IEEE Open Journal of
Intelligent Transportation Systems

Received 23 May 2021; revised 13 August 2021; accepted 25 October 2021. Date of publication 8 November 2021; date of current version 22 November 2021.

*Digital Object Identifier 10.1109/OJITS.2021.3125740*

# Cooperative Driving in Mixed Traffic: An Infrastructure-Assisted Approach

**RAHI AVINASH SHET [1] (Graduate Student Member, IEEE), AND SHENGYUE YAO [2]**

[1] Institute of Communications Technology, Leibniz University of Hannover, 30167 Hannover, Germany
[2] Institute of Transportation and Urban Engineering, Technische Universität Braunschweig, 38106 Braunschweig, Germany

CORRESPONDING AUTHOR: R. A. SHET (e-mail: rahi.shet@ikt.uni-hannover.de)

This work was supported in part by the German Research Foundation (DFG) under Grant 227198829/GRK1931.

*(Rahi Avinash Shet and Shengyue Yao contributed equally to this work.)*

**ABSTRACT** Automated driving in urban traffic requires extensive information from the surroundings. The most promisring approach to facilitate automated driving in mixed traffic is platooning of connected and automated vehicles (CAV). In this research, we investigate a human-leading strategy (HL) by which CAVs drive in platoons with the CAV leading the platoon driven by a human. We thoroughly formulate the problem of managing CAV platoons by the HL strategy, systematically model the platoon dynamics and the traffic system, as well as propose two approaches to implement this strategy. By conducting experiments in a simulation framework that combines the traffic and the communication network, the implementation of the HL strategy is evaluated with the consideration of travel time, automated driving experience, and communication reliability. The simulation results revealed that the HL strategy makes it feasible for CAVs to drive in automated mode in an urban mixed traffic network, while its performance relies on the CAV penetration rate and communication reliability. In addition, the results suggest that the performance of the HL strategy can be significantly improved by approaches that allow uninterrupted platooning and result in stable platoon dynamics.

**INDEX TERMS** CAV management, platoon dynamics, vehicular communication, traffic system modeling.

## I. INTRODUCTION

WITH the rapid development of vehicular automation technology in recent years, a vast proportion of vehicles have SAE level 2 or higher automation capabilities [1]. Furthermore, the booming development of communication technology catalyzed vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, which enables an upgrade of automated vehicles (AV) to connected automated vehicles (CAV). In contrast to AVs, CAVs can cooperate with each other and the traffic infrastructure resulting in more efficient and safer travels. Although a scenario with 100% CAV penetration is hard to realize, a mixed traffic scenario including CAVs and conventional vehicles can be envisioned in the near future. However, many studies have revealed that without proper coordination, CAVs would have less impact on traffic efficiency or even deteriorate the traffic efficiency [2], [3], [4]. The major reason is twofold: (1) when CAVs distribute sporadically in the traffic network without a sufficient penetration rate, CAVs cannot cooperate resulting in CAVs perform as AVs [5], which normally maintain a larger time-headway than conventional vehicles to guarantee safety [6], [7]; (2) even if CAVs drive closely on the road, disturbances from surrounding conventional vehicles would trigger deactivation of their automated driving function and request the drivers to take over the driving tasks, which would deteriorate the traffic efficiency due to drastic headway changes. [4], [8]. Such situations are more likely to occur under low speed and dense traffic conditions, especially on signalized urban roads [9]. Therefore, it is non-trivial to formulate a proper approach to coordinate CAVs in an urban road network.

The review of this article was arranged by Associate Editor Jiaqi Ma.

The recent development of V2V and V2I communication allows CAVs to cooperate and organize themselves into platoons, in which multiple CAVs drive as a string with short time-headways [10]. The performance of CAV platoons in mixed traffic system has been thoroughly examined in various studies in terms of traffic efficiency [11], [12], safety [13] and fuel consumption [14]. As a result, approaches to coordinate CAVs in mixed traffic, which can instruct them to drive in platoons and minimize the disturbance from surrounding conventional vehicles, have attracted growing interest in research. Two strategies proposed by the PATH project are considered to be the most promising: (1) the managed lane strategy (ML) in which the CAVs are instructed to drive on a dedicated lane to increase the opportunity of forming platoons [15]; (2) equipping conventional vehicles with vehicle awareness devices (VAD) so that they can perform as CAV platoon leaders [16]. These strategies have inherent defects in terms of their application in urban road networks. On one hand, having a CAV dedicated lane will complicate traffic signal planning and deteriorate throughput at intersections; on the other hand, it is not guaranteed to find a stable CAV platoon leader with a limited penetration rate of VAD-equipped vehicles. In order to circumvent the difficulties of forming CAV platoons and isolate CAVs from conventional vehicles in urban road networks, our previous research proposed a human leading (HL) platooning strategy, which allows CAVs to form platoons with the first CAV manually driven [17].

To execute the HL strategy, it is essential to investigate two dynamics of CAV platoons: the merging dynamic denoting CAVs merging into a platoon, and reversely the splitting dynamic denoting a CAV platoon splitting into individual CAVs or several CAV platoons with smaller sizes. Most existing studies focus on modeling dynamics of a single platoon or two adjacent CAV platoons. For instance, Segata *et al.* are one of the pioneers in modeling CAV platoon merging dynamics in simulation [18], Maiti *et al.* and Chen *et al.* investigated the merging of two adjacent CAV platoons with various relative positions [19], [20], Amoozadeh *et al.* investigated both platoon splitting and merging dynamics in simulation [21]. In addition, some studies have modeled multiple CAV platoon dynamics in a road network, for instance, Mena-Oreja *et al.* evaluated the impact of forming CAV platoons on a ring road with different configurations, such as desired gap, safe gap and maximum platoon size on traffic efficiency under a 100% CAV penetration scenario [22], [23]. However, modeling dynamics of multiple CAV platoons is more challenging in the mixed traffic scenario, where a convenient way was provided by the HL strategy. Following the HL strategy as proposed in [17], the CAV platoon leader is manually driven and all the following CAVs are driven in the automated mode, hence the CAV platoon dynamics could be represented by modeling the driving mode dynamics of each CAV in the road network over space and time. Specifically, the platoon merges can be realized by switching a certain group of CAVs from the manual driving mode to the automated driving mode and vice versa. Taking the advantage of modeling CAV platoon dynamics based on the HL strategy, the aforementioned research has mathematically formulated the problem of managing CAV platoons in an urban road network with the consideration of maximizing the average CAV platoon size. In addition, three operational approaches were proposed to solve this problem suboptimally. However, the evolution of CAVs' driving mode over space and time was not formulated; hence the problem formulation is incapable of capturing practical factors that may influence the CAV platoon dynamics (e.g., delay or failure in communication, CAV drivers' compliance rate, etc.). Therefore, the problem of managing CAV platoons needs to be systematically formulated on the basis of the CAVs' state-space evolution.

To implement the HL strategy in an urban road network, two practical issues are necessary to be considered. Firstly, a feasible infrastructure assistance method is required, which normally implies a supportive traffic signal plan. A substantial number of studies have investigated the method of promoting intersection throughput by optimizing traffic signal plans with the merits of CAV platoons [24], [25]. Our previous research has mentioned a principle of designing traffic signal plans to cope with the HL strategy [26]; however, such an intelligent signal plan is yet to be formulated in detail. Another non-trivial issue to be considered is the V2V and V2I communication reliability. Existing studies have proposed various communication schemes to coordinate CAVs in a road network, it is reported that the V2V and V2I communication performance can be unsatisfactory within these schemes due to packet losses and delays [27], [18], [28]. Our previous research has proposed a centralized communication scheme to apply the HL strategy in CAV platoon formations [26]. By the proposed communication scheme, CAVs in the managed road network send/receive merging requests/orders respectively through the roadside unit (RSU) via V2I communication, whereas they follow the preceding platoon members in the automated driving mode via V2V communication. The communication reliability was examined in terms of the ratio of the completed merging dynamics against the generated merging requests. However, the V2I communication reliability is significantly influenced by factors such as the number of RSUs and their location, as well as the terrain of the road network, rendering it an intricate task to examine the V2I communication reliability in simulation. Therefore, a communication scheme that is able to circumvent this problem and produce a close-to-realistic scenario, by which the communication reliability could be assessed in simulation, needs to be proposed.

With respect to the aforementioned research gaps, the key contributions of this paper are:

1) systematically formulating the problem of managing CAV platoons by the HL strategy in an urban road network, with the consideration of improving the traffic efficiency (i.e., to reduce travel time delay) and the automated driving experience of CAV drivers (i.e., to produce long and stable automated rides).

2) proposing a supportive traffic signal plan to model the traffic system with the HL strategy implemented.
3) proposing a distributed communication scheme for coordinating CAV platoons by the HL strategy, investigating its reliability and the impact of communication failures on the performance of the HL strategy.
4) evaluating the performance of the HL strategy regarding the traffic efficiency and the automated driving experience.

The key findings of our study are:

1) The CAVs can form platoons with a merge success rate of 95.4% and merge completion duration less than 5s in 95% cases. The platoon splitting dynamic process has a longer duration than merging on average, while the maximum splitting duration is within 15s. Thus, the HL strategy is feasible in practice with the proposed communication scheme.
2) The HL strategy is apt for adoption in mixed traffic scenarios; it improves traffic efficiency, as well as stabilizes CAV platoon dynamics over space and time, which facilitates the automated driving experience. Especially, in the best-case scenario, the CAV drivers experience automated driving for 75% of their total driving duration, making it feasible to engage in other activities.

The rest of this paper is organized as follows: the CAV platoon management problem is formulated in Section II. In Section III, a distributed solution to the platoon management problem is introduced. Section IV describes the simulated traffic system including CAV kinematic models, the traffic signal model, and the communication scheme. In Section V, we describe the experimental settings and the use cases considered, which is followed by the simulation results in Section VI and the conclusion and future work in Section VII.

## II. PROBLEM DESCRIPTION

### A. PROBLEM DEFINITION

The paper focuses on the problem of managing CAV platoons on one-lane urban arterial roads. This problem is described under the following assumptions:

1) Considering the analytical tractability, CAVs are modeled as homogeneous particles with identical lengths, detailed kinodynamics is not considered.
2) This research focuses on urban arterial roads which are equipped with an RSU for centralized computing. Since the deployment of RSUs is not considered in this study, the communication range of the RSU is assumed to cover the entire network for the purpose of simplicity. In addition, as the communication between CAVs and the RSU is restricted (which is elaborated in Section III), the effect of packet losses in the communication between RSU and CAVs is negligible, and perfect V2I communication is assumed in this study.
3) The realistic V2V communication is based on the IEEE 802.11p protocol standard.
4) CAVs fully comply to control inputs.

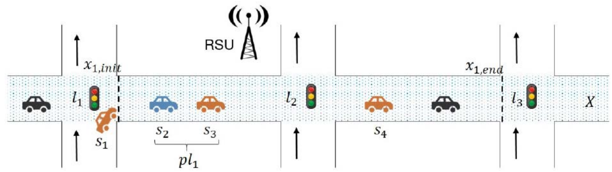



**FIGURE 1.** Platoon management problem scenario.

Based on these assumptions, the CAV platoon management problem is described below.

For a CAV $i$, its state $s_i(t)$ at time step $t$ can be uniquely defined as $s_i(t) = [x_i(t), role_i(t), v_i(t)]^\top$, in which $x_i(t), role_i(t), v_i(t)$ denote its position, platoon role (whether it is a platoon leader or a follower) and speed at time step $t$, respectively. CAV $i$ changes its state based on the control input $u_i(t) = [a_i(t), switch_i(t)]^\top$, in which $a_i(t), switch_i(t)$ denote its acceleration (which is determined automatically by CAV $i$) and role switching decision (whether to switch from platoon leader to follower or vice versa), respectively. The state dynamic of CAV $i$ can be represented by a state-space system $f$ as:

$$\frac{ds_i(t)}{dt} = \begin{bmatrix} v_i(t) \\ switch_i(t) \\ a_i(t) \end{bmatrix} = f(s_i(t), u_i(t)) \tag{1}$$

The state-space system can be further formulated as a linear time-varying system:

$$\frac{ds_i(t)}{dt} = As_i(t) + Bu_i(t) \tag{2}$$

where

$$A = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{2a}$$

$$B = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{2b}$$

Fig. 1 depicts a typical urban scenario that is focused in this research. Specifically, a one-way, one-lane road with signalized intersections is considered as the managed road context (blue dotted area in Fig. 1), which can be uniquely represented by $\Psi = \{X, L\}$, where set $X$ represents coordinate space and $L$ represents a set of $k$ consecutive signalized intersections contained in the road context, such that $L = l_1, l_2, \ldots, l_k$. There exist an RSU as shown in the Fig. 1 which serves as a centralized computing unit to make platoon role switching decisions and to transmit these decisions to CAVs driving on the managed road. In addition, the RSU collects routes of CAVs once they enter the managed road network, the CAV platoon information (including members of each CAV platoon and the platoon role of each CAV within the platoon) once a platoon dynamic is completed, as well as the CAV platoon information and the kinematic characteristics once a CAV is approaching an intersection, the details will be elaborated in following sections. CAVs drive on the road context individually or within a CAV platoon following the aforementioned HL strategy (e.g., in Fig. 1, CAV 1, 4 are driving individually, while CAV 2, 3 are driving within one platoon). Once a CAV $i$ joins the managed road, it seeks to travel from its initial state $s_{i,init}$ to its terminal position $x_{i,end}$ via an optimal sequence of states $S_i^*(T_i) = \{s_i^*(0), s_i^*(t_s), \ldots, s_i^*(T_i)\}$ and an optimal sequence of control inputs $U_i^*(T_i) = \{u_i^*(0), u_i^*(t_s), \ldots, u_i^*(T_i)\}$ within a time horizon $T_i$ with time step interval $t_s$. Without loss of generality, $role_i(t) \subseteq \{0, 1\}$, meaning CAV $i$ drives as platoon leader (1) or as platoon follower (0) at time step $t$; $switch_i(t) \subseteq \{-1, 0, 1\}$, meaning CAV $i$ changes its role from platoon leader to follower (-1) or from platoon follower to platoon leader (1) or maintains its current role (0) at time step $t$; $v_i(t) \subseteq [0, v^f]$, where $v^f$ is the free flow speed on the managed road; $a_i(t) \subseteq [a_{min}, a_{max}]$, where $a_{min}$ and $a_{max}$ are lower and upper limits of acceleration respectively. In addition, $x_i(t) \subseteq X$ to guarantee CAV $i$ is driving on the managed road.

In this research, platoon dynamics on the managed road are focused rather than CAV kinodynamics. Therefore, the objective function of CAV $i$ with the consideration of its travel time and its automated driving experience is designed as:

$$J_i(s_i(t), u_i(t)) = \min \int_0^{T_i} 1 - s_i(t)^\top Q s_i(t) + u_i(t)^\top R u_i(t)\, dt \tag{3}$$

where

$$Q = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \gamma_{role} & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{3a}$$

$$R = \begin{bmatrix} 0 & 0 \\ 0 & \gamma_{switch} \end{bmatrix} \tag{3b}$$

where $\gamma_{role}$ and $\gamma_{switch}$ are weighting coefficient regarding the square of platoon role and role switching respectively; note that $\gamma_{role} > 0$ and $\gamma_{switch} > 0$. The objective function is composed of three parts: the number 1 represents the travel time; $s_i(t)^\top Q s_i(t)$ represents the time duration of being a platoon follower (i.e., the automated driving time duration according to the adopted HL strategy); $u_i(t)^\top R u_i(t)$ represents the collective frequency of role switching during the managed period. In general, CAVs seek to drive through the managed road as fast as possible with the longest automated driving duration to reduce the driving mode switching frequency as much as possible.

Therefore, the platoon management optimization problem can be mathematical formulated as:

$$(S_i^*(T_i), U_i^*(T_i)) = \arg\min J_i(s_i(t), u_i(t)) \tag{4}$$

s.t.

$$\frac{ds_i(t)}{dt} = A s_i(t) + B u_i(t) \tag{4a}$$

$$C s_i(t) \subseteq X \tag{4b}$$

$$D s_i(t) \subseteq \{0, 1\} \tag{4c}$$

$$E s_i(t) \subseteq [0, v^f] \tag{4d}$$

$$F u_i(t) \subseteq [a_{min}, a_{max}] \tag{4e}$$

$$G u_i(t) \subseteq \{-1, 0, 1\} \tag{4f}$$

$$s_i(0) = s_{i,init} \tag{4g}$$

$$C s_i(T_i) = x_{i,end} \tag{4h}$$

$$G u_i(t) \subseteq g(s_i(t), s_{i-1}(t), \Pi) \tag{4i}$$

where $C = [1, 0, 0]$, $D = [0, 1, 0]$, $E = [0, 0, 1]$, $F = [1, 0]$, $G = [0, 1]$. Eq. (4a) to Eq. (4h) guarantee that the optimal state and control input sequences are within the aforementioned constraints. Without Eq. (4i), the optimization problem can be readily solved following the Pontryagin's maximum principle (PMP) [29]. However, constraints on control inputs are more complex in practice when considering practical platooning strategies (e.g., the HL strategy), V2V and V2I communications (e.g., communication range of CAV, interference of communication failure on platoon merging) and driving task takeover time. Therefore, Eq. (4i) is introduced to further restrict control inputs to be within a set, which can be derived by a function of its current state $s_i(t)$, its preceding CAV's (i.e., the CAV driving downstream of CAV $i$, with no conventional vehicle driving in between) state $s_{i-1}(t)$, and the strategy set $\Pi$, which will be discussed in detail in Section II-B.

### B. PLATOON ROLE SWITCHING CONSTRAINTS

We will elaborate on practical control input constraints in this section. The constraints cover three aspects: firstly, control inputs must abide by platooning strategies; secondly, platoon merging and splitting are realized via V2I and V2V communication, hence these control inputs are restricted by communication-related constraints; lastly, the time delay of CAV drivers taking over the driving task is considered.

#### 1) PLATOONING STRATEGY CONSTRAINTS

- *The human-leading platooning strategy ($\pi_1$):* As discussed in the previous sections, the HL strategy is adopted in this research, by which CAVs are managed to drive in platoons, with the first CAV being driven manually. According to the HL strategy, the driving mode of CAV $i$ (i.e., automated driving or manual driving) at time step $t$ is restricted by its concurrent platoon role, hence its kinematic control input ($a_i(t)$) follows a certain rule:

$$a_i(t) = a_i^h(t), \quad \text{if } role_i(t) = 1 \tag{5}$$

  where $a_i^h(t)$ is the preferred acceleration of CAV $i$ at time step $t$ while it is manually driven. Eq. (5) indicates that when CAV $i$ drives as a platoon leader, its acceleration is not under control and depends on the driver's preference.
- *Maximum platoon size limit ($\pi_2$):* As mentioned in [30], the platoon size is normally restricted on the road in

order to prevent deadlock or accidents triggered by overlong platoons. This constraint is formulated as:

$$\begin{cases} switch_i(t) \neq -1 & \text{if } dim(pl_k(t)) \geq \delta \\ & \text{and } i-1 \subseteq pl_k(t) \\ \sum_{j \subseteq pl_k(t)} switch_j(t) \geq 1 & \text{if } dim(pl_k(t)) > \delta \\ & \text{and } i \subseteq pl_k(t) \end{cases} \quad (6)$$

where $pl_k(t)$ represents a set of sequenced CAV indices that drive in one platoon, which has an index of $k$ at time step $t$. In addition, the sequence of CAV indices indicates the position sequence of CAVs in platoon $k$. In Fig. 1, $pl_1 = \{3, 2\}$. According to Eq. (6), CAV $i$ is prohibited from merging in a downstream platoon when the size of the downstream platoon exceeds the maximum size limit $\delta$. In addition, if CAV $i$ drives in a platoon $k$ which exceeds the maximal limit, there must be more than one CAV in platoon $k$ that switches its platoon role at time step $t$.

- *Overlapping route strategy ($\pi_3$):* According to the studies [17] and [31], coordinating CAVs with a certain length of overlapped route benefits in stabilizing platoon dynamics (e.g., CAVs driving in one platoon will adjust their speed less frequently during platoon merging/splitting) as well as reducing energy consumption. Therefore, CAV$_i$ is restricted to drive in a platoon only when it has a certain length of overlapped route with its proceeding CAV$_{i-1}$. This constraint is formulated as follow:

$$switch_i(t) = 1, \quad \text{if } \min(x_{l'} - x_{i-1}(t), x_{l'} - x_i(t)) \leq \xi \quad (7)$$

where $\xi$ indicates the overlapped route distance and $x_{l'}$ is the coordinate of intersection $l'$ from where CAV$_i$ and CAV$_{i-1}$ drive on different routes.

According to the aforementioned strategies, $\Pi = \{\pi_1, \pi_2, \pi_3\}$.

### 2) COMMUNICATION CONSTRAINTS:

- *Communication request-acknowledge restriction:* Unlike our previous work [26], the platoon merging and splitting are realized via V2V and V2I communication. However, the V2I communication is assumed to be perfect and does not affect the platoon dynamic process, while the V2V communication is based on a request-acknowledge process in this research. In general, once CAV $i$ receives a control order from the RSU to switch its platoon role, it will prompt a switching request and send the request to the target CAV immediately, yet this control order is not implemented as a control input until it receives an acknowledgment from the target CAV (i.e., until the 'handshake' process is accomplished). In addition, if no response has been received within a certain period of time step $\tau$, the CAV $i$ will abort its request and maintain its current state.

The communication related constraint is formulated as follows:

$$switch_i(t) = \tilde{switch}_i(t-\tau) \int_{t-\tau}^{t} \lambda_i^r(\omega)\, d\omega \int_{t-\tau}^{t} \lambda_i^a(\omega)\, d\omega \quad (8)$$

where $\tilde{switch}_i(t)$ is an auxiliary variable which indicates the instant role switch control order that CAV $i$ would receive at time step $t$ from the RSU. $\lambda_i^r(t) \subseteq \{0, 1\}$ is a variable that indicates whether CAV $i$ sends a switching request at time step $t$ ($\lambda_i^r(t) = 1$) or not ($\lambda_i^r(t) = 0$). Similarly, $\lambda_i^a(t) \subseteq \{0, 1\}$ indicates whether CAV $i$ receives an acknowledgment at time step $t$ ($\lambda_i^a(t) = 1$) or not ($\lambda_i^a(t) = 0$). The communication scheme and the 'handshake' platooning process will be described in detail in Section IV.

- *V2V communication range restriction:* Apart from the constraint rooted in the V2V communication process, control inputs are also restricted by communication restrictions, one of which is the V2V communication range. In this research, CAV $i$ is able to merge in a preceding platoon only when CAV $i$ and its preceding CAV $i-1$ (i.e., the tailed CAV in the preceding platoon) are within the communication range of each other. This constraint is formulated as follow:

$$switch_i(t) \neq -1, \text{if } \|x_i(t) - x_{i-1}(t)\| < \rho \quad (9)$$

where $\rho$ is a coefficient parameter representing the communication range of CAVs.

### 3) DRIVING TASK TAKEOVER CONSTRAINT

In general, CAV drivers taking over the driving task can be triggered by drivers' subjective willingness [8] or critical situations [32], which will induce a time delay when switching from the automated driving mode to the manual driving mode. In our case, the driving task takeovers occur while platoon splittings are instructed by the RSU. Therefore, without the consideration of CAV drivers' subjective willingness, a sufficient time delay (including a notification time and a driving task switching time) should be considered in practice to avoid critical situations. In addition, the term 'time budget' is used in many studies to indicate the maximum time period that CAVs could avoid critical situations without reaching their kinematic limits. According to [32], a time budget of lower than 7 seconds is tested to be insufficient for driving task takeovers and a time budget of higher than 15 seconds can be regarded as no foreseeable risk. Therefore, a notification time of 15 seconds is considered in this research before a CAV sends a request to switch from the automated driving mode to the manual driving mode. Hence, Eq. (8) is modified to:

$$switch_i(t) = \tilde{switch}_i(t-\tau-\iota) \cdot \int_{t-\tau-\iota}^{t} \lambda_i^r(\omega)\, d\omega \int_{t-\tau-\iota}^{t} \lambda_i^a(\omega)\, d\omega \quad (10)$$

where $\iota = 15/t_s$ if $\tilde{switch}_i(t-\tau-\iota) = 1$, otherwise, $\iota = 0$.

## III. DISTRIBUTED SOLUTION

As explained in Section II, the optimization problem formulated in Eq. (4) is very hard to solve with the consideration of constraints in Section II-B. On one hand, the control inputs involve integer variable $switch_i(t)$ and the convexity/concavity of the optimization problem cannot be proved, hence it is intricate to solve the problem by using optimizers (e.g., GUROBI, CPLEX, etc.); on the other hand, the existence of Eq. (6)-(9) makes it extremely difficult to solve this problem by PMP-based methods, since the control inputs of CAV $i$ is related to the state of its preceding CAV $i-1$. In addition, the value of $\lambda_i^r(t)$ and $\lambda_i^a(t)$ in Eq. (8) is acquired via vehicular network simulator, which renders a nearly impossible task to analytically solve the optimization problem. Therefore, we adopt approaches that were proposed in [26] in a distributed framework to reach an approximate optimal solution. We will examine the performance of these approaches through simulation based on the platoon merging and splitting models proposed in Section IV-C.

According to approaches in [26], when CAV $i$ drives in the automated driving mode as a platoon follower, its optimal acceleration overtime period $T_i$, $a_i^*(T_i)$ was derived from a CACC model, which will be introduced in Section IV-A, rather than solving Eq. (4). Besides, CAV $i$ was instructed to switch its platoon role accordingly to reach the optimal platoon size of its preceding platoon. Similar to [17], for the purpose of guaranteeing communication between RSU and CAVs and stabilizing CAV platoon dynamics, CAV $i$ only receives platoon role switching orders when entering a road section (i.e., at intersections in our research), except for the order of splitting from an overlong platoon, which can be formulated as:

$$\tilde{switch}_i(t) = 0, \ \text{if } x_i(t) \nsubseteq X_L \\ \text{and } dim(pl_k(t)) \le \delta, i \subseteq pl_k(t) \quad (11)$$

where $X_L$ is a set of intersections' coordinates within the managed road, that $X_L = \{x_{l_1}, x_{l_2}, .., x_{l_j}\}$.

Accordingly, the optimal auxiliary variable over time period $T_i$, $\tilde{switch}_i^*(T_i)$ is derived from:

$$\tilde{switch}_i^*(T_i) = \arg\max dim(pl_k(t)) \quad (12)$$

s.t.

$$i-1 \subseteq pl_k(t) \quad (12a)$$

$$\tilde{switch}_i^*(T_i) \subseteq \{-1, 0, 1\} \quad (12b)$$

$$\text{Eq. (6)-(11)} \quad (12c)$$

Based on Eq. (12), two approaches were introduced regarding the eligibility of switching platoon roles for each CAV.

### APPROACH 1: FREE SWITCH APPROACH

For the free switch approach, all CAVs are allowed to switch their platoon roles multiple times when they are driving on the managed road. Therefore, $\tilde{switch}_i^*(t)$ is derived according to Eq. (12) at each time step without further restriction.

### APPROACH 2: FIXED SWITCH APPROACH

For the fixed switch approach, only a predefined group of CAVs (represented by a set of CAVs acting as potential leaders $LC$) are allowed to switch their platoon roles multiple times, while other CAVs are not allowed to switch their platoon roles from the platoon follower to the platoon leader after merging in a platoon until they reach their destination. In this research, the CAV that entered the managed road has a probability of $p_{lc}$ to be assigned as a potential leader. Therefore, $\tilde{switch}_i^*(t)$ is derived according to Eq. (12) at each time step with one further constraint:

$$\int_0^{T_i} | \tilde{switch}_i(t) | \, dt \le 2, \ \text{if } i \nsubseteq LC \quad (13)$$

As it is mentioned in [26], both approaches aim to reduce the travel time and prolong the automated driving duration by forming platoons with larger sizes; while the fixed switch approach considers reducing the platoon role switching frequency by restricting the role switching eligibility of a certain group of CAVs. The performance of these two approaches was partially reported in [17] assuming ideal communication for platoon dynamics. In addition, it is worthwhile to mention that the instant platoon role switching order $\tilde{switch}_i^*(T_i)$ is centrally determined by the RSU and distributed to the CAV $i$ via V2I communication. Based on the instant order, the platoon dynamic process involving 'request-acknowledgments' is carried out in a decentralized manner by CAVs via V2V communication.

## IV. TRAFFIC SYSTEM MODELING FRAMEWORK

Having the HL strategy and the specific CAV platoon management approaches, it is necessary to develop a traffic system framework for examining these approaches in simulation. In this section, the CAV longitudinal kinematic model (both in the manual driving mode and in the automated driving mode), the traffic signal plan, and the CAV platoon dynamics considering the communication scheme are elaborated.

### A. CAV KINEMATIC MODEL

#### 1) MANUAL DRIVING MODEL

The CAV driving behavior in the manual mode is modeled using the Intelligent Driver Model (IDM) [33], which is formulated by Eq. (14)

$$a_i^h(t) = a_{max}\left[1 - \left(\frac{v_i(t)}{v^f}\right)^{\alpha} - \left(\frac{s_i^*}{\Delta x_i(t)}\right)^2\right] \quad (14a)$$

$$s_i^* = gap_{min} + v_i(t)h^{idm} + \frac{v_i(t)\Delta v_i(t)}{2\sqrt{a_{min}a_{max}}} \quad (14b)$$

where $\Delta x_i(t)$ and $\Delta v_i(t)$ are the gap and the speed difference between CAV $i$ and its preceding vehicle at time step $t$, $gap_{min}$ is the standstill gap, $h^{idm}$ is the desired head-to-tail time gap in manual driving mode and $\alpha$ is a coefficient parameter. In this research, conventional vehicles follow the same kinematic model as manually driven CAVs. Note that although the leading CAVs do not behave according to the collected information, they will transmit awareness messages (BeaconVehicle messages) continuously. These messages are used to instruct the behavior of its following CAVs. The details of messages transmitted is explained in the later sections.

### 2) AUTOMATED DRIVING MODEL

In the automated driving mode, CAV $i$ behaves according to the state of its preceding CAV $i-1$. The preceding CAV state is transmitted within beacon messages, which include $v_{i-1}(t)$ and $x_{i-1}(t)$. In this research, a hybrid cooperative adaptive cruising control (CACC) model is adopted which is proposed in [34]. The CACC model is composed of three modes. In the emergency mode, CAV $i$ will brake with the maximum deceleration, when the bumper-to-tail gap is less than the safe gap $g_i^{safe}$, that $|x_{i-1} - x_i| - l_{CAV} < g_i^{safe}$. The safe gap is calculated as:

$$g_i^{safe}(t) = \min(0, \sigma v_i(t) + \frac{v_i(t)^2 - v_{i-1}(t)^2}{2a_{min}} + gap_{min}), \quad (15)$$

where $\sigma$ is a coefficient parameter. When the time headway of CAV $i$,

$$h_i(t) = \frac{|x_{i-1} - xi|}{v_i(t)} \quad (16)$$

is less than 1.5s, the CAV is in the gap control mode, and its acceleration $a_i(t)$ is calculated following a feed-forward feedback law by Eq. (17).

$$a_i(t) = \frac{1}{h^{gc}}\left(k_p e_i(t) + k_d \dot{e_i}(t)\right) + \frac{1}{h^{gc}}(v_{i-1}(t) - v_i(t)) \quad (17a)$$

$$e_i(t) = (|x_{i-1}(t) - x_i(t)| - l_{CAV}) - \left(gap_{min} + h^{gc} v_i(t)\right) \quad (17b)$$

where $h^{gc}$ is the desired head-to-tail time gap and $k_p$, $k_d$ are coefficient parameters. When $h_i(t)$ is larger than 2s, the CAV is in speed control mode and $a_i(t)$ is calculated by Eq. (18).

$$a_i(t) = k_{sc}(v_f - v_i(t)), \quad (18)$$

where $k_{sc}$ is a coefficient parameter. When $h_i(t)$ is between 1.5s and 2s, the vehicle stays in the same mode as the last time step. In addition, the acceleration and deceleration values are constrained to a specified boundary following Eq. (4e).

## B. TRAFFIC SIGNAL PLAN

In this research, the traffic plan is modeled to meet two tasks: (1) to accord CAV platoons a higher priority than individual CAVs and conventional vehicles when driving through signalized intersections; (2) to guarantee CAV platoons to drive through intersections entirely without splitting, so that instantaneous driving task takeovers by CAV drivers is prevented. In accordance with the above tasks, a signal plan following an actuated framework is modeled in this section.

For ensuring uninterrupted passing of platoon at an intersection, the leader of a platoon communicates with the RSU when it arrives at a certain position, which is

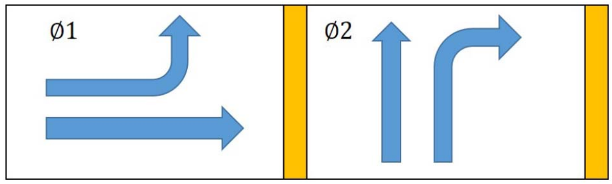



**FIGURE 2.** Signal plan structure.

$d_{com}$ meters upstream to a signalized intersection. The platoon leader transmits platoon information such as the CAV length ($l_{CAV}$), its current speed ($v_i$), its free flow speed ($v^f$), its acceleration limit ($a_{max}$), the current platoon size ($dim(pl_k), i \subseteq pl_k$) and the desired time headway within the platoon ($h^{gc}$) to the RSU. Having this information transmitted, three variables are derived by the RSU, which are the minimum platoon arrival time to the intersection ($t_k^{min\_a}$), the minimum time that the entire platoon would drive through the intersection ($t_k^{min\_c}$) and the estimated time that the entire platoon would drive through the intersection ($t_k^{est\_c}$). These variables are derived from the following equations:

$$t_k^{min\_a} = \frac{v^f - v_i}{a_{max}} + \frac{d_{com} - \left({v^f}^2 - {v_i}^2\right)/2a_{max}}{v^f} \quad (19)$$

$$t_k^{min\_c} = t_k^{min\_a} + h^{gc} \cdot (dim(pl_k) - 1) + \frac{l_{CAV} \cdot dim(pl_k)}{v^f} \quad (20)$$

$$t_k^{est\_c} = \frac{d_{com}}{v_i} + h^{gc} \cdot (dim(pl_k) - 1) + \frac{l_{CAV} \cdot dim(pl_k)}{v^f} \quad (21)$$

Initially, a basic traffic signal plan is assigned to signals with a ring and barrier structure, a signal plan structure example based on the context of Fig. 1 is shown in Fig. 2. Regardless of different road contexts, phase 1 (∅1) is assigned to the movements on the managed road (including exiting the managed road); while Phase 2 (∅2) is assigned to the movements of joining the managed road and driving across the managed road. In addition, there is an amber time between phases, which is served as a buffer time to clear the intersection. Each phase is assigned with a predefined phase time ($t_{\varnothing 1}$, $t_{\varnothing 2}$, $t_{amber}$), a maximum phase time ($t_{\varnothing}^{max}$) and a minimum phase time ($t_{\varnothing}^{min}$).

Traffic signals will apply the basic signal plan unless a CAV platoon has arrived at the communication position and the following three instances occur:

1) *Extending ∅1 instance.*
   In this instance:

$$t_k^{min\_a} < t_{l\_\varnothing 1}^{end} \quad (22a)$$

$$t_k^{min\_c} > t_{l\_\varnothing 1}^{end} + t_{amber} \quad (22b)$$

$$t_k^{est\_c} \leq t_l^{max\_gr} \quad (22c)$$

where $t_l^{max\_gr} = t_{l\_\varnothing 1}^{start} + t_{\varnothing}^{max}$, $t_{l\_\varnothing 1}^{start}$ and $t_{l\_\varnothing 1}^{end}$ represent the starting and ending moment of the current ∅1 at intersection $l$ respectively. Under this circumstance, the traffic signal will extend the time period of ∅1 in the current cycle to guarantee that $pl_k$ could drive through the intersection without dispersion. The extending period of $l\_\varnothing 1$ is derived as:

$$t_l^{ed\_g} = t_k^{est_c} - t_{l\_\varnothing 1}^{end} - t_{amber} \tag{23}$$

2) *Shortening ∅1 instance.*
In this instance:

$$t_k^{min\_a} < t_{l\_\varnothing 1}^{end} \tag{24a}$$
$$t_k^{min\_c} > t_{l\_\varnothing 1}^{end} + t_{amber} \tag{24b}$$
$$t_k^{est\_c} > t_l^{max\_gr} \tag{24c}$$

Under this circumstance, the platoon $pl_k$ could arrive within ∅1; however, the entire platoon cannot be guaranteed to drive through the intersection within a maximum time period of ∅1. Therefore, the traffic signal plan is adjusted to prevent the platoon leader of $pl_k$ from driving through the intersection by shortening the time period of ∅1. The shortened time period of ∅1 is derived as:

$$t_l^{sn\_g} = t_{l\_\varnothing 1}^{end} + t_{amber} - t_k^{min_a} \tag{25}$$

3) *Shortening ∅2 instance.*
In this instance:

$$t_k^{min\_a} < t_{l\_\varnothing 2}^{end} \tag{26a}$$
$$t_k^{min\_a} \geq t_l^{min\_r} \tag{26b}$$

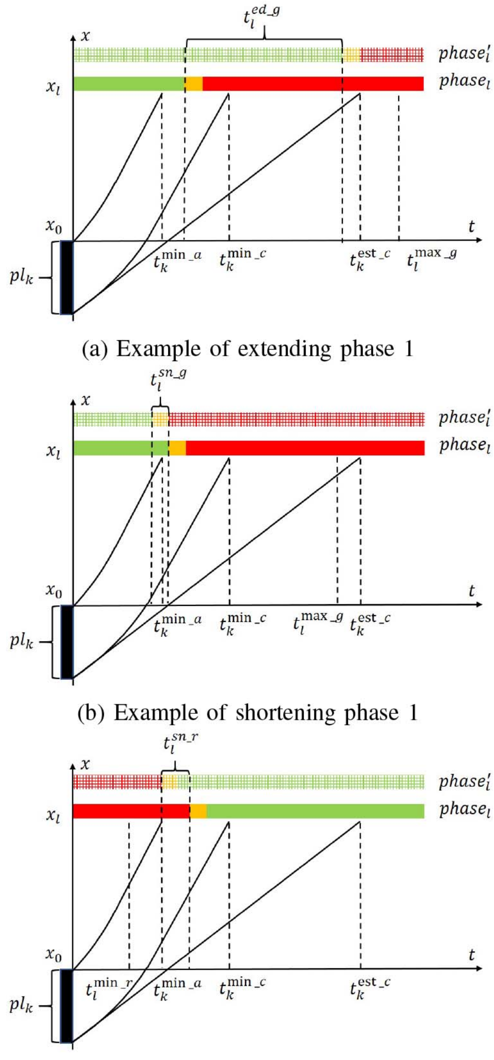
where $t_l^{min\_r} = t_{l\_\varnothing 2}^{start} + t_{\varnothing}^{min}$, $t_{l\_\varnothing 2}^{start}$ and $t_{l\_\varnothing 2}^{end}$ represent the starting and ending moment of the current ∅2 at intersection $l$ respectively. As it is mentioned previously, the traffic signal plan is modeled to accord CAV platoons a higher priority. Therefore, under the circumstance that the platoon $pl_k$ would arrive before ∅1 and after $t_l^{min\_r}$, the time period of the current ∅2 is shortened so that platoon $pl_k$ can drive through the intersection without yielding. The shortened time period of ∅2 is derived as:

$$t_l^{sn\_g} = t_{l\_\varnothing 2}^{end} - t_{amber} - t_k^{min_a} \tag{27}$$

Examples of these three instances are presented in space-time diagrams in Fig. 3. In each diagram, the lower solid color bar represents the traffic signal plan before the platoon leader communicates with the RSU ($phase_l$), while the upper grid color bar represents the adapted traffic signal plan corresponding to each instance ($phase'_l$). The traffic signal plan model is not optimal; however, it is capable of coordinating with the platoon management strategy and the CAV approaches in a safe and computationally efficient manner.

### C. PLATOON DYNAMIC MODEL CONSIDERING COMMUNICATION

In this section, the platoon dynamics are described by proposing a communication scheme with the HL strategy applied.




(a) Example of extending phase 1

(b) Example of shortening phase 1

(c) Example of shortening phase 2

**FIGURE 3.** **Supportive signal plan examples.**

#### 1) V2I COMMUNICATION

The CAVs communicate their routes to the RSU as well as their willingness to lead a platoon when they enter the managed network. The RSU then decides if they can merge to form platoons. When the CAVs are leaving the managed network, the RSU organizes the platoon split dynamics based on the routes of the CAVs. The RSU orders the CAVs to initiate platoon role switch as they approach a certain distance close to an intersection. The decision to start the platoon dynamic process is computed at the RSU as explained in the previous sections. The platoon dynamic decision triggers the CAVs to send platoon merge/split requests to perform the respective platoon dynamics. From this point the CAVs merging to form platoon or splitting into two platoons communicate with each other in a decentralized manner via V2V communication. After each platoon dynamic is complete, the CAV sends the updated platoon list to the RSU and the RSU stores the state of the platoon in its database.

Apart from the role switching decisions, the RSU is also responsible for calculating platoon arrival time at intersections and extending and shortening the phases of the traffic signals to provide uninterrupted platooning. The RSU can compute the arrival time of each CAV using the vehicle trajectory data transmitted as part of the awareness messages broadcasted by the CAVs.

### 2) V2V COMMUNICATION

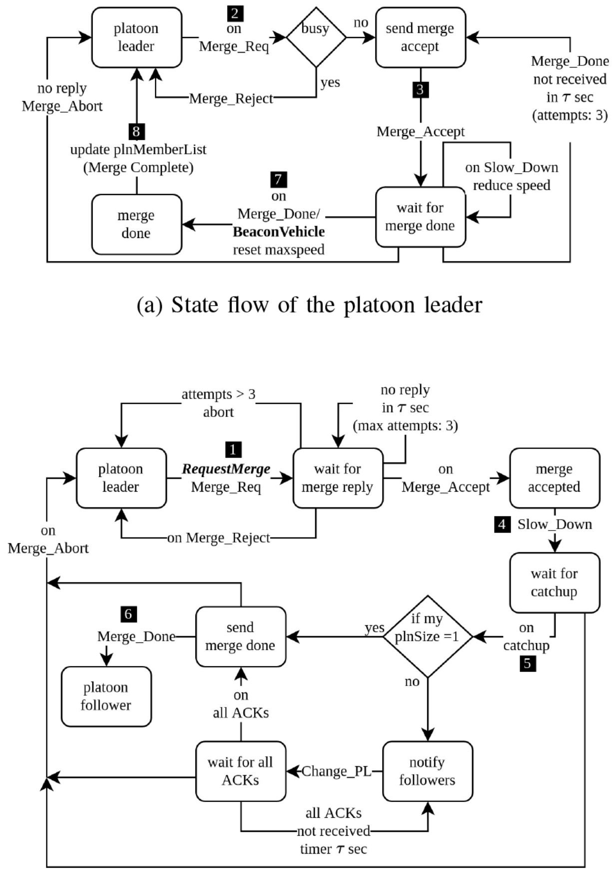
The communication between CAVs is based on the IEEE 802.11p protocol standard. All CAVs are equipped with a dedicated short-range communication (DSRC) unit, and they can transmit four kinds of messages. Each message contains a command based on which the CAVs decide their course of action. The four kinds of messages are listed below.

- *BeaconVehicle:* This update message is transmitted dynamically to create awareness of its presence using the jerk beaconing protocol [35]. According to the protocol, the message frequency is adapted based on the change in speed of the transmitting vehicle. The BeaconVehicle message includes the speed, acceleration, deceleration, and the platoon ID of the vehicle.
- *RequestMerge:* This message is sent by the following platoon leader or the following individual CAV to the leading platoon leader to request a merge. This message contains a 'Merge_Req' command. It is a unicast message. The decision is made by the RSU based on Eq. (12) and is transmitted to the leader of the following platoon which then generates this message. The RequestMerge message is then sent by the platoon leader to the leading platoon as shown in Fig. 4(b). The message includes sending platoon ID, receiving platoon ID, and the size of the platoon requesting the merge.
- *RequestSplit:* When the platoon approaches an intersection where the switch is ordered as per Eq. (12) and Eq. (6), the RSU informs the platoon follower that a split is mandatory. To initiate the split, the platoon follower sends the unicast RequestSplit message to the platoon leader.
- *PlatoonMsg:* Platoon message is used to command vehicles within a platoon. Each message contains the sender ID, the receiver ID, command, sending platoon ID, and receiving platoon ID, and a value that depends on the command sent. It is a modification of the messaging protocol proposed in [21]. Apart from the previous messages which are used to initiate the respective dynamics and create awareness, all other messages consist of commands sent as part of the PlatoonMsg.

The commands sent during platoon merge and split dynamics along with the process flow are explained below.

*Platoon Merging Dynamics*

The state flow of platoon merge is illustrated in Fig. 4 where the numbering indicates one possible scenario. The state transitions, the number of messages required, and the platoon merging duration vary in each case depending on the communication reliability. The state flow of the leading platoon leader and the merging platoon leader is shown in Figs. 4(a) and 4(b), respectively. The process starts with the platoon merge decision which is transmitted by the RSU to the leader of the merging platoon. On receiving the merge decision, the merging platoon leader sends the Merge_Req command as part of the RequestMerge message. On sending a request to merge message the following platoon leader switches state to wait for merge reply (1). The CAV waits for $\tau$s for a reply after which it retransmits a Merge_Req. The maximum number of trials is limited to 3. On receiving a Merge_Req, the potential new leader checks if the vehicle is busy (2). If the vehicle is busy performing another maneuver such as split, Merge_Reject command is issued. Otherwise, the merge request is accepted with a Merge_Accept command within a PlatoonMsg (3). The potential leader then waits for a merge done or a beacon vehicle message from the following vehicle. Once the following platoon receives the Merge_Accept, it adjusts the platoon leader's desired speed to $v^{f'}$ to slow down for fast catch up. Since all vehicles drive at the maximum speed permitted on a given lane, the gap between the vehicles cannot be closed unless the leading vehicle slows down. The gap between the CAVs within a platoon should be less than the inter-platoon gap




(a) State flow of the platoon leader

(b) State flow of the merging platoon

**FIGURE 4.** Platoon merging.

to avoid cut-ins or interference from free agents or human-driven vehicles. Hence, the human-driven leading CAV is instructed to drive slower by 1m/s until the gap after platoon merge is closed (4). While the leading CAV is slowing down as well as waiting for Merge_Done, the following CAV closes the gap. The condition for successful catch-up is as follows:

$$catch\_up = \begin{cases} gap(t) \le (v(t) * h_{idm} + gap_{min} + \epsilon), & true \\ gap(t) > (v(t) * h_{idm} + gap_{min} + \epsilon), & false \end{cases} \quad (28)$$

where $\epsilon$ is the error margin which we considered as 2m. Once the following CAV catches up, it decides the next step based on its platoon size (5). If the merging platoon has no platoon followers, it can directly confirm the merge with a Merge_Done message. Otherwise, the merging platoon sends the change platoon leader (Change_PL) command to its followers. Each follower acknowledges (ACK) the platoon leader change message. After the following platoon catches up and all of its followers acknowledge the Change_PL message, the Merge_Done command is sent and the CAV can finally switch its role to platoon follower and update other parameters such as the transmission power (6). When the leading platoon receives the Merge_Done command or a BeaconVehicle message with an updated platoon ID, it resets the desired speed (7). It then updates the platoon member list as well as communicates the updated platoon data to the RSU (8). On completion of the merge dynamics, the platoon leader is available for further platoon dynamics. If messages are lost and the timer to wait for a particular message expires and it cannot be renewed, the merge is aborted. If the vehicle receives a request to split from the platoon, since splitting has higher priority, the vehicle aborts the merge with the abort command.

*Platoon Splitting Dynamics*

The platoon splitting dynamics are illustrated in Fig. 5. Fig. 5(a) and Fig. 5(b) show the state flow of the platoon leaders of the initial platoon and the splitting platoon respectively. The platoon split is initiated by the RSU when the CAVs have different routes or the optimal platoon size is exceeded. The splitting starts when the splitting CAV receives the decision from the RSU. The splitting CAV then sends the RequestSplit message (1) and waits for the platoon leader to send the change platoon leader command (Change_PL). If the platoon leader is occupied performing other platoon dynamics and does not respond, the RequestSplit message is sent again in $\tau$s. On receiving the request to split from the platoon follower, the leader replies with a Change_PL command as part of the PlatoonMsg (2). The splitting platoon changes its platoon leader to itself and acknowledges the message (3). The splitting platoon waits for Split_Done for $\tau$s and if no reply is received it sends an ACK again. On receiving the ACK from the splitting platoon leader, the old platoon leader checks if any further action is required, i.e., if there are more followers behind the splitting CAV that should join the new platoon (4). Following this, if the splitting platoon has followers behind it that would

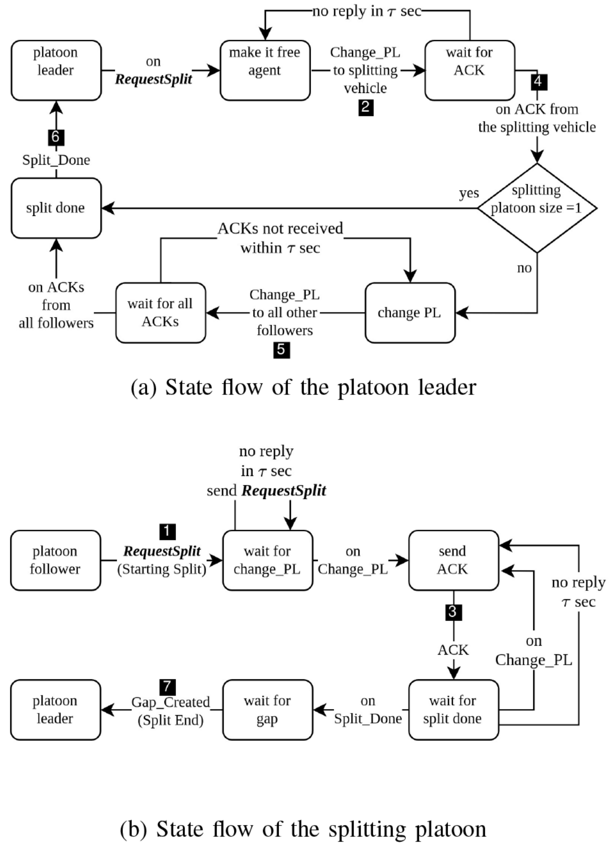



**FIGURE 5.** Platoon splitting.

join it after the split, Change_PL command is sent to the followers (5). The followers respond with ACKs confirming the change. After receiving a leader change confirmation from all CAVs which are part of the splitting platoon, the old platoon leader sends Split_Done to the splitting vehicle making it the platoon leader (6). On receiving the Split_Done, the leader removes the CAV(s) from its member list and is available for other platoon dynamics. Moreover, the old platoon leader as well as the leader of the newly formed platoon communicate the platoon member list to the RSU. The split communication process is completed at this point. The time required from starting split to this point is what we for convention call as the split approved duration. On receiving Split_Done, the new platoon leader starts increasing the time headway to the preceding vehicle. The target gap after the split is calculated as:

$$targetGap = (v(t) * h_{idm}) + gap_{min} \quad (29)$$

The platoon split operation is completed after the gap is more than the *targetGap* (7). The time from starting split to the point where a sufficient gap is created between the two platoons is the total split completion duration. The platoon split dynamics is initiated after a predefined takeover time as discussed in Section II-B.3, which should also be considered as part of the splitting duration. It is only after the

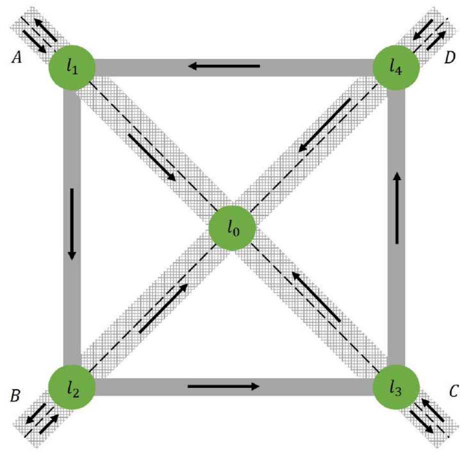



**FIGURE 6.** Simulation context sketch (gray solid roads are managed arterial roads; gray dashed roads are inner-urban roads including entries and exits of the arterial roads, which are not managed; green circles are signalized intersections; solid arrows indicate the driving direction.).

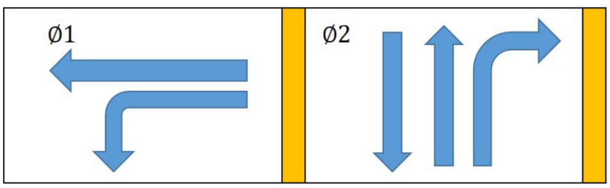



**FIGURE 7.** Modified signal plan structure based on the simulated context.

**TABLE 1.** Communication parameters.

| Parameter | Value |
|---|---|
| Wireless protocol | WAVE Short Message Protocol |
| Channel | CCH 178 |
| Center frequency | 5890MHz |
| Channel bandwidth | 10MHz |
| Transmission power | |
| Platoon leader | 20mW |
| Platoon follower | 10mW |
| BeaconVehicle | 96 bytes |
| RequestMerge | 192 bytes |
| RequestSplit | 192 bytes |
| PlatoonMsg | 192 bytes |
| Transmission rate | adaptive 2-10Hz |
| Data rate | 6Mbps |

gap creation that the human driver gets back control of the vehicle.

## V. SIMULATION EXPERIMENT

The experiments are carried out in a joint simulation framework where the communication network is simulated in OMNeT++ and the traffic network is simulated in SUMO. A one-way one-lane ring road with entries and exits is developed in the simulation to mimic the urban arterial road and to produce replicated traffic flows. Fig. 6 presents a sketch of the simulated context. The simulated arterial roads have 4 links with the length of 1km, together with 4 signalized intersections at the vertexes of each link. Each vertex is attached with one exit lane and one entry lane linking the arterial road and locations A, B, C, D respectively, both of them are 200m. Traffic signals at intersections $l_1$, $l_2$, $l_3$ and $l_4$ perform the signal plan described in Section IV-B; as $\varnothing 1$ is assigned to the movements on the managed road and $\varnothing 2$ is assigned to the movements of joining the managed road and driving across the managed road, the basic signal plan is modified as shown in Fig. 7 based on the simulated context.

All vehicles are evenly generated from positions A, B, C, and D during the first 1800s, which includes a peak hour during the time interval between 1200s to 1500s. In addition, a total volume of 565 vehicles is generated during the off-peak hour (with a traffic flow rate of 1600veh/h) and 200 vehicles are generated during the peak hour (with a traffic flow rate of 2400veh/h). CAVs are randomly generated among all vehicles with a penetration rate of $p_{rate}$. The vehicles departing from the four starting positions are evenly assigned to travel to a destination (apart from its starting position) through the arterial roads (e.g., vehicles depart from A are evenly assigned to 3 routes: (1)A-$l_1$-$l_2$-B; (2)A-$l_1$-$l_2$-$l_3$-C; (3)A-$l_1$-$l_2$-$l_3$-$l_4$-D). Besides, links between $l_0$ and other intersections are developed to mimic inner-city roads. Specifically, one CAV could take a detour via inner-city roads to reach its assigned destination if it failed to split from a CAV platoon, which is caused by a communication failure mentioned in Sections II-B.2 and IV-C (e.g., if a CAV is assigned to reach D and failed to split from a CAV platoon, which is driving to B, before $l_4$; it could keep requesting for splitting and try to exit the arterial road at $l_1$, then take the route $l_1$-$l_0$-$l_4$ to reach D). In addition, the traffic signal at $l_0$ gives identical priority to movements from each link (with 15s green time for movements from each link, which conduct a cycle time of 60s). The simulation will stop until all generated vehicles reach their destinations.

The DSRC communication parameters used in all experiments are listed in Table 1. The CAVs in the automated following mode transmit messages with reduced power. The BeaconVehicle message rate was adapted dynamically. The message sizes including the header for the different message types are also listed.

In this simulation study, we have systematically examined the CAV platoon management approaches in multiple scenarios with different parameter settings. The values of universal parameters in the aforementioned models are listed in Table 2. Specifically, the value of $r_{switch}$ is assigned to be 7.5 as each splitting dynamic request is acted upon after 15s notification time and this time delay is evenly penalized to the platoon role switching while merging and splitting. As we adopted two ad-hoc approaches to solve the problem in Eq. (4), the performance of these approaches is dependent on the values of hyperparameters in the constraints and the solution of Eq. (5)-(13). The hyperparameters which are related to the technological capability of the CAVs (e.g., $\tau$, $\rho$, etc.) and safety (e.g., $\iota$) are beyond the scope of this study; apart from these parameters, there are three hyperparameters to be tuned for examining the performance: the

**TABLE 2.** Modeling parameters.

| Parameter | Value |
|---|---|
| $v^f$ | $14m/s$ |
| $v^{f'}$ | $13m/s$ |
| $a_{min}$ | $-0.73m/s^2$ |
| $a_{max}$ | $1.67m/s^2$ |
| $r_{role}$ | 1 |
| $r_{switch}$ | 7.5 |
| $\delta$ | 5 |
| $t_s$ | 0.1s |
| $\tau$ | $0.5/t_s$ |
| $\rho$ | 50m |
| $gap_{min}$ | 2m |
| $\alpha$ | 4 |
| $h^{idm}$ | 1.6s |
| $h^{gc}$ | 0.7s |
| $l_{CAV}$ | 5m |
| $\sigma$ | 0.1 |
| $k_p$ | 1 |
| $k_d$ | 1 |
| $k_sc$ | 0.4 |
| $d_{com}$ | 50m |
| $t_p^{max}$ | 40s |
| $t_p^{min}$ | 15s |

**TABLE 3.** Examined parameters in different scenarios.

| Parameter | Value |
|---|---|
| **Approach 1** | |
| $p_{rate}$ | 0.2, 0,4, 0.6, 0.8, 1 |
| $\xi$ (km) | 1, 2, 3 |
| **Approach 2** | |
| $p_{rate}$ | 0.2, 0,4, 0.6, 0.8, 1 |
| $p_{lc}$ | 0.2, 0.4, 0.6, 0.8 |
| $\xi$ (km) | 1, 2, 3 |

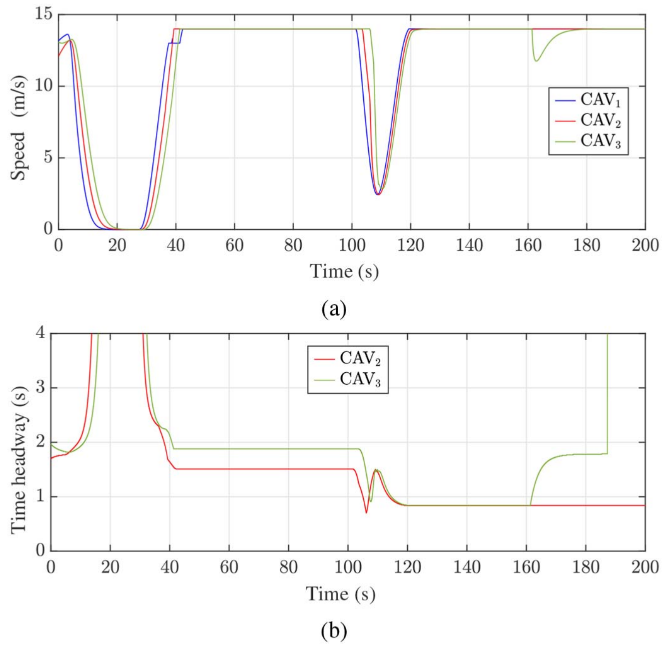



**FIGURE 8.** Speed and time headway trajectories of CAVs in a platoon.

maximum platoon size ($\delta$), the overlapped route distance ($\xi$) and the potential leader assignment rate ($p_{lc}$) in approach 2. However, the impact of different settings of the maximum platoon size mainly lies on yielding adjacent vehicles from changing lanes in a multi-lane road network [36], which is also beyond the scope of this study. Therefore, we selected discrete values of $\xi$ and $p_{lc}$ to examine the performance of the proposed approaches. In addition, the examination is applied under different CAV penetration rates and a benchmark scenario with 0 CAV penetration rate. As a result, we examined a total number of 75 scenarios and the detailed settings of scenarios are listed in Table 3.

## VI. RESULTS AND DISCUSSION

The results section is divided into three subsections: the first part presents the speed and time headway trajectory of involved CAVs during platoon dynamics, the second part explains the performance of the communication process within the platoon dynamics, and the last part evaluates the performance of the HL strategy regarding different scenarios with the consideration of communication reliability.

### A. TRAJECTORY RESULTS

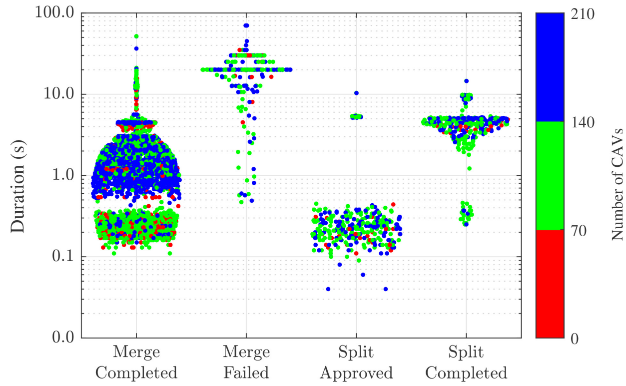
A random sample taken from the simulation is presented in Fig. 8, which depicts the speed and the time headway trajectories of merging and splitting dynamics of a platoon (with 3 CAVs involved) within a time period of 200s. In this sample, all three vehicles were initially driving in the manual mode and they successively entered the managed road at 36s through a signalized intersection. The $CAV_2$ requested the $CAV_1$ to join the platoon at 36.2s and the first platoon merging was completed at 38.5s, after which $CAV_2$ switched to the automated driving mode. Following this, the $CAV_3$ requested to join the platoon at 38.7s and the process of 3-vehicle platoon merging was completed at 41.4s, following which $CAV_3$ switched to the automated driving mode. The CAV platoon drove through the second signalized intersection at 112s; thereafter, the platoon splitting dynamic occurred at 161.1s, at which the $CAV_3$ requested to split from the platoon and the splitting was completed at 166s.

From Fig. 8(a), it is observed that the $CAV_1$ adjusted its desired speed twice at around 40s while waiting for other CAVs to join the platoon; whereas $CAV_3$ decelerated at 161.2s for splitting from the platoon. While three CAVs traveled as a platoon, a synchronized cruising speed and smooth acceleration were recorded. It can be observed from Fig. 8(b) that the time headway between the platoon members can be larger than $h^{idm}$ as long as it follows the criteria in Eq. (28). The time headway reduces to $h^{gc}$ after a stop-and-go movement at the second intersection. In addition, the time gap of $CAV_3$ increased to $h^{idm}$ after it left the platoon. Note that the infinity value of time headways in Fig. 8(b) indicates either a standstill situation or the CAV has left the managed road and its kinematic data cannot be detected.

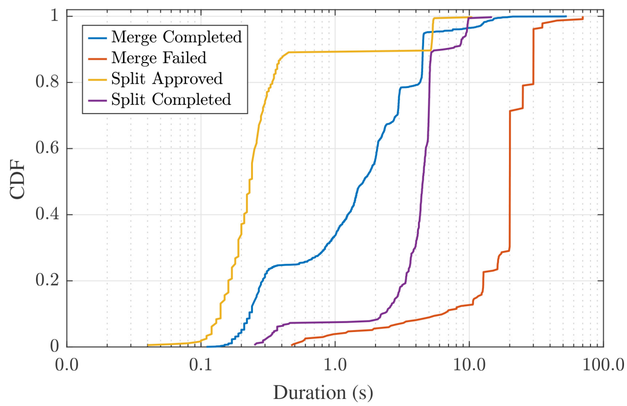
### B. COMMUNICATION PROCESS RESULTS

For the communication process within the platooning dynamics, the process duration and the number of exchanged messages are assessed in the case of merge completion, merge failure, split approval, and split completion. The merge completion process can be further divided into merge approval and merge completion including gap closure. However, in this research, the CAV only has to reduce its time gap to the preceding platoon member and no interference from adjacent CAVs is considered. Therefore, we did not consider the duration of the merging request approval separately. According to Section IV-C.2, the duration of a completed merging dynamics is calculated as the time from a CAV starts to request merging to the point where the catch-up condition given by the Eq. (28) is satisfied. In addition, since merging requests have a lower priority than splitting requests, these requests can be aborted on receiving a splitting request or after a certain number of attempts, hence a considerable number of merging efforts were failed. The merge failure duration is calculated as the time from the start of requesting to merge until the request is aborted. In the case of platoon splitting dynamics, the CAV has to create a sufficient gap as defined by Eq. (29) to the preceding vehicle before handing over driving tasks to the driver, which causes a considerable delay. Within this delayed period, communication between the platoon leader and the splitting CAV is still maintained and the splitting CAV is still registered as a platoon member under the circumstances of driving through a signalized intersection. Therefore, the split completion duration is divided into two cases: the splitting approval, which is the communication duration regarding the 'handshake' process; as well as the split completion duration which includes the gap creation duration.

*Duration of platoon dynamics:* Fig. 9(a) shows the swarm plot of durations for the aforementioned cases in all designed scenarios. Each dot represents a platoon dynamic process and the color of dots represents the level of the total number of CAVs present on the managed road at the moment that the corresponding platoon dynamic is initiated. The three colors red, green, and blue represent low, medium, and high instantaneous CAV amount levels respectively. In addition, cases with the same duration are scattered over the x-axis for a better representation. The cumulative distribution function (CDF) of the duration in all scenarios is plotted in Fig. 9(b). From Fig. 9(b), we can infer that 94% of the successful merge dynamics have a duration less than or equal to 4.55s. The completed merging dynamic normally takes longer time duration (longer than 0.4s) at a high CAV flow level, since the probability of having communication network congestion as well as the probability of the merging 'handshake' process being interrupted by a splitting request increases with the increase of CAV flow level. 4.6% of the generated merge requests were aborted and the merge failures occurred at random intervals. Among the failed merging cases, the merging was aborted at 0.47s for the fastest case and after 70s for the worst case. These merging failures can be inferred with different causes. In general, the merging failures within a short duration are caused by multiple splitting request interceptions, hence the failure cases are evenly distributed among medium and high CAV flow levels; whereas the merging



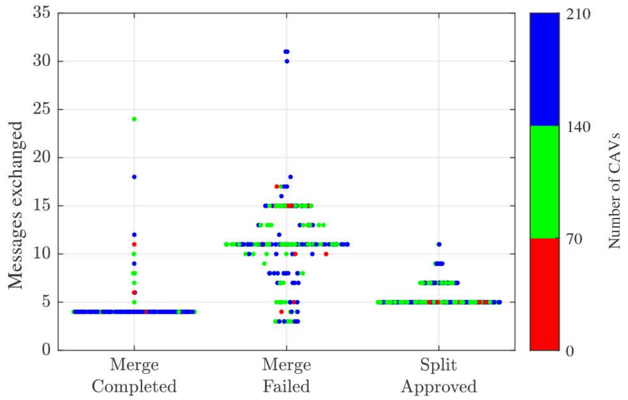

(a) Swarm plot of platoon dynamics durations. The x-axis shows four considered cases and the y-axis represents the respective duration on a log scale.



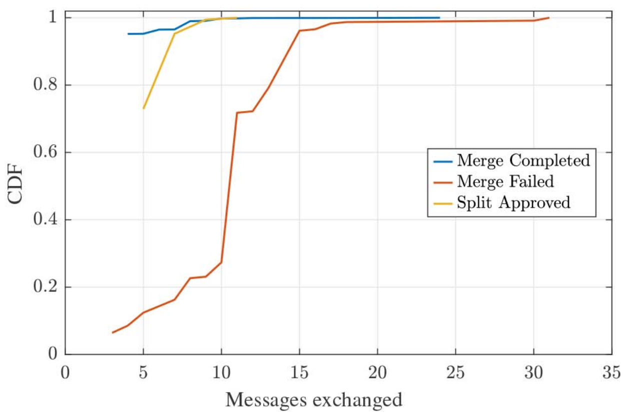

(b) CDF plots of platoon dynamics durations for four considered cases

**FIGURE 9.** Duration of platoon dynamics.

failures with a long duration (longer than 10s) are caused by communication network congestion and are dominated by cases at a high CAV flow level. In addition, the merge failure rarely occurred when CAV density was low. It can be inferred that 89% of the splitting requests were approved within 0.45s due to a higher processing priority than merging requests, the rest of splitting requests can take up to 10.6s as a result of waiting for foregoing splitting requests approval, communication network congestion or packet losses. In general, the splitting dynamics were completed with a longer duration than merging dynamics and can take up to 14.6s. Note that the CAV drivers were given a reaction time of 15s before the splitting dynamics were initiated, which raises the entire splitting completion duration to 29.6s. Even though we designed inner-city roads in Fig. 6, there is no splitting failure as the splitting request messages were repeatedly sent without a limit and the splitting dynamics were all completed before the requesting CAV leaving the managed road. In addition, in the splitting approval CDF curve in Fig. 9(b) a step is observed at 5s. This is rooted in a high occurrence of a single $CAV_i$ located in the middle of the platoon, leaving the platoon to follow a route different than its preceding




(a) Swarm plot of sent messages.




(b) CDF plot of sent messages.

**FIGURE 10.** Messages exchanged.

$CAV_{i-1}$ and following $CAV_{i+1}$. Under this circumstance, two platoon splitting dynamics are required, and the $CAV_{i+1}$ must request to split upon a splitting completion of $CAV_i$, which takes around 5s in most cases according to Fig. 9(a).

*Message requests:* The number of messages exchanged by the CAVs during platoon dynamics in all scenarios is plotted in Fig. 10(a), whereas its distribution characteristics are depicted in Fig. 10(b). The number of messages does not include the V2I communication, but rather focuses on the communication between CAVs. It is observed in Fig. 10(a) that most of the merging dynamics required 4 messages. The number of sent messages increases with increased communication traffic, which is induced by increased CAV traffic in the network or packet losses. The merging dynamics were aborted after a minimum of 3 messages and a maximum of 31 messages, which can be expected since once the communication network is congested, the number of packets lost in the next steps increases exponentially. In addition, most merging failures occurred when the CAV flow level in the network is above 70, which has similar reasons as the increase of merging dynamic durations. The splitting dynamics require up to 11 messages. In the best case (i.e., when a CAV requests to split from a platoon with a size of 2), 5 messages are required for the splitting dynamic. More messages were sent between CAVs under the circumstances that a CAV requests to split from a larger platoon or it is located in the middle of the platoon. This is because of the fact that apart from requesting and receiving approval messages, the following CAVs have to acknowledge the splitting and the change of their platoon leader. Moreover, it can be observed that the splitting dynamics required more messages at a high CAV flow level, as a result of repeated trials with a more congested communication network and a higher packet loss probability.

The above communication process results suggest that to improve communication reliability, a CAV platoon management approach should be able to reduce the occurrence of platoon dynamics. With an increase in the number of platoon dynamics especially splitting dynamics, the number of platooning messages increases and so is with BeaconVehicle messages which are generated more often when the vehicle is changing speed continuously, which will increase the communication network congestion level. This suggestion is consistent with the proposed objective function in Eq. (3).

### C. HL STRATEGY EVALUATION RESULTS

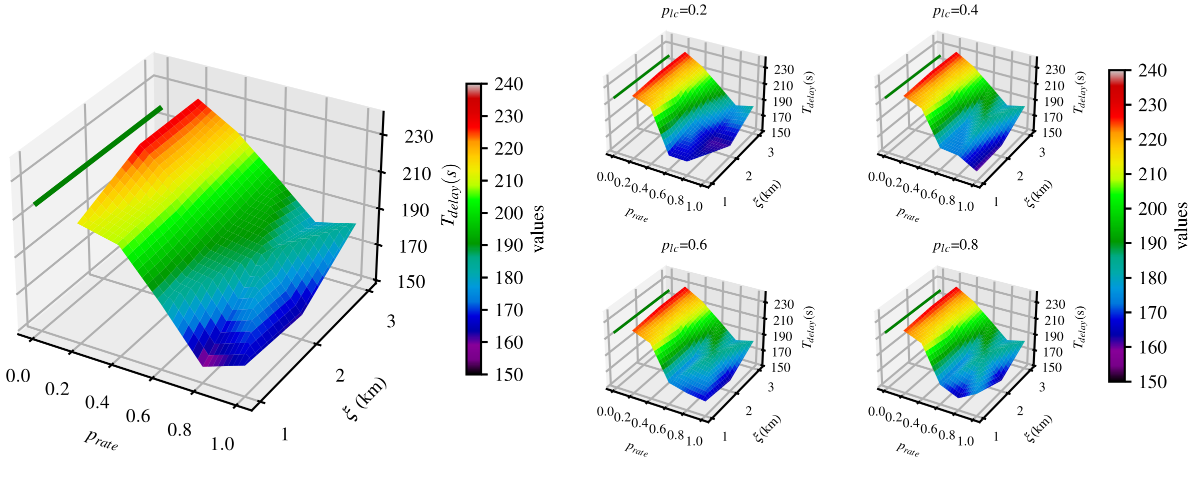
In this section, the performance of the HL strategy with two aforementioned approaches is evaluated in different scenarios with the consideration of all three factors in the objective function Eq. (3), namely the travel time, the automated driving duration, and the role switching frequency.

Since all vehicles were randomly assigned different routes, the travel time is evaluated by the metric average travel time delay of all generated vehicles ($T_{delay}$). $T_{delay}$ is calculated using Eq. (30), where $dis_i$, $T_i$ are the traveled distance and the travel time of vehicle $i$ respectively, while $N$ is the set of total generated vehicles and $size(N)$ is the total number of generated vehicles in each scenario.

$$T_{delay} = \frac{\sum_{i \subseteq N} \left( T_i - \frac{dis_i}{v^f} \right)}{size(N)} \tag{30}$$

The travel time delay under the HL strategy for the two approaches is depicted by surface plots in Fig. 11. In general, the average travel time delay of vehicles in mixed traffic is improved when the penetration rate is above 40%. The performances of approach 1 and approach 2 are similar, that the delay decreases with a higher penetration rate and lower overlapping distance constraint ($\xi$) while merging. These results are within our expectations that a higher penetration rate can increase the probability of platooning and allows more CAVs to drive automatically, while a higher value of $\xi$ reduces such probability. However, a lower value of $\xi$ may induce more platoon splitting dynamics and delays rooted in the gap creation process, which makes the impact of forming more platoons less significant in terms of automated driving duration; such phenomenon can be observed in Fig. 11(b) with $p_{lc} = 0.2$ and $p_{lc} = 0.8$.

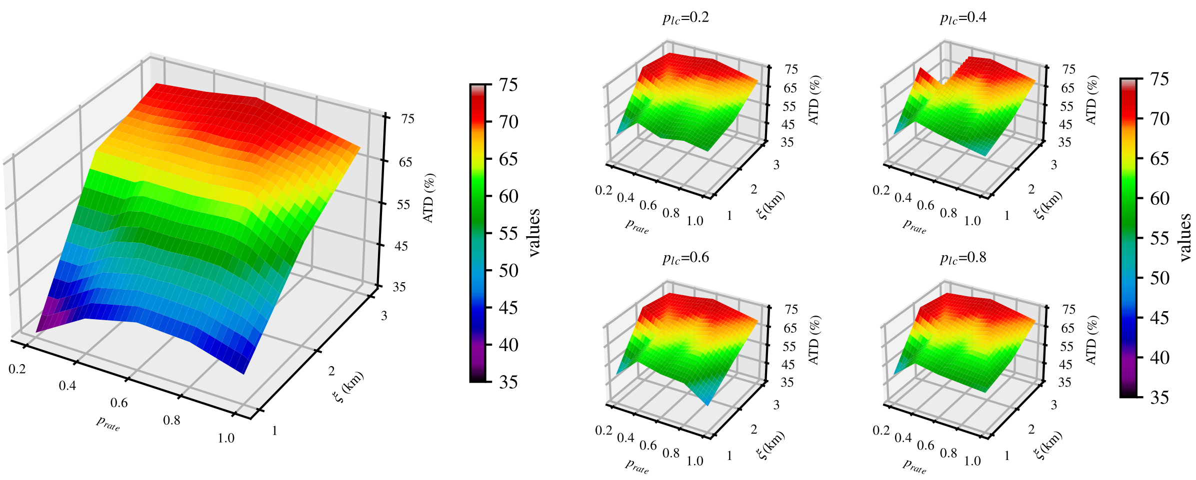
The platoon followers' average automated driving durations (ATD) in different scenarios is presented in Fig. 12. Since routes were assigned arbitrarily to the generated CAVs,




(a) Approach 1

(b) Approach 2

**FIGURE 11.** Average travel time delay for all generated vehicles. Green lines indicate the value of the benchmark scenario with 0 CAV penetration.




(a) Approach 1

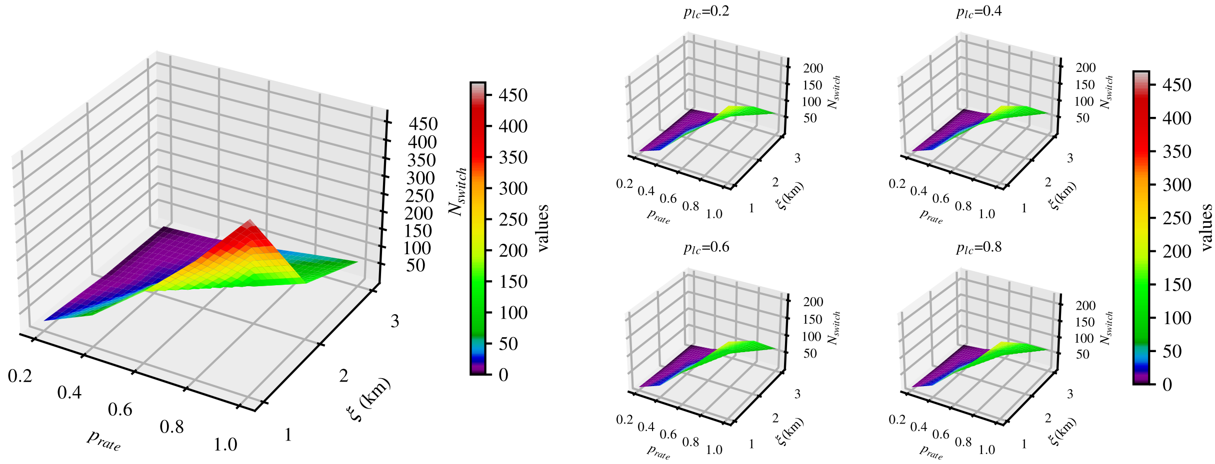
(b) Approach 2

**FIGURE 12.** Automated driving duration ratio for CAV followers.

the average ATD is calculated as the sum of the ratios of the individual ATD of each CAV to the total travel time divided by the number of CAVs and is calculated by Eq. (31), where $ATD_i$ is the automated driving duration of CAV $i$, $N_{CAV_f}$ is the set of CAVs that drove in the automated mode and $size(N_{CAV_i})$ is the total number of CAVs in each scenario.

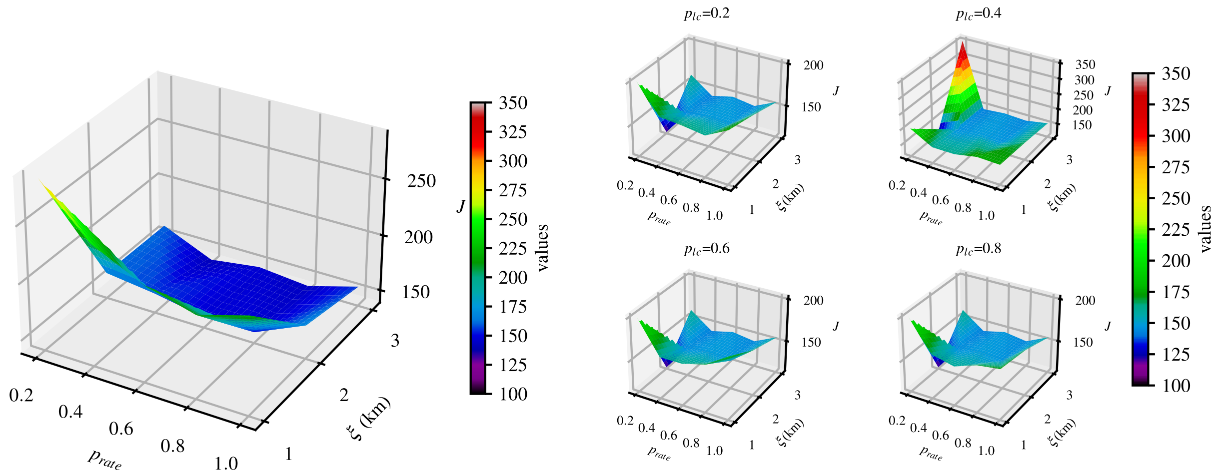
$$ATD(\%) = \frac{\sum_{i \subseteq N_{CAV_f}} \frac{ATD_i}{T_i}}{size(N_{CAV_f})} * 100 \tag{31}$$

It is observed from Fig. 12 that ATD increases as $\xi$ increases, which was expected since a higher value of $\xi$ guarantees a more stable automated driving experience, i.e., less number of platoon splits due to mismatched route. Further, with a higher value of $\xi$ the CAV drivers can expect a lower probability to be instructed to take over the driving tasks once they have merged in a platoon. However, the ATD is not always increased with the increase of CAV penetration rate, since few CAV platoons can be formed under a low $p_{rate}$, which can deteriorate the ATD ratio. The ATD ratio reaches peak at a $p_{rate}$ value of about 0.6. Moreover, approach 2 performs better than approach 1 with respect to ATD since the number of platoon dynamics is reduced. In addition, a higher $p_{lc}$ produces a better performance with a lower $p_{rate}$ and a lower $p_{lc}$ produces a better performance with a higher $p_{rate}$. This phenomenon is also foreseeable, since assigning a certain group of CAVs to be the potential leader can stabilize the automated driving experience of other CAVs, which has a more significant impact when the value of $p_{rate}$ is higher. Note that for both approach 1 and approach 2, maximum ATD is observed to be around 75%, which is the maximum value that can be reached with the consideration of travel times on the entry/exit links of the managed network and platoon merging durations.




(a) Approach 1 (b) Approach 2

**FIGURE 13.** **Total number of role switches.**




(a) Approach 1 (b) Approach 2

**FIGURE 14.** **Objective function value.**

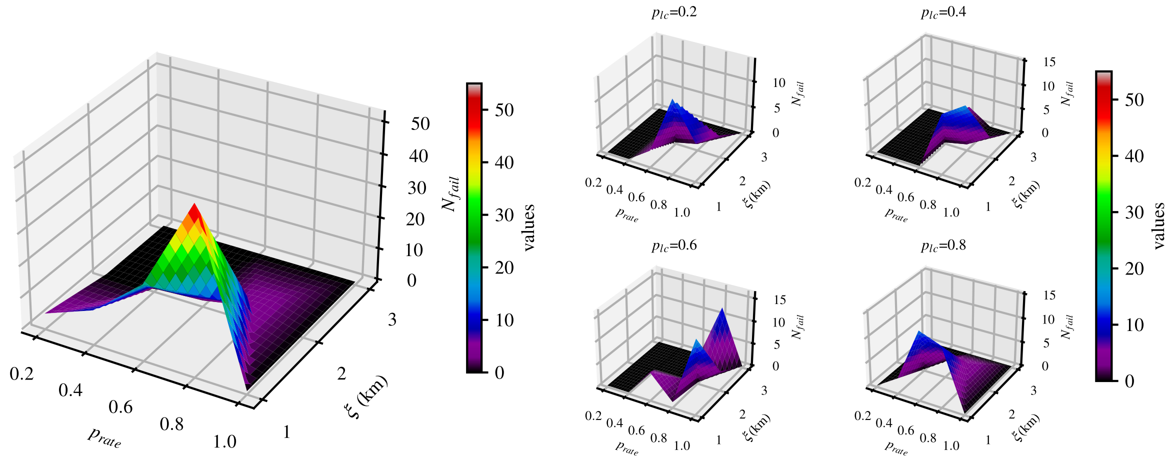
Fig. 13 presents the results of the number of role switches ($N_{switch}$) in all scenarios. It is evident from Fig. 13 that $N_{switch}$ grows with the increase of CAV penetration rate and the decrease of overlapping travel distance ($\xi$) required for merging. The reason is similar to what is argued in describing the ATD ratio results, that a higher value of $p_{rate}$ and a lower value of $\xi$ normally induces more platooning dynamics. However, approach 2 has a significant improvement in $N_{switch}$ compared to approach 1; the peak of the switching count is reduced to half when we limit the number of potential leaders. As a result, when adopting the HL strategy, assigning a certain group of CAVs as the potential leader can significantly release the CAV drivers' stress of taking over the driving tasks while the CAVs are driving in the automated mode.

With the consideration of the aforementioned results, we further evaluate an average overall performance of the HL strategy in terms of the objective function value ($J$) as stated in Eq. (3). $J$ is calculated as,

$$J = \frac{\sum_{i \subseteq N_{CAV}} J_i}{size(N_{CAV})} \tag{32}$$

where $N_{CAV}$ indicates the set of all generated CAVs in a scenario and $size(N_{CAV})$ represents its the total number of CAVs.

It is observed from Fig. 14, that as the objective function seeks to minimize travel time and to increase the automated driving stability (i.e., longer automated driving duration and lower switching frequency), the HL strategy performed better with an intermediate value of $p_{rate}$ and $\xi$, which indicates that platooning with HL strategy is recommended in a mixed traffic scenario, while the constraint of overlapping distance for merging should not be too strict or too forgiving. In general, the performance of approach 2 is better than approach 1 when applying the HL strategy and a choice of 0.4 for $p_{lc}$ can be recommended for all values of CAV penetration rate.



(a) Approach 1

(b) Approach 2

**FIGURE 15.** Number of merge failure occurrences.

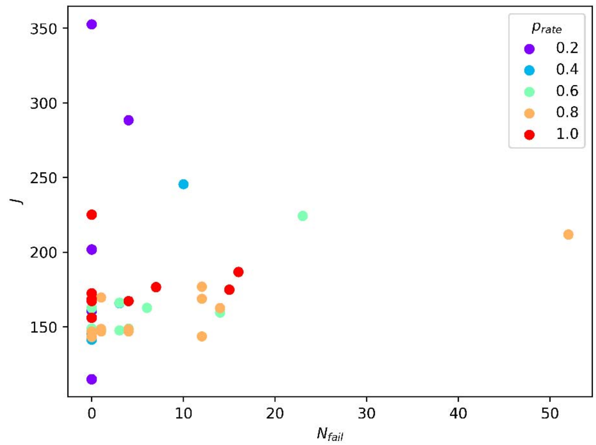


**FIGURE 16.** Correlation between communication failure and objective function value.

To have an insight into the communication reliability when applying the HL strategy in different scenarios, we further present the occurrences of communication failure cases in Fig. 15. It is evident from Fig. 15 that a lower value of $\xi$ induces more communication failure cases, as more stable platooning dynamics render less communication network congestion and fewer interruptions from splitting requests. However, a higher CAV penetration rate does not always induce more communication failures, which can be evident from Fig. 9 and Fig. 10, as the communication congestion level is a temporal dependent indicator and a higher value of $p_{rate}$ only increases the opportunity of inducing communication network congestion. Therefore, as the amount of communication failures mainly relies on the stability of platooning dynamics, when applying the HL strategy, approach 2 has significantly better performance than approach 1, which can be observed from Fig. 15.

To further understand the impact of communication reliability on the overall performance of the HL strategy, the corresponding relationship between the communication failures $N_{fail}$ and the objective function values ($J$) in all scenarios is depicted in Fig. 16. It can be evident that the value of $J$ is distributed more sparsely with more reliable communication and low losses. However, the high cost under a reliable communication condition mainly results from a low level of CAV penetration rate with fewer platooning opportunities, while more reliable communication can always render a lower cost in the extreme case. These results suggest that if a more reliable and low latency communication technology is provided, policymakers can have higher flexibility to apply a certain CAV platoon management approach (e.g., the choice of $\xi$) with the consideration of the traffic density and the CAV drivers' preference (e.g., the willingness of driving in the automated mode).

## VII. CONCLUSION

In this research, we thoroughly modeled the problem of managing CAV platoons in an urban road network, proposed the HL strategy and two distributed approaches for implementing the HL strategy, proposed a decentralized communication scheme to apply the HL strategy, as well as evaluated the HL strategy with the consideration of travel time, automated driving experience, and communication reliability in a simulated traffic system. Specifically, by modeling V2V communications, we investigated the communication characteristics such as platoon dynamics duration and messages exchanged in different cases. We further evaluated the application of the HL strategy regarding travel time, automated driving duration, and role switching frequency. Our simulation results showed improvement in travel time in the urban network, which is more significant with a CAV penetration rate higher than 40%. With the HL strategy, the CAV drivers can experience automated driving for 75% of their duration. In addition, switches between platoon roles and driving modes of CAVs can be maintained to a low level with a proper choice of

HL application approach and platoon merging constraints ($\xi$). In general, assigning a certain group of CAVs as potential drivers when adopting the HL strategy results in better overall performance and a $p_{lc}$ value of 0.4 outperformed other choices of $p_{lc}$. Finally, we examined the communication reliability in different scenarios, which indicates that a CAV platoon management approach that can generate more stable platoon dynamics is able to guarantee better communication reliability; on the other hand, better communication reliability can contribute to a better performance of a certain cooperative platoon management approach, which will provide more flexibility to policymakers under different situations. Note that in this research, no splitting failures were found due to the constraint of Eq. (11) and the design of the simulated context. This phenomenon suggests that the performance of the HL strategy can be further improved by relaxing the constraint of Eq. (11) regarding the link length between the intersections; however, investigating to what extent the constraint can be relaxed is out of the scope of this research.

This research has several limitations. Firstly, the HL strategy provides only a sub-optimal solution for managing CAV platoons. Secondly, ideal communication is considered between CAVs and RSU, and also no obstacles (e.g., buildings, bridges, etc.) are simulated in this study. Thirdly, the CAV drivers' preference was not considered and CAVs fully complied with platoon role control orders. Lastly, lateral behaviors were not considered in this study, in order to avoid interference from adjacent CAVs while platooning dynamics.

Nevertheless, this research sheds some light on how to manage the CAVs cooperatively in an urban network with the consideration of traffic efficiency, automated driving experience, and communication reliability. As one of the pioneers to jointly investigate traffic management strategy and V2V communication, this research revealed that the HL strategy is feasible to be applied in mixed traffic with assistance from the infrastructure. Moreover, the results showed that traffic efficiency can be improved significantly by providing a cooperative traffic management approach that is capable of producing stable platooning dynamics and reliable communication.

To address the aforementioned limits in the future, this research can be further extended by considering more realistic scenarios, such as implementing realistic V2I communication with 5G network and analyzing the effect of losses and delays on platooning, modeling CAV lateral behaviors in a multi-lane road network and considering CAV drivers' preferences. In addition, the CAV management problem could be optimally solved by meta-heuristic algorithms, which can be addressed in further research.

## REFERENCES

[1] *Automated Driving: Levels of Driving Automation are Defined in New SAE International*, SAE International Standard J3016, 2014.

[2] I. A. Ntousakis, I. K. Nikolos, and M. Papageorgiou, "On microscopic modelling of adaptive cruise control systems," *Transp. Res. Procedia*, vol. 6, pp. 111–127, Dec. 2015.

[3] H. Liu, X. D. Kan, S. E. Shladover, X.-Y. Lu, and R. E. Ferlis, "Modeling impacts of cooperative adaptive cruise control on mixed traffic flow in multi-lane freeway facilities," *Transp. Res. C, Emerg. Technol.*, vol. 95, pp. 261–279, Oct. 2018.

[4] L. Xiao, M. Wang, W. Schakel, and B. van Arem, "Unravelling effects of cooperative adaptive cruise control deactivation on traffic flow characteristics at merging bottlenecks," *Transp. Res. C, Emerg. Technol.*, vol. 96, pp. 380–397, Nov. 2018.

[5] A. Talebpour, H. S. Mahmassani, and S. H. Hamdar, "Effect of information availability on stability of traffic flow: Percolation theory approach," *Transp. Res. Procedia*, vol. 23, pp. 81–100, Dec. 2017.

[6] T.-W. Lin, S.-L. Hwang, and P. A. Green, "Effects of time-gap settings of adaptive cruise control (ACC) on driving performance and subjective acceptance in a bus driving simulator," *Safety Sci.*, vol. 47, no. 5, pp. 620–625, 2009.

[7] M. Makridis, K. Mattas, and B. Ciuffo, "Response time and time headway of an adaptive cruise control. An empirical characterization and potential impacts on road capacity," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 4, pp. 1677–1686, Apr. 2020.

[8] F. Viti, S. P. Hoogendoorn, T. P. Alkim, and G. Bootsma, "Driving behavior interaction with ACC: results from a field operational test in the Netherlands," in *Proc. IEEE Intell. Veh. Symp.*, 2008, pp. 745–750.

[9] S. C. Calvert, G. Klunder, J. L. L. Steendijk, and M. Snelder, "The impact and potential of cooperative and automated driving for intelligent traffic signal corridors: A field-operational-test and simulation experiment," *Case Stud. Transp. Policy*, vol. 8, no. 3, pp. 901–919, 2020.

[10] S. E. Shladover, C. Nowakowski, X.-Y. Lu, and R. Ferlis, "Cooperative adaptive cruise control: Definitions and operating concepts," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2489, no. 1, pp. 145–152, 2015.

[11] J. Lioris, R. Pedarsani, F. Y. Tascikaraoglu, and P. Varaiya, "Platoons of connected vehicles can double throughput in urban roads," *Transp. Res. C, Emerg. Technol.*, vol. 77, pp. 292–305, Apr. 2017.

[12] S. W. Smith *et al.*, "Improving urban traffic throughput with vehicle platooning: Theory and experiments," *IEEE Access*, vol. 8, pp. 141208–141223, 2020.

[13] K. Higashiyama, K. Kimura, H. Babakarkhail, and K. Sato, "Safety and efficiency of intersections with mix of connected and non-connected vehicles," *IEEE Open J. Intell. Transp. Syst.*, vol. 1, pp. 29–34, 2020.

[14] H. Liu, X.-Y. Lu, and S. E. Shladover, "Mobility and energy consumption impacts of cooperative adaptive cruise control vehicle strings on freeway corridors," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2674, no. 9, pp. 111–123, 2020.

[15] S. E. Shladover, D. Su, and X.-Y. Lu, "Impacts of cooperative adaptive cruise control on freeway traffic flow," *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2324, no. 1, pp. 63–70, 2012.

[16] V. Milanés and S. E. Shladover, "Handling cut-in vehicles in strings of cooperative adaptive cruise control vehicles," *J. Intell. Transp. Syst.*, vol. 20, no. 2, pp. 178–191, 2016.

[17] S. Yao and B. Friedrich, "Managing connected and automated vehicles in mixed traffic by human-leading platooning strategy: A simulation study," in *Proc. IEEE Intell. Transp. Syst. Conf. (ITSC)*, 2019, pp. 3224–3229.

[18] M. Segata, B. Bloessl, S. Joerer, F. Dressler, and R. L. Cigno, "Supporting platooning maneuvers through IVC: An initial protocol analysis for the JOIN maneuver," in *Proc. 11th Annu. Conf. Wireless On-Demand Netw. Syst. Services (WONS)*, Apr. 2014, pp. 130–137.

[19] S. Maiti, S. Winter, L. Kulik, and S. Sarkar, "The impact of flexible platoon formation operations," *IEEE Trans. Intell. Veh.*, vol. 5, no. 2, pp. 229–239, Jun. 2020.

[20] T. Chen, M. Wang, S. Gong, Y. Zhou, and B. Ran, "Connected and automated vehicle distributed control for on-ramp merging scenario: A virtual rotation approach," 2021, *arXiv:2103.15047*.

[21] M. Amoozadeh, H. Deng, C. Chuah, H. Zhang, and D. Ghosal, "Platoon management with cooperative adaptive cruise control enabled by VANET," *Veh. Commun.*, vol. 2, no. 2, pp. 110–123, Apr. 2015.

[22] J. Mena-Oreja and J. Gozalvez, "On the impact of platooning maneuvers on traffic," in *Proc. IEEE Int. Conf. Veh. Electron. Safety (ICVES)*, Sep. 2018, pp. 1–6.

[23] J. Mena-Oreja, J. Gozalvez, and M. Sepulcre, "Effect of the configuration of platooning maneuvers on the traffic flow under mixed traffic scenarios," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2018, pp. 1–4.

[24] Y. Feng, D. He, and Y. Guan, "Composite platoon trajectory planning strategy for intersection throughput maximization," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 6305–6319, Jul. 2019.

[25] X. J. Liang, S. I. Guler, and V. V. Gayah, "An equitable traffic signal control scheme at isolated signalized intersections using Connected Vehicle technology," *Transp. Res. C, Emerg. Technol.*, vol. 110, pp. 81–97, Jan. 2020.

[26] S. Yao, R. A. Shet, and B. Friedrich, "Managing connected automated vehicles in mixed traffic considering communication reliability: A platooning strategy," *Transp. Res. Procedia*, vol. 47, pp. 43–50, Jan. 2020.

[27] W. Zhang, N. Aung, S. Dhelim, and Y. Ai, "DIFTOS: A distributed infrastructure-free traffic optimization system based on vehicular ad hoc networks for urban environments," *Sensors*, vol. 18, no. 8, p. 2567, Aug. 2018.

[28] G. G. M. N. Ali, B. Ayalew, A. Vahidi, and M. Noor-A-Rahim, "Analysis of reliabilities under different path loss models in urban/sub-urban vehicular networks," in *Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall)*, Sep. 2019, pp. 1–6.

[29] L. S. Pontryagin, *Mathematical Theory of Optimal Processes*. Boca Raton, FL, USA: Routledge, 2018.

[30] H. Liu, X. Kan, D. Wei, F.-C. Chou, S. E. Shladover, and X.-Y. Lu, "Using cooperative adaptive cruise control (CACC) to form high-performance vehicle streams," Inst. Transp. Stud., Univ. California, Berkeley, CA, USA, Rep., 2018. [Online]. Available: https://ideas.repec.org/p/cdl/itsrrp/qt8pw857gb.html

[31] F. Luo, J. Larson, and T. Munson, "Coordinated platooning with multiple speeds," *Transp. Res. C, Emerg. Technol.*, vol. 90, pp. 213–225, May 2018.

[32] B. Zhang, J. de Winter, S. Varotto, R. Happee, and M. Martens, "Determinants of take-over time from automated driving: A meta-analysis of 129 studies," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 64, pp. 285–307, Jul. 2019.

[33] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top.*, vol. 62, no. 2, pp. 1805–1824, 2000.

[34] R. A. Shet and F. Schewe, "Performance evaluation of cruise controls and their impact on passenger comfort in autonomous vehicle platoons," in *Proc. IEEE 89th Veh. Technol. Conf. (VTC-Spring)*, 2019, pp. 1–7.

[35] M. Segata, F. Dressler, and R. L. Cigno, "Jerk beaconing: A dynamic approach to platooning," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2015, pp. 135–142.

[36] S. Calvert, W. J. Schakel, and B. van Arem, "Evaluation and modelling of the traffic flow effects of truck platooning," *Transp. Res. C, Emerg. Technol.*, vol. 105, pp. 1–22, Aug. 2019.