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Effects of Coordinated Formation of Vehicle Platooning in a Fleet of Shared Automated Vehicles: An Agent-based model

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Abstract

This paper aims to explore the performance of the autonomous mobility-on-demand system (AMoD) with the coordinated formation of vehicle platooning. In this study, an agent-based model (ABM) is developed to explicitly simulate the operations of platooning formation and interactions between shared automated vehicles (SAVs) and real-time travel requests. The objective is to capture the real-time behavior of SAVs as trip makers, and then assess the performance of the AMoD system with the mechanism of coordinated formation of platoons. We conclude that the impact of vehicle assignment strategies in the AMoD system with vehicle platooning formation predominately affects the average waiting time and system capacity to transport travelers as a whole; however, vehicle platooning, to some extent, could lengthen the travel time of platoon vehicles. The hold-on time (imposed delay) of leading vehicles in order to form a platoon could affect the average time delay of vehicles part of those platoons. The developed ABM provides the first insight into the impact of the pervasive formation of vehicle platooning on the performance of the AMoD system.

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Keywords: vehicle platooning; shared automated vehicles; demand-responsive service; agent-based model

1. Introduction

Automated vehicles (AV) hold great promise to transform the current passenger transport system. AVs could promote the shared use and on-demand transit service to facilitate people's transportation. The AMoD system could move people with fewer vehicles and kilometers driven, thereby reducing the congestion, pollution and energy consumptions (Correia et al. 2016; Fagnant et al. 2014; Greenblatt et al. 2015).

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Although the deployment of the AMoD system to serve transport demand is still in its infancy, studies have investigated the implications of the AMoD system on urban parking demand, energy use, complementarity with other modes, and traffic congestion (Levin et al. 2017; Liu et al. 2018; Zhang et al. 2015); however, there are still some questions as to how to manage and organize the operations of vehicles in the AMoD system as an efficient and sustainable system.

Vehicle platooning designed for Automated Highways System gains more and more attention with the rapid advancement of automated driving technologies. Vehicle platooning is a coordinated movement mechanism in which vehicles travel close to each other without mechanical linkage (Maiti et al. 2017). A set of automated driving technologies and connected vehicle technologies make vehicle platooning feasible, better implemented and operational. Vehicle platooning offers many benefits. First, vehicles in a platoon experience less aerodynamic drag since they follow each other very close. Therefore, the operational mechanism has the potential to save energy consumption of heavy-duty vehicles in platoons (Alam et al. 2015). Second, vehicle platooning may increase road capacity (Lioris et al. 2017).

Truck platooning focusing on road traffic efficiency and fuel economy has been investigated (Bhoopalam et al. 2018; Saeednia et al. 2016); however, this mechanism in the AMoD system has not yet been investigated. AVs with full automation (level-5 (SAE International, 2018)) enable vehicle platooning formation to become pervasive in the AMoD system but little is known about the impact of introducing vehicle platooning into the AMoD system.

In this study, an agent-based modelling (ABM) is developed to simulate the real-time operations of the SAVs in the AMoD system with the pervasively coordinated formation of vehicle platooning. First, the simulation model is to explicitly simulate the real-time operations of vehicle platooning to investigate the impacts of the formation of platoons on the performance of the AMoD system. Second, the interaction between SAVs and travel requests are explicitly modelled to capture the real-time behavior of SAVs. In the share-used mobility system, the total vehicular trips, which could be empty trips for the pickups or occupied trips for the drop-offs, are the outcome of interactions between travel requests and SAVs. Third, a mesoscopic traffic flow model is implemented within the ABM in order to reproduce the traffic dynamics and consider the impact of vehicle platooning on traffic dynamics.

The remainder of the paper is organized as follows. Section 2 presents the model specifications. Section 3 gives a detailed description of the model application. Section 4 provides an analysis of the simulation results. Finally, conclusions are drawn and future work is put forward in section 5.

2. Model Specifications

The proposed ABM includes a dynamic time-dependent demand generation and vehicle assignment, vehicle platooning and a mesoscopic traffic simulator. A central operator is responsible for vehicle assignment, route calculation and the formation of platoons. In particular, the central operator for vehicle assignment has no knowledge about travel requests in advance. Pre-booking of SAVs is not considered. After a traveler request a vehicle, the central operator starts to find a SAV to transport the traveler in a real-time fashion. Note that there is no proactive rebalancing of SAVs in this paper.

2.1. Dynamic time-dependent demand generation and vehicle assignment

In this study, the explicit interaction between travel requests and SAVs is modelled to capture the real-time behavior of SAVs in shared-use scenarios. The central operator will assign vehicles to serve the real-time travel requests according to the designed rules of vehicle-to-request assignment. In fact, the shared-use vehicles can generate a certain number of empty trips that are revealed after all travel requests are served at the end of the simulation. The attributes of empty trips (origin, destination, and occurrence time) are unknown before the vehicle assignment. These uncertainties determine the need to explicitly model the interaction between SAV and travel requests. The interactions can be generalized into the following three steps: First, according to the aggregate travel demand, individual travel requests are dynamically generated in the starting time for each time interval with spatial-temporal characteristics: time for requesting service, origin and destination. Second, vehicle assignment decision by the central operator is based on the vehicle's exact geographical locations, in order to assign the nearest idle vehicles to serve the travel requests. The assignment quality is improved by adding a searching radius for vehicle searching. That means that the central operator will assign the nearest idle vehicle within a searching radius to transport the travelers according to first-come, first-served principle. Third, after the travel requests are dropped off at their destinations, the vehicle will become idle and ready to be assigned to serve the other demand. By the explicit simulation of the interaction, we can understand the behavior of vehicles and travelers and how they behave over time. Not that the travel requests failing in the vehicle assignment will disappear from the system. The state transition from waiting for vehicle assignment to leave the system is triggered by a time event. That is to say, travelers will give up requesting a SAV when the waiting time for the vehicle assignment exceeds a fixed time threshold.

2.2. A mesoscopic traffic flow model

To reproduce the dynamics of traffic flow, a queue-based mesoscopic traffic flow model used in DynaMIT (Ben-akiva et al. 1998), DYNASMART (Mahmassani 2001), and MATsim (Axhausen 2016) is adopted. In this study, the exact movement of the individual vehicle along with the corresponding road segment is simulated. The traffic simulation is divided into two parts: vehicle movement along the road segment and vehicle transfer between adjacent road segments. Therefore, vehicles are either in the state of movement along its corresponding road segment or in the state of being stacked in a vertical queue at the end of a road segment for the transfer from an upstream road segment to a downstream road segment.

The queue-based model involves the outflow capacity, storage capacity, and a macroscopic speed-density relationship constraint. The storage capacity constraint means the maximum number of vehicles accommodated in each road segment thus capturing the queue spillbacks phenomena (Zhou et al. 2014). Outflow capacity can capture delay at the signalized intersection by multiplying saturation flow with an adjustment factor. In addition, the queue-based model satisfies the first-in, first-out principle. That is, only the vehicle in the first place of an upstream road segment can move to the downstream road segments, then the following vehicles can move one by one. Therefore, a vehicle in order to move from an upstream road segment to a downstream road segment needs to meet the following requirements:

- Vehicles need in the first place of the upstream road segment queue. It means that no preceding vehicles are stacking in the waiting queue for the transfer from an upstream road segment to the downstream road segment.
- A check whether the vehicle could leave the traversing road segment is needed by monitoring the outflow capacity.
- The downstream road segment has adequate space to accommodate the incoming vehicle.

Note that there is no special handling of diverging junctions because the traversing road segments are known for a vehicle at the moment when the central intelligent operator assigned vehicles to serve the real-time travel requests. That is to say, vehicles' traversing route comprising road segments are obtained after vehicle assignment. The destination locations of vehicles are the results of vehicle assignments to transport real-time travel requests. In fact, the routes between the origin and destination of vehicles are computed after the vehicle assignment by the Dijkstra algorithm.

The speed of a vehicle on its corresponding road segment is calculated according to a modified Smulder's speed-density relationship (Equation 1). When a vehicle enters a road segment, the speed of this vehicle will be updated according to the speed-density relationship. In addition, the speeds of the vehicles in the corresponding road segment will be updated with a constant time step, according to the observed density.

$$u(k) = \begin{cases} u_0(1 - \frac{k}{k_j}), & k < k_c \\ \gamma(\frac{1}{k} - \frac{1}{k_j}), & k \geq k_c \end{cases} \tag{1}$$

There are four parameters: k_c, k_j, u_0, γ. The parameter γ can be estimated as $\gamma = u_0 k_c$ from the requirements that $u(k)$ is continuous at the point $k = k_c$. The critical density k_c could be formulated as a linear function of jam density k_j: $k_c = \alpha * k_j$, α is a constant (Hoogendoorn et al. 2013).

A simplified method for estimating the outflow capacity is adopted to consider traffic lights (Zhou et al. 2014). The adjustment factor can be estimated at the signalized intersections by the ratio of effective green time to the cycle time. The equation for calculating the outflow capacity for each lane is given below:

$$C = \frac{g}{c} \times Q \tag{2}$$

Where:

- C is the outflow capacity;
- Q is the saturation flow rate;
- g is an effective green time;
- c is the full cycle time.

According to the calculated outflow capacity, the maximum number of outgoing vehicles per cycle time can be estimated. A cyclic event is used to schedule the refreshing actions for the maximum number of outgoing vehicles per cycle time.

2.3. Vehicle platooning

The formation of vehicle platooning is achieved by the hold-on strategy that the vehicle will stop at the designated point (stations) for forming a platoon. A vehicle can join an existing platoon or create a new platoon with newly connected vehicles. After a platoon departs, vehicles are not allowed to join and leave the en-route platoons. The hold-on time is a time difference between a leading vehicle taking the hold-on strategy and vehicles starting to move as platoon vehicles, which is the extra delay resulting from the platooning formation.

The release policies of platoons depend on the threshold vehicle size (maximum platoon vehicle size) reached or hold-on time (maximum imposed delay) of leading vehicles elapsed. Either of two release policies is satisfied, the release event of the platoon can be triggered. We assume that all SAVs in the AMoD system are the platoon-capable vehicles.

In this model, the leading vehicle in a platoon will carry all the information about this platoon. The leading vehicle is responsible for the communication with the corresponding road segment infrastructure that calculates the traffic-related variables, like jam density, critical density, etc. To consider the impact of platoons on traffic dynamics, jam density is formulated as a function of a proportion of vehicles in platoons. The jam density can be estimated by the following equation:

$$k_j = \frac{1}{d_a} \times \frac{n_a}{n_t} + \frac{1}{d_p} \times \frac{n_p}{n_t} \tag{3}$$

Where:

- d_a is the average spacing of vehicles (meters);
- d_p is the average spacing of vehicles in platoons (meters);
- n_a is the maximum number of vehicles operating independently;
- n_p is the number of vehicles in platoons;
- n_t is the maximum number of vehicles that each road segment can accommodate.

Note that n_t is the maximum number of vehicles that each road segment can dynamically accommodate. The n_t is calculated based on the number of vehicles (n_p) in platoons in corresponding road segments plus the maximum number of vehicles (n_a) that the rest of the road segment can accommodate.

The critical density can be formulated as a function of a proportion of vehicles in platoons according to its linear relation with jam density. We assume the minimum distance spacing of vehicles in platoons is a fixed value that is independent of the speed of vehicles. In the case of traffic mixed with platoons and independent vehicles, the change of both the jam density and critical density is used to consider the effect of platoons. In addition, the detailed inter-vehicle interactions are not modelled in this mesoscopic traffic flow model. It means that the microscopic traffic behaviors, such as car-following behavior, lane-changing behavior and so on, are not simulated. Therefore, the potential of vehicle platooning on microscopic traffic dynamics is ignored.

3. Experiment setup

The simulation model is developed from scratch in Anylogic proprietary ABM platform coded with Java programming language. In this study, the red part of the road network in Figure 1 almost covers eight districts of the city of The Hague, Netherlands, and adjacent towns of Voorburg, Rijswijk, and Wateringen. All the data are exported from OmniTRANS that is a multimodal transport planning software package. As depicted in Table 1, the road network comprising 836 links and 510 nodes is used for the simulation. The number of intersections where three or more road segments cross is 263.

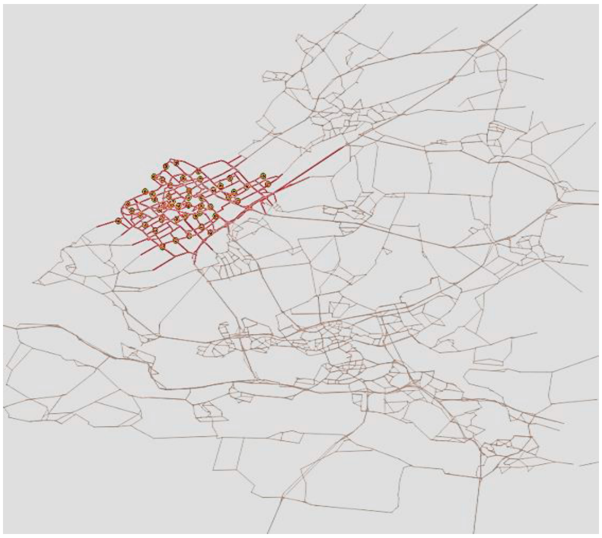

Fig.1 The road network

27,452 requests distributed over 18 periods are used as input to the simulation, each of which corresponds to a 15-minute interval from 5:30 to 10:00. The OD matrix contains 2,401 non-zero pairs over 49 traffic analysis zones. Therefore, the travel requests are generated in every 15-minute time interval and distrusted uniformly over the corresponding time interval. The fleet size for each simulation is predetermined. To be exact, the fleet size is estimated for an average waiting assignment time of 5 minutes. The vehicles are uniformly deployed over the 49 designated stations.

The deployment of SAVs has not yet occurred in a city and therefore there is no empirical data to calibrate the traffic-related parameters. In this study, we assume that the jam density is 125 vehicles per kilometer. That is, the minimum distance headway between two adjacent vehicles is 8 meters, which is acceptable. The inter-vehicle distance maintained in a platoon is 2 meters. As mentioned, the critical density can be calculated according to the linear relation with jam density. The storage capacity can be estimated by multiplying the road length with jam density.

We assume that SAVs operate in dedicated lanes within a designated city area. It means that there is no interaction with human-driven vehicles in the road segments. In addition, we assume that there are no interactions with pedestrians in the intersections. Each road has two lanes for two opposite directions. This study considers single-occupancy vehicles. Other parameters are listed in Table 1.

Table 1. Input parameters

Category	Value	Category	Value
The perimeter of the study area	46 km	Traffic light green time	30 seconds
The study area	139 km^2	Jam density	125 vehicles/km
Road links	836	Adjustment factor α	0.142
Road nodes	510	Time steps of speed update	6 seconds
No. of intersections	263	Maximum vehicle size of platoons	10 vehicles
Travel requests	27452 trips	Hold-on time of leading vehicles	{0,3,6,9} minutes
Stations	49	The searching radius for vehicle assignment	{6000, 6500} meter
Fleet size	93×49 (No. of stations)	Vehicle seat capacity	1 person
Free-flow speed	15 meters per second	The maximum time for waiting assignment	20 minutes
Cycle time of intersections	60 seconds	Minimum distance headway	8 meters
Inter-vehicle distance in platoons	2 meters		

4. Simulation results and discussion

In this study, multiple scenarios are simulated for two general purposes. First, with the fixed searching radius for vehicle assignment and fixed maximum vehicle size in platoons, scenarios that vary hold-on time (imposed maximum delay) of leading vehicles are simulated. Second, simulations with a different searching radius are performed to investigate its influence on the performance of the AMoD system with the formation of platoons. We provide an analysis of system performance in terms of a set of key performance indicators. In particular, the indicator of size-out platoons means the number of platoons released due to reaching the constraint of in-platoon vehicle size. The indicator of vehicles in size-out platoons means the total number of vehicles in size-out platoons.

Table 2. Key indicators with a 6000-meter searching radius for vehicle assignment and maximum 10-vehicle platoon size

Leading vehicle hold-on time (min)	0	3	6	9
Avg. waiting time of served demand (min)	7.13	6.13	6.43	6.31
Avg. travel time (min)	17.83	16.19	16.95	17.39
Avg. delay of leading vehicles	0	2.89	4.73	5.87
Avg. delay of vehicles in platoons (min)	0	1.81	2.78	3.26
Avg. vehicle sizes in platoons	0	5.58	7.40	7.97
Total vehicular trips in platoons	0	5298	5978	6321
No. of platoons	0	949	808	793
Vehicular trips lengths in platoons (km)	0	34538	39291	40382
Total trip lengths (km)	161575	161763	160593	160815
Dropouts (trips)	8010	8301	8504	8513
Size-out platoons	0	173	420	522
Vehicles in size-out platoons	0	1619	3971	5014

Compared to the scenario without the formation of vehicle platooning (hold-on time of leading vehicles equals to zero in Table 2 and 3), the formation of vehicle platooning could slightly reduce the average travel time for all the served travel requests in the A MoD system. One possible explanation is that the system transports fewer travelers with the increase of the hold-on time of leading vehicles. In fact, the indicator of dropouts (unsatisfied trips) experiences a growing trend with the increase of the hold-on time of leading vehicles. Another reason is that the formation of platoons improves traffic in the road network. The average travel time for all the served travel requests slightly increases with the increase in the hold-on delay of leading vehicles in Table 2 and Table 3. In particular, the average delay of the leading vehicles is 80.7 % higher than the average delay of vehicles in platoons. It is obvious that travelers in leading vehicles will have a relatively longer travel time because they have to wait the most.

Simulation results in Table 2 indicate that there is an increase in the number of vehicular trips in platoons with the growth of hold-on time of leading vehicles, taking up from 30.3% to 36.5% of the total number of served travel requests. Therefore, the synchronization of the departure time of leading vehicles could significantly facilitate the formation of vehicle platooning. The same confirming evidence is obtained from the simulation scenarios with the reduced searching radius for vehicle assignment in Table 3. Simulation results both in Table 2 and in Table 3 indicate that the total vehicular trip length in platoons accounts for a relatively large percentage of the total vehicular trip lengths, peaking at 25.1% and 25.4 % respectively. The more vehicular trips in platoons the system has, the more likely the system could save more energy.

Table 3. Key indicators with a 6700-meter searching radius for vehicle assignment and maximum 10-vehicle size in platoons

Leading vehicle hold-on time (min)	0	3	6	9
Avg. waiting time of served demand (min)	11.88	10.22	10.79	10.71
Avg. travel time (min)	21.56	20.31	20.93	21.20
Avg. delay of leading vehicles (min)	0	2.85	4.77	5.81
Avg. delay of vehicles in platoons (min)	0	1.75	2.74	3.26
Avg. vehicle sizes in platoons	0	5.89	7.53	7.95
Total vehicular trips in platoons	0	5938	6668	6942
No. of platoons	0	1008	886	873
Vehicular trips lengths in platoons (km)	0	40641	46233	47582
Total trip lengths (km)	196854	191697	188979	186632
Dropouts (trips)	5353	5886	6109	6287
Size-out platoons	0	221	456	582
Vehicles in size-out platoons	0	2015	4306	5546

Table 2 and Table 3 show that the average waiting time with the increase in the hold-on time of leading vehicles is close to each other. Compared to the results in Table 3, simulation results in Table 2 demonstrate that the relatively smaller searching radius for vehicle assignment significantly reduces the average waiting time at the cost of a large number of dropouts (unsatisfied trips). This means that the vehicle platooning formation has little impact on the average waiting time that is predominately affected by the searching radius in the vehicle-to-traveler assignment.

Simulation results both in Table 2 and in Table 3 indicate that both the number of size-out platoons and vehicles in size-out platoons increase significantly with the increase in hold-on time of leading vehicles. It means that many more formed platoons are released because of reaching the constraints of in-platoon vehicle size when the hold-on time of leading vehicles becomes relatively longer. The impact of platoon-release-related parameters (platoon threshold vehicle size and hold-on time of leading vehicles) could be investigated with the objective of maximizing the number of vehicular trips in platoons while providing acceptable service quality of the system.

5. Conclusion and Future work

The preliminary simulation results indicate that the formation of platoons could increase the time delay of participating vehicles, but they have little impact on the average waiting time for the travelers, which depends on the most on the vehicle assignment radius. The conclusive evidence is that the hold-on time of leading vehicles, to some extent, degrades system performance in terms of reduced system capacity and increased travel time. According to the analysis of simulation results, we conclude that the imposed time delay of leading vehicles could affect the vehicular trips engaging in platoons. Next, we could explore the right combination between hold-on of leading vehicles and maximum in-platoon vehicle size to reduce the average time delay of vehicles in platoons as well as maximize the number of vehicular trips in platoons. Besides the experimental parameter of searching radius for vehicle-to-traveler assignment, how the optimal vehicle assignment strategies can affect the performance of the system with the formation of platoons could be investigated. Finally, vehicle platooning has the potential to reduce energy consumption due to the reduced air drag effect. The pervasive formation of platoons may have a great impact on energy consumption in a whole city area. Therefore, the energy-saving issue could be investigated for vehicle platooning.

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