles subjected to nonlinearities, uncertainties and range and angle constraints. Applied Ocean Research, 110, (2021).
11. Wang, X., Jiang, G. P., Yang, W., Su, H., Wang, X.: Neighborhood Interval Observer Based Coordination Control for Multi-agent Systems with Disturbances. IFAC-PapersOnLine, 53(2), 10994-10999 (2020).
12. Besselink, B., Johansson, K. H.: String stability and a delay-based spacing policy for vehicle platoons subject to disturbances. IEEE Transactions on Automatic Control. 62(9), 4376-4391 (2017).
13. Bian, Y., Zheng, Y., Li, S. E., Wang, Z., Xu, Q., Wang, J., Li, K.: Reducing Time Headway for Platoons of Connected Vehicles via Multiple-Predecessor Following. In: 21st International Conference on Intelligent Transportation Systems (ITSC), pp. 1240-1245. Maui, HI, USA (2018).
14. Zheng, Y., Bian, Y., Li, S., Li, S.E.: Cooperative control of heterogeneous connected vehicles with directed acyclic interactions. IEEE Intelligent Transportation Systems Magazine. 13(2), 127-141(2021).