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Managing Connected Automated Vehicles in Mixed Traffic Considering Communication Reliability: a Platooning Strategy

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Abstract

Managing connected and automated vehicles (CAV) in mixed traffic scenario necessitates special attention when introducing them into the market. The coexistence of CAVs and non-CAVs leads to complex interactions. To simplify the interactions in the envisioned scenario, a strategy that operates CAVs in a platoon which is led by a CAV driven by a human is proposed in this paper. Implementing this strategy in practice requires feasible platooning approaches of assigning CAV roles in platoons (i.e. to be a leader or a follower) and reliable communication between CAVs and roadside units (RSU). Two rudimentary rule-based approaches are designed in this paper and examined in a micro-simulation. All CAVs are assumed to be V2X enabled. CAVs start communicating with each other and RSU when they enter the CAV zone. The RSU require CAVs to follow a certain platooning approach and CAVs cooperate with each other to form platoons. The impacts of different platooning approaches and communication reliability level are evaluated by total travel time and the automated driving mode duration.

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1. Introduction

Improving road traffic by using connected and automated vehicles (CAV) is widely investigated for the past decades (1)(2). In the near future, introducing CAVs in the market will be an unalterable trend; hence a mixed traffic scenario including CAVs and non-CAVs (SAE 0 level vehicles (3)) can be envisioned.

However, imposing a significant positive impact on mixed traffic scenario requires social acceptance and cooperation among CAVs. Previous studies showed that a large share of drivers prefer to avoid direct interactions with CAVs (4). Moreover, deploying CAVs cannot guarantee a significant improvement of traffic efficiency in mixed traffic scenario (5)(6). Therefore, introducing CAVs into the market requires management methods to cope with social acceptance of CAVs and the traffic efficiency.

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Existing literature focuses on managing CAVs into one platoon, by which several CAVs travel together as a string with short headway (7). Dynamics within one platoon such as information exchange (8), CAV behavioural modelling (9), communication establishment (10), etc. has been thoroughly investigated. With the knowledge of CAV dynamics within one platoon, investigating the coordination of CAVs to form multiple platoons in a road network merits further attention. Particularly, it is non-trivial to investigate this coordination in mixed traffic scenario.

One primary issue to consider when designing the CAV platoon coordination algorithm is the communication reliability. According to Segata et al., 2014, if packet loss ratio (PLR) is more than 10% the platoon join maneuvers are aborted where the beacon transmission frequency is 10Hz (11). Consequently, the performance of managing CAVs can be significantly affected by unreliable communication (8). Therefore, evaluating the CAV communication reliability under management is essential.

To the best of our knowledge, there is no research has designed detailed coordination method along with assessing the impact of them with a consideration of communication reliability.

This paper will fill this research gap by proposing a strategic platoon management method for private CAVs in mixed traffic scenario. While having all CAVs in a road network coordinated can instigate intricate algorithms and overload computational complexity, developing management strategy and corresponding approaches to regulate CAVs' behaviour in a decentralized manner is an alternative way to circumvent this problem. Specifically, the management strategy provides a fundamental principle of forming platoons; whilst the corresponding approaches manipulates detailed platooning dynamics by regulating the role choice of each CAV, namely to be a platoon leader or a platoon follower.

Specifically, a strategy that platoons CAVs with human leaders (HL) is proposed in this paper. This strategy is inspired by the platoon experiment of heavy-duty vehicles (12). In the HL strategy, CAVs are operated as a platoon, in which the first CAV is manually driven. The driver of each CAV can switch between automated mode and manual driving mode. In addition, as the first step towards a decentralized algorithm for platooning advice, two rudimentary approaches to operationalize the strategy are designed. By the proposed method, CAVs are organized in platoons; meanwhile direct interactions between CAV and non-CAV are eliminated. The proposed management method is further evaluated in micro-simulation with a special consideration of communication reliability.

The rest of this paper is structured as follows. Section 2 elaborates the management method of this research. Section 3 describes the simulation experiment, whereas section 4 gives the results and discussions. Finally, the research is concluded in section 5.

2. Methodology

The research scenario is depicted in fig 1. It consists of a one-lane urban arterial road ($L1$) with consecutive intersections ($T1$, $T2$, etc.). The solid arrows represent the driving directions. V2X communication is available in the communication area, which is covered by blue grid. On the targeted road, the blue vehicles are CAV platoon leaders, the black vehicles are CAV platoon followers, whilst the grey vehicles are non-CAVs. When platoon $[pl_1, pl_2, pl_3]$ encounter after passing the intersection ($T1$), they may form new platoons and switch their roles accordingly for the purpose of reducing their travel time (by forming a platoon with bigger size) or achieving a hand-free driving experience (by switching their roles from a platoon leader to a platoon follower). In order to form new platoons, the platoon leaders $[1, 2, 3]$ will communicate with the road side unit (RSU) and distribute the new roles to their followers. Afterwards, all involved CAVs will behave accordingly. Similarly, new platoons may form after vehicle $[4]$ merging on $L1$. Note that pl_3 is considered as a platoon with only one member $[3]$.

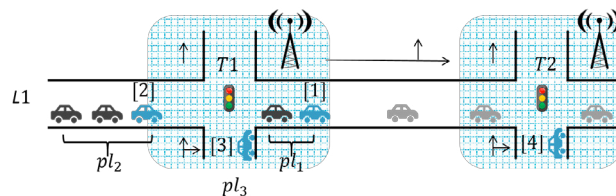


Fig. 1: Research situation scheme

The platoon dynamics are managed by manipulating the role switch of each CAV in this paper. A model to describe how CAVs are managed in the research scenario is introduced in section 2.1. Further, the detailed design of the platooning management approach is elaborated in section 2.2. Table 1 provides an overview of notations used in this paper.

Table 1: Symbol and description

Symbol	Description
i	The index of vehicles
$role_i^t$	The role of vehicle i at time t . The value 1 denotes platoon follower and 0 denotes platoon leader.
$mode_i^t$	The driving mode of vehicle i at time t . The value 1 denotes automatic driving mode and 0 denotes manual driving mode
v_i^{desire}	The desired speed of vehicle i
TL_i	Total travel length of vehicle i
TTT_i	Total travel time of vehicle i
$response_i$	The positive response that CAV i received; the value is a subset of $\{split, merge\}$
$x_{decision}$	The location at which platoon leaders start sending merge request and CAV followers inspect their routes
NV	The set of all vehicles in the network
LC	The set of all potential leaders
$size()$	The function for retrieving the amount of members in a certain vehicle group or a CAV platoon

2.1. Management method structure

In this section, the CAV's behaviour under the platoon management is modeled following the structure of a multi-regime model with three stages (i.e. perception, planning and actuation) by Xiao et al. (13). The proposed model is depicted in fig. 2. In fig. 2, the behavioural procedures are linked by arrows; especially, the dashed arrows represent transitions between behavioural procedures which involve communication.

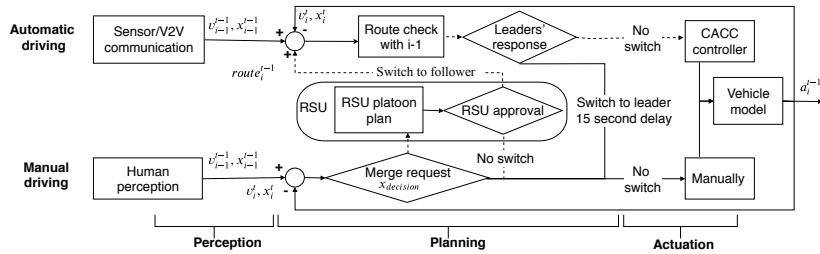


Fig. 2: CAV behavioural model under the platoon management

Within one simulation step t , one CAV will behave either in the automatic driving response loop or the manual driving response loop; and the CAV will follow the behavioural procedures within each loop sequentially. The driving mode switch is instructed by the HL strategy as function of the role. For CAV i :

$$mode_i = f(role_i) = \begin{cases} 0 & \text{if } mode_i = 0 \\ 1 & \text{if } mode_i = 1 \end{cases} \quad (1)$$

Hence, one CAV will drive automatically only when it drives in a CAV platoon as a follower; whereas it will drive manually only when it is a platoon leader.

When a target CAV is driving automatically in a platoon, it will keep perceiving kinematic data via sensors and the vehicle-to-vehicle (V2V) communication; meanwhile, it will communicate with its leader (the predecessor CAV) and the platoon leader within each simulation step for the permission of staying in the platoon. If both leaders forward a positive response to the target CAV, a preferred acceleration rate will be calculated by the cooperative adaptive cruising control law (CACC). After perceiving the preferred acceleration rate, the practical acceleration rate will be actuated by

the low-level vehicle model. Finally, the practical speed and position of the target CAV at the next simulation step will be delivered to the next behavioural loop. In this paper, the request of staying in the platoon will always be permitted with two exceptions: when the platoon leader instructs the target CAV to leave the platoon or when the target CAV will drive to a different road than its leader. If the target receives a negative response from the leader, it will send a split request to the platoon leader. After receiving the permission of splitting, the target CAV will split from the platoon and switch its role. In addition, we assume that CAV drivers will not supervise the driving task when the CAV drives autonomously; hence a 15 second delay is assumed between the time instant the splitting permission is received by the target CAV and its switching action.

The target CAV will follow a similar behavioural procedure when it drives manually as a platoon leader. After perceiving kinematic data by human drivers, the target CAV will send a request of joining a platoon to the RSU at a certain location $x_{decision}$. Consequently, the RSU will respond the target CAV with a positive or negative acknowledgement. If a positive response is received by the target CAV, it will join a platoon by RSU's instruction and switch to be a platoon follower and drive automatically. However, if a negative response is received by the target CAV, it will keep driving manually. Note that the role switch of the platoon leader may trigger consequent role switches of its followers. As described above, these role switches will be distributed via V2V communication.

In the aforementioned CAV behavioural model, the proposed platoon management is performed by the communication between the RSU and the platoon leaders. Explicitly, the RSU communicates with platoon leaders and collects the information including the platoon merging requests, platoon information (i.e. their positions, members and sizes) and kinematic data of platoon leaders. When a platoon leader requests the RSU to merge with the preceding platoon, this request is sent to the RSU by a unicast message. When receiving a merging request, the RSU will first check if the preceding platoon is available of receiving new platoon members by inspecting its coordination and size. Whether a positive response is granted further depends on a certain platooning approach. The designed platooning approaches will be elaborated in section 2.2. With a positive response, the RSU will instruct the requested platoon leader to join a specific platoon and assign new roles for its followers. Consequently, the requested platoon leader will distribute this information to its followers and all the involved CAV will behave accordingly. Note that if no response message is received from the RSU either due to loss of the request message or the RSU response, the CAV should resend the request message within 10 seconds. This procedure is depicted by fig. 3, where the dash arrows represent procedures involve V2X communication and the ellipses contain information transmitted in communication.

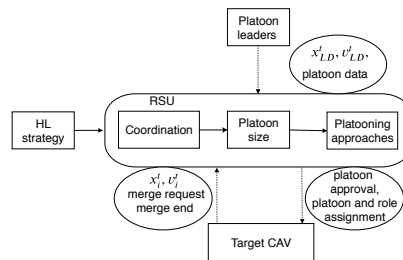


Fig. 3: RSU model of managing platoons

2.2. Management approach

Two decentralized approaches are designed in the section. In general, traffic flow with a smaller average time headway and more synchronized actions will produce more throughput and smaller travel time delay (2). In addition, by staying in the automatic driving mode for a longer time, one CAV driver can enjoy a better undisturbed hand-free driving experience. Having more CAVs consistently controlled by CACC derives a smaller average headway, more synchronized actions and more hand-free drivings. Furthermore, we assume traffic signals will grant a phase extension to allow CAV platoons to pass intersections without splitting (this assumption is elaborated in section 3.1), thus a longer effective green time can be achieved by forming platoons with bigger sizes (i.e. number of CAVs in one platoon). Therefore, we design the management approaches with general objectives of maximizing the average platoon size, minimizing the average driving mode switching frequency of all CAVs and maximizing their automatic driving duration.

While reaching a global optimization by decentralized approaches is intricate, we propose two rudimentary approaches to reach an approximate local optimization. Specifically, all CAV platoon leaders are pursuing to join their proceeding platoons at $x_{decision}$ to maximize the size of their proceeding platoons. However, whether they can join the proceeding platoons depends on the regulated maximal platoon size (which is assumed as 4 CAVs in this paper) and a certain switching rule, which is restricted by different approaches:

- [1] **Free switch approach:** By this approach, all CAVs are free of being platoon leaders and switching from one driving mode to another to reach the platooning objective. Thus, for each CAV i in a platoon, the positive response for its request is:

$$response_i = \arg \max_{response_i} size(PL_i^{pre}) \quad (2)$$

- [2] **Fixed switch approach:** By this approach, only a proportion of CAVs are free of being platoon leaders, referred as potential leaders; whereas other CAVs can only switch from the platoon follower to the platoon leader while they are driving on the managed roads. As a result, only potential leaders can lead other CAVs in a platoon. Thus, for each CAV i in a platoon, the positive response for its request is:

$$response_i = \arg \max_{response_i} size(PL_i^{pre}) \quad (3)$$

$$s.t. response_i \neq split, \forall i \notin LC$$

These two approaches are the most intuitive way of controlling CAV platoon role switches. However, these approaches have their practical significance. In practice, some CAV drivers has a stronger incentive then others to be a platoon follower; whereas other CAV drivers hold a neutral altitude to be a leader or a follower. Therefore, policy maker can choose to subsidies part of CAV drivers to be the potential leader, in order to facilitate other CAV drivers' driving experience.

In this paper, the designed approaches are evaluated by a matrix consists of 6 criteria: (1) the average travel delay (ATD), (2) the average frequency of CAVs switching from one driving mode to another (AF), (3) the average duration of CAVs driving automatically (ADA), (4) the total number of merging request (MR) to RSU and (5) the total number of permitted merging request (MP) by RSU. The first criteria is adopted for evaluating the traffic efficiency, the second and third criteria are adopted for evaluating the undisturbed driving experience. Criteria (4) and (5) are adopted for evaluating communication performances in different approaches. In general, one approach will outperform another if the it can deliver a lower ATD, a smaller AF, a longer ADA and a higher response rate $\frac{MP}{MR}$.

For clarification, the travel time delay for each vehicle is defined as its simulated travel time minors its desired travel time, which is defined as its total travel length divided by its desired speed:

$$ATD_{NV} = \frac{\sum_{i \in NV} (TTT_i - TL_i / v_i^{desire})}{size(NV)} \quad (4)$$

3. Simulation experiment

3.1. Simulation environment

An integrated simulation environment composed of the microscopic traffic simulation package SUMO (14) and the communication network simulation simulator OMNET++ (15) is used in this research. The TraCI interface (16) is used for conjunction of two simulation packages retrieving values from the simulation environment and controlling objects' behaviours in simulation. In the simulation, human-driven vehicles behave according to the intelligent driver model, referred as IDM (17). When CAVs drives automatically, it will behave according to a first order CACC model by van Arem et al.(1). All vehicles have a maximum acceleration rate of 0.8 m/s² and a maximum deceleration rate of -4.5 m/s². The desired time headway for human drivers is 1.6 second (17). Several field tests suggest that the desired time headway for CACC is within the range of 0.3-0.6 second (1)(18). In this paper, a desired time headway of 0.5 second is assumed for the CACC controller. Note that the headway refers to time gap between the fronts of two consecutive vehicles. A simple actuated traffic light control is adopted in this research, by which all platoons are guaranteed to pass the intersection as a whole. In addition, the maximum and minimum phase time duration is

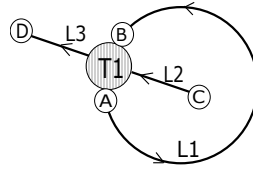


Fig. 4: RSU model of managing platoons

predefined for traffic lights with 28s and 32s. Specifically, when one platoon is passing the intersection, if the first vehicle is arriving the intersection in the green phase while the tail vehicle is arriving in the red phase, this platoon will obtain a phase extension if the extended phase time is within the maximum phase duration. The communication is modelled based on IEEE 802.11p protocol. Each CAV broadcasts cooperative awareness messages (CAMs) at an adaptive rate determined by the jerk beaconing protocol (10) without re-transmission. RSU is dedicated short range communication (DSRC) equipped. In addition, the merge request and response messages which are event-based are unicast messages.

3.2. Experiment design

The simulated context are depicted in fig.4. A one-lane ring arterial road L1 with one signalized intersection T1 is simulated in this paper to produce replicated traffic flows. CAVs driving on L1 are managed by the proposed method. In the simulation, vehicles can merge in via L2 and merge out via L3 to L1 through T1. The length of L1 is 400m; while L2 and L3 are both 100m. All roads have a permitted speed of 50 km/h, which is adopted as the desired speed of each vehicle. RSU is located at T1; therefore, we define point A as $x_{decision}$. In figure 4, arrows represent the driving directions, points A and C represent starting points of L1 and L2, whilst points C and D represent the ending points of L1 and L3 respectively. 20 vehicles with at least 5 CAVs are randomly generated within 200 second from point C with different routes. Specifically, 5 CAVs are assigned with route (a): C-A-B-A-B-A-B-D-C and the rest will be assigned with route (b): A-B-A. Note that no travel time is assumed from point D to point C and one vehicle will start the next trip immediately when their previous trip is finished. In each simulation, 6 different CAV penetration rates (0%, 20%, 40%, 60%, 80%, 100%) of vehicle taking route (a) are assumed. In addition, different proportion of CAVs (20%, 50% and 80%) are assumed as potential leaders when adopting the fixed switch approach. Therefore, a total number of 18 simulations will be executed. The simulation will have a step length of 0.1 second and it will stop after all the simulated vehicles have reached point A for 10 times.

4. Results and discussion

The simulation results are presented in table 2. Especially, the results of selecting 20%, 50% and 80% CAVs as potential leaders are presented in one bracket sequentially. The results demonstrate a trend that the ATD decreases with the increase of penetration rate. Moreover, in approach [1], a higher penetration rate conducts a higher AF, a higher ADA and a lower response rate. Within approach [2], it is observed that when the CAV penetration rate is lower than 60%, a moderate potential-leader share conducts the lowest ATD; whereas a big potential-leader share conducts the lowest ATD when the CAV penetration rate is higher. Regarding the hand-free driving experience, platoons are only formed with a big potential-leader share when the CAV penetration rate is lower than 20%; when the CAV penetration rate is higher, a small potential-leader share conducts the lowest AF, meanwhile the longest ADA is conducted by a big share of potential leaders. Considering the communication reliability, assigning 80% CAVs as potential leaders outperforms others when the CAV penetration rate is lower than 40 %; whereas assigning 20 % CAV potential leaders outperforms others when the CAV penetration rate is higher.

In general, approach [1] outperforms approach [2] in reducing ATD. However, the difference is insignificant when the CAV penetration rate is 0% and 80%. The differences between approaches are significant considering the hand-free driving experience. Specifically, employing approach [2] can produce a lower AF and a longer ADA under all CAV penetration rate. Meanwhile, approach [2] outperforms approach [1] in communication reliability by producing a higher response rate. In this paper, CAVs will substantially generate more intensive requests by approach [1] (i.e.

Table 2: Simulation results

CAV penetration	ATD (s)	AF	ADA (s)	MR	MP	$\frac{MP}{MR}$
approach [1]						
0%	504	0.3	62	5	2	0.4
20%	451	0.6	123	16	5	0.31
40%	489	0.6	187	21	6	0.28
60%	404	1.1	223	38	10	0.26
80%	448	1.7	334	50	13	0.26
100%	370	2.1	324	67	17	0.25
approach [2]						
0%	(537;537;537)	(0;0;0.2)	(0;0;63)	(0,0,4)	(0,0,2)	(0,0,0.5)
20%	(537;537;547)	(0;0;0.4)	(0;0;135)	(0,0,8)	(0,0,4)	(0,0,0.5)
40%	(611;578;627)	(0.3;0.4;0.6)	(109;178;210)	(9,14,15)	(3,4,6)	(0.33,0.29,0.4)
60%	(663,509,550)	(0.4;0.7;0.8)	(87;226;257)	(4,26,28)	(2,7,8)	(0.5,0.27,0.29)
80%	(536,471,431)	(1.0;1.0;1.0)	(188;377;391)	(19,26,32)	(8,10,10)	(0.42,0.38,0.31)
100%	(590;452;415)	(1.2;1.4;1.3)	(278;341;364)	(21,45,47)	(10,15,13)	(0.47,0.33,0.28)

more unicast requests are sent during a period of time), hence the RSU is more likely to handle multiple requests at the same time; therefore, the probability of losing response from RSU is higher.

From the results above, comparing the performance of approach [2] with approach [1], a trade-off can be found between reducing ATD and producing hand-free driving experiences with reliable communication. This trade-off is significantly found by a specific tuning of approach [2], which is to assign 80% CAVs as potential leaders when the CAV penetration rate is lower than 60% and to assign 50% CAVs as potential leaders when the CAV penetration rate is higher. The trade-off is depicted in fig. 5.

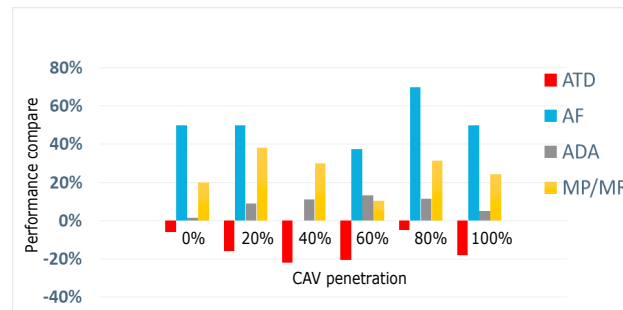


Fig. 5: RSU model of managing platoons
performance comparison = (Approach1/Approach2) - 1

From fig. 5, it can be observed that with a minor increase of ATD (no more than 20%), approach [2] can produce a significantly lower AF, a longer ADA and a significantly more reliable communication, especially when the CAV penetration rate is higher than 60%. When the CAV penetration rate is lower than 40%, it is observed that the trade-off between ATD, AF and ADA is vague, that is because a lower chance of platooning under these circumstances by approach [2]. Additionally, we can observe that improving the communication reliability has no significant impact on improving traffic efficiency, but can significantly improving the undisturbed hand-free driving experiences.

5. Conclusion

In this paper, we propose a management method to coordinate CAVs in mixed traffic scenario with the consideration of communication reliability. Specifically, a strategy that organize CAVs in platoons which are leading by human-driven CAVs and two rudimentary approaches are designed. Evaluated by simulation, the proposed method can eliminate direct interactions between CAVs and non-CAVs, improve traffic efficiency, meanwhile produce undisturbed hand-free driving experiences. In addition, by assigning specific CAVs as potential leaders, the method can significantly improve the CAV driving experiences and communication reliability without sacrificing traffic efficiency, especially when the CAV penetration rate is higher than 60%; thus CAVs may benefit from platooning without a perfect communication infrastructure development.

This research has several limitations. Initially, a simple road network is focused, in which all CAVs arrive in sequence, no lateral behaviour is considered and the communication reliability is hardly influenced by the network context. Moreover, there is no global optimization for both designed approaches. However, as the first step towards a sophisticated platoon advice algorithm, this management method provides an instruction on organizing CAVs under different CAV penetration rates and different communication conditions.

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