Resource allocation schemes in multi-vehicle cooperation systems

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Abstract: With the rapid development of smart driving and communications technologies, an increasing number of vehicles are cooperating with each other to improve traffic efficiency and travel safety. This paper conducts a comprehensive survey of multi-vehicle cooperation from the aspects of control and communication. Firstly, three typical multi-vehicle cooperation scenarios are summarized. Communication issues relating to multi-vehicle cooperation are then introduced, including communication types, requirements, and potential solutions. To address the control requirements, a general resource allocation solution for multi-vehicle cooperation is formulated; specifically, two types of resource allocation scheme for intersection management are proposed. Finally, performance of the proposed schemes is evaluated and compared.

Keywords: multi-vehicle cooperation, formation control, convoy driving, intersection management, vehicular communications, resource allocation

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1 Introduction

Multi-vehicle cooperation is a fundamental aspect of smart driving, and is closely related to various other technologies, including environment perception, information communication, and decision planning^[1]. It has considerable potential for application in the areas of intelligent transportation systems, military missions, and exploration of dangerous environments.

The automobile has become an indispensable means of transportation. The rapid increase in number of vehicles, traffic congestion, number of acci-

dents, and the environmental pollution caused by road traffic and fuel consumption, have become important global issues. In the USA, the cost of traffic congestion in time and energy reached 160 billion dollars in 2014, up from 42 billion dollars in 1982. In cities with over one million people, in 2014 auto commuters experienced an average of 63 hours extra travel time, and a road network that was congested for six hours during an average weekday^[2]. According to the 2015 WHO (World Health Organization) report into road safety, more than 1.2 million people die each year on the world's roads, making road traffic a leading cause of death globally^[3]. The im-

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provement of road and transportation system efficiency, with the intention of ensuring vehicle safety, has attracted attention from both government and academia.

In specific cases, such as driving in low visibility conditions or complicated terrain, formations of cooperating vehicles can successfully complete tasks such as exploration, patrol, or rescue. Research into the control of motorcades comprising cooperating vehicles has therefore also gained considerable attention.

Compared with traditional intelligent vehicles, which are dependent on sophisticated sensors, multi-vehicle cooperation systems place emphasis on communications between vehicles and other infrastructure. Reliable communication technologies have led to effective real-time information transmission in multi-vehicle cooperation systems^[4]. With the rapid development of various communications technologies, the current multi-vehicle cooperation system may be superposed by various new technologies. Allocation of the limited resources available and reduction of interference in heterogeneous networks, become crucial topics in multi-vehicle communication research.

This paper therefore focuses on multi-vehicle cooperation and its communication issues. The main contributions in this paper are as follows:

- We summarize three typical multi-vehicle cooperation scenarios: formation control, convoy driving, and intersection management. The important research problems relating to each scenario are discussed.
- The communication requirements for multi-vehicle cooperation system are reviewed. The potential solutions that can be used for multi-vehicle cooperation are also summarized.
- A general communication resource allocation solution is established. Considering both fairness and efficiency, two resource allocation schemes in a cooperative intersection management scenario are then proposed, and their performance evaluated.

The remainder of this paper is organized as follows. Section 2 presents three typical multi-vehicle

cooperation scenarios. Communication issues are listed in section 3, whilst section 4 discusses problems relating to communication resource allocation for multi-vehicle cooperation. Two kinds of resource allocation scheme in an intersection management scenario are proposed in section 5. Finally, section 6 concludes the paper.

2 Multi-vehicle cooperation scenarios

Environments in which multi-vehicle cooperation may occur can be grouped into three categories: wilderness, freeway, and urban. Wilderness scenarios mainly cover military and security patrols, and formation control is typical in this environment. In contrast, freeway and urban traffic systems focus on everyday traffic situations, and have the greatest potential for improvement in travel safety and efficiency^[5]. Convoy driving and intersection management are their typical application scenarios. In this section, we present the three typical scenarios for multi-vehicle cooperation, and introduce the related key research points.

2.1 Formation control

The idea of formation control originated from the cluster behavior of sociable animals such as birds, fish, horses and also bacterial colonies. Compared with the independent actions of an individual animal, this kind of cooperation has certain advantages, including avoiding predators, dealing with natural enemies, increasing the chance of finding food, and also reducing physical energy consumption. The generally recognized definition of multi-vehicle formation control in the academic world is described as follows: During the process of moving to a predetermined target or performing a predetermined task, vehicles in a cluster formation should keep a specific geometric shape, such as triangle, square, or straight line. Each vehicle must also address external environment constraints, such as the existence of obstacles or physical space limitations^[6].

Multi-vehicle formation control has several advantages, including increased instrument resolution, improved efficiency, reduced cost, reconfiguration ability, and overall system robustness^[7]. It also has broad applications, for example, search and rescue in hazardous environments, or area coverage and reconnaissance in military missions. The key problems arising from the study of multi-vehicle formation control are listed below.

2.1.1 Formation selection

Control performance is closely related to the formation selection. Various factors impact the formation selection, such as the number of vehicles and the type of target. Several basic formations for a team of vehicles are shown in Fig. 1, and these are: Line, in which vehicles travel line abreast; column, in which vehicles travel one after the other; diamond, in which vehicles travel in a diamond; and wedge, in which vehicles travel in a “V” formation^[8]. The line formation is appropriate for a linear motion path, the column formation is suitable for a curved motion path, and the diamond and wedge formations maintain a polygon formation among the vehicles, which maintains a relatively stable structure. Additionally, vehicles must change their formation during a task to adapt to complex mobile surroundings.

2.1.2 Formation maintenance

Two steps are required to maintain the formation during movement. First, the target position of each vehicle is determined according to their current surroundings. Next, the control command is generated on the basis of a particular control strategy, and the vehicles are instructed to move to the target position in a certain formation.

So far, the three typical multi-vehicle formation control approaches are the leader-follower approach, the behavior-based approach and the virtual structure approach, and each approach has its strength and weakness. A brief introduction of these three approaches is as follows.

- **Leader-follower approach:** The basic idea of the leader-follower approach is that a particular vehicle

in a group of vehicles will be specified the leader, while the others will be the followers and will follow the leader at a certain distance^[9]. This approach can be expanded based on the above description, meaning that more than one vehicle may be the leader. Therefore, different network topologies can be formed according to the relative position of the leader and the followers. By applying this approach to formation control, cooperation is realized by sharing the mutual leader. The strength of this approach is that the behavior of the whole cluster can be controlled, as long as the behavior or the path of the leader is provided. The weakness of the system lies in the lack of explicit formation feedback, which means that the follower may not be able to follow the leader if it goes too fast, and the formation cannot be maintained if the leader loses efficacy. Corresponding measures can be adopted aimed at the above weakness, such as applying feedback linearization and specifying another vehicle as the leader while the previous one is out of control.

- **Behavior-based approach:** The basic idea of the behavior-based approach is firstly to set a primary behavior for the vehicle, which includes obstacle avoidance, target achievement and formation maintenance under general conditions. When the sensor of the vehicle accepts external stimuli, the correct behavior will be selected according to the information input, and the vehicle will react in the way that best meets the intention. In this approach, the cooperation is realized by sharing the positions and states among the vehicles. The advantage of the behavior-based approach is that it can easily obtain the appropriate control strategy when several competitive targets exist. The system can also give explicit formation feedback, due to the fact that each vehicle reacts according to the other vehicles' positions. Although this approach can realize distributed control, it still cannot clearly define the cluster behavior and conduct mathematical analysis.

- **Virtual structure approach:** The virtual structure approach uses the movement of a rigid body, with varying degrees of freedom for reference. When a rigid body moves with varying degrees of freedom,

Figure 1 Formations for four vehicles. (a) line; (b) column; (c) diamond; (d) wedge

although the position of each spot on the rigid body is changing, their relative position stays the same. To compare the vehicles to the spots on the rigid body, it can be seen that the coordinates of each vehicle and the relative position among the vehicles remains unchanged under the fixed coordinate system; this means that these vehicles can keep a rigid structure with a specific geometric shape. This type of structure is called a virtual structure. Different spots on the rigid body are treated as tracking targets by the vehicles, and therefore a certain formation can be achieved. In the virtual structure approach, the cooperation is realized by sharing the state of the virtual structure. There are several advantages to this approach, including the fact that the behavior of the cluster can be easily set, and the feedback and tracking results can be obtained with high precision; additionally, no complicated communication protocol is involved, because there are no specific differences in function among the vehicles. The disadvantage is that the stability of the system is hard to analyze, because the complete state of the virtual system and the position of each vehicle must be transmitted to every single group member.

2.2 Convoy driving

As a vital component of multi-vehicle cooperation, in recent decades, convoy driving has gained increasing attention in both research and industry. Convoy driving refers to intelligent vehicles driving on the same road and in the same direction; the vehicles are driven at close range to ensure that they can operate using a soft connection. Using cooperation,

the vehicles can maintain a smaller safety distance and a relatively stable speed. Additionally, they are able to make decisions to ensure the safety of the vehicles, including braking as soon as possible in an emergency.

It has been shown that, compared with driving individually, convoy driving can bring many benefits. For example, because vehicles in the same group are much closer to each other, the road capacity can increase and the traffic congestion may decrease accordingly. Convoy driving can reduce energy consumption and exhaust emissions, and can also make passengers safer and more comfortable.

The two typical approaches to grouping vehicles on freeways are platoon-based convoy driving and multi-lane convoy driving (Fig. 2).

Figure 2 Convoy driving patterns in a freeway scenario. (a) platoon-based driving pattern; (b) multi-lane driving pattern

2.2.1 Platoon-based driving pattern

The platoon-based driving pattern has been well studied for many years. In a platoon, vehicles are

grouped in the same lane, and are a small and nearly constant distance away from the preceding vehicle^[10]. A platoon typically consists of a leader vehicle and some follower vehicles. Vehicles must act cooperatively to manage the platoon, including merging, splitting, and braking as required. In this section, we mainly address two different road layout conditions encountered during the merging procedure: parallel lanes, and entrance ramp.

Figure 3 Platoon merging procedures. (a) Parallel lane environment; (b) entrance ramp environment

As shown in Fig. 3, a parallel lane environment will not cause adverse merging effects. However, an entrance ramp environment will cause a merging time constraint, since the merging activity must be completed at the ramp junction and there will usually be a limited length of auxiliary road. Due to the difference in position of the new vehicles, three situations are possible:

- The new vehicle joins at the back of the platoon.
- The new vehicle joins in the middle of the platoon.
- The new vehicle joins at the front of the platoon.

Clearly, when the new vehicle joins the back of the platoon, a low workload is required to coordinate the physical location and organizational structure. Evidently the position cannot always be selected and in practice may be limited by objective conditions; however, the new vehicle can join the back of the platoon as long as conditions permit. Joining the middle of the platoon requires a higher workload to coordinate and control the physical location and organizational structure, but also allows higher selec-

tivity and flexibility of the position. Although there is less need to coordinate the physical position when joining the front of the platoon, the first vehicle is often the core manager of the platoon; if it is replaced by the new vehicle, considerably more coordination work for the organization structure will be required to achieve the motorcade management transfer.

Merging is also usually affected by factors such as the surrounding vehicles, and the driving state of the new vehicle. When joining the platoon for example, the speed of the new vehicle can only be adjusted within a very limited range, since it is influenced by the vehicles ahead and behind.

2.2.2 Multi-lane driving pattern

In contrast to platoons, a multi-lane driving pattern is not constrained to a single lane. Existing literature^[11] shows that in a multi-lane driving pattern, the safety level can increase because vehicles cooperate not only with vehicles in the same lane, but also with vehicles in neighboring lanes.

An ongoing European project named AutoNet2030 is a typical multi-lane convoy use case. It does not create leaders or centralized controllers; instead, the vehicles cooperate in a distributed way, and its structure is loose and dynamic.

2.3 Intersection management

A road intersection connects roads from different directions to ensure that all vehicles in the road traffic network are free to turn. However, an intersection can also lead to frequent collisions due to the conflicts between different traffic flows. With the development of global satellite positioning technology, wireless communication technology, and intelligent vehicle technology, multi-vehicle cooperation has gradually provided possible solutions to this problem. There are three types of control mode for multi-vehicle cooperation at intersections, as shown in Fig. 4.

- Adaptive traffic light control mode: Adaptive traffic lights automatically adjust the signal time according to the information received from intelligent

Figure 4 Three control modes for multi-vehicle cooperation at intersections. (a) Adaptive traffic light control mode; (b) centralized control mode; (c) distributed control mode

vehicles, so that the vehicles are safe and the delay time at intersections is minimized.

- **Centralized control mode:** This mode is mainly applied in intersection areas without traffic lights. Vehicles communicate with the central controller in real-time using centralized control, to ensure the order of traffic.

- **Distributed control mode:** Vehicles can organize the traffic order spontaneously through mutual communication, thus avoiding traffic conflicts and realizing efficient and safe driving at intersections. This type of control mode offers the most flexibility and is the most advanced control mode so far.

3 Communication issues in multi-vehicle cooperation

The main scope of this section is to summarize communication issues in multi-vehicle cooperation, including basic communication types, communication service requirements, and potential solutions.

3.1 Communication types

In principle, there are two basic types of communication in the field of multi-vehicle cooperation, as shown in Fig. 5^[12].

3.1.1 V2I communications

V2I (Vehicle-to-Infrastructure) communications, also called RVC (Road-Vehicle Communications), provide connections between vehicles and fixed roadside

infrastructure. The communication network between the vehicles and the roadside infrastructure is similar to a WLAN (Wireless Local Area Network), where the roadside infrastructure corresponds to the AP (Access Point) in the WLAN. When vehicles travel

Figure 5 Basic types of communication in multi-vehicle cooperation. (a) V2I Communications; (b) V2V Communications

within the communication coverage area of these access points, links will be built automatically. The main V2I communication process is as follows: When a certain vehicle requires communication with an item of infrastructure, it should initially communicate with the roadside infrastructure unit using the

control channel to obtain available channel information. If no available channel exists, then it must wait. Otherwise, the vehicle can complete communication with the roadside infrastructure unit using the assigned channel.

By assigning available channels using roadside infrastructure units, collisions generated by free channel competition can be prevented to a great extent; the network is therefore highly reliable, which is a significant advantage of V2I communication. However, disadvantages also exist. In some remote area, due to the difficulty in establishing roadside infrastructure units and the dilemma of equipment maintenance, V2I communication is difficult to implement. Additionally, communication is generally intermittent due to the restricted communication coverage area of the access points, which will again lead to a failure in multi-vehicle communication.

3.1.2 V2V communications

V2V (Vehicle-to-Vehicle) communications, also called IVC (Inter-Vehicle Communications), refer to direct connections between two vehicles, without a relay station. The main V2V communication process is as follows: The vehicle will first form a temporary network with other surrounding vehicles, and can then directly communicate with any vehicle covered by its wireless network.

By adopting V2V communication, data such as speed, position, and traffic conditions can be integrated among vehicles; this can help to effectively avoid traffic accidents caused by blind spots or other abnormalities.

3.2 Communication requirements

To facilitate various multi-vehicle cooperation based applications, an effective design for vehicular communication is very important^[13]. The requirements are as follows:

- Flexibility: P2P (Point-to-Point) and P2MP (Point-to-Multi-Point) communication should be achieved among intelligent vehicles, and between vehicles and infrastructure. Various communication

technologies should also be applicable, and different technology needs should be applied according to the corresponding communication distance^[14].

- Mobility: Communication can take place among intelligent vehicles and between vehicles and infrastructure, in a relatively static or dynamic environment.

- Security: Certificate authority is required among intelligent vehicles, and between vehicles and infrastructure, to provide access to all kinds of information and also to guarantee communication safety. Sensitive data can be encrypted.

- Reliability: Reliability is of great importance in a multi-vehicle cooperation system, and loss or misunderstanding of information may trigger severe security issues. Highly reliable communication and rapid recovery during network failure, are required.

- High message rate: Under complicated traffic conditions, every information element plays a significant role. If communication efficiency is low, then integration of safety information among intelligent vehicles, and between vehicles and infrastructure, cannot be achieved in the available time. High communication efficiency is therefore required to ensure transmission of safety information.

- Low latency: To avoid traffic accidents, information should quickly be transmitted to vehicles when a latent safety hazard is about to occur. If long delays occur during this process, there will be insufficient time for the vehicles to brake; thus, low latency communication is required.

- Anti-interference: Multi-network superposition exists in a multi-vehicle cooperation system; the terminal device networks may be superposed by various technologies, and surrounded by multiple items of electronic equipment. To avoid interference generated by other networks and devices, an anti-interference system terminal is therefore necessary.

3.3 Potential solutions

In a multi-vehicle cooperation system, information sharing among vehicles is mainly realized using short-distance communication^[15]. In some particu-

Table 1 Summary of communication technologies that may be used in multi-vehicle communication

	technology	coverage	data rate	frequency band	mobility	real-time
short range	bluetooth	1-10 m	720 kbit/s-3 Mbit/s	2.4-2.48 GHz	low	medium
	UWB	a. 1-3 m b. 3-10 m	a. 480 Mbit/s b. 110 Mbit/s	3.1-10.6 GHz	low	medium
	Wi-Fi	10-100 m	802.11a: 54 Mbit/s 802.11b: 11 Mbit/s 802.11g: 54 Mbit/s 802.11n: 600 Mbit/s	2.4 GHz 5 GHz	medium	medium
	ZigBee	10-200 m	256 kbit/s-1 Mbit/s	868 MHz 915 MHz 2.4 GHz	low	medium
	DSRC	300-1 000 m	3-27 Mbit/s	5.8 GHz	high	high
medium & long distance	EDGE	35 km	384 kbit/s	800 MHz/900 MHz/ 1 800 MHz/1 900 MHz	high	medium
	WCDMA	60 km	UL: 5.76 Mbit/s DL: 14.4 Mbit/s	1 920-1 980 MHz/ 2 110-2 170 MHz	high	medium
	LTE	100 km	FDD: 150 Mbit/s TDD: 100 Mbit/s	700-2 600 MHz	high	high

lar conditions however, such as collection and release of current traffic information conducted by the traffic control center, medium and long distance communication is required. Tab. 1 summarizes some types of communication technology that may be adopted in a multi-vehicle cooperation system.

4 Communication resource allocation for multi-vehicle cooperation

The three typical multi-vehicle cooperation scenarios require communicated information to control the vehicles. In this section, a general communication resource allocation solution for multi-vehicle cooperation is established.

In a formation control scenario, vehicles must avoid crashing into external obstacles, and must maintain formation as precisely as possible. Vehicles must also arrive at their destination, or complete a mission on schedule. The vehicles must keep their relative position using V2V communication during the entire process, and must share obstacle information with the motorcade. In the meantime, the formation must gain terrain information utilizing V2I

communication to ensure the validity of the route. To achieve the stated formation control scenario target, precise and punctual control information must be transmitted from the control center to the vehicles, and environmental information must be determined by the vehicles. If there is any interference during information transmission, control will be seriously impacted. The available wireless resources for a formation system are limited, and it is therefore crucial that the formation control process rationally allocates the limited resources; this is necessary to enhance the control effectiveness of the entire system, and to reduce communication interference.

To ensure safety in a convoy driving scenario, the number of available vehicles planning to join the convoy should be as high as possible, and the interval should be small. To efficiently handle emergent situations, vehicles from the same convoy must continue exchanging their condition information using V2V communication. V2V communication is also necessary for the leaders from different convoys to exchange their individual driving states, while V2I communication is applied to rationally assign radio resources, and to reduce interference.

Table 2 Summary of different multi-vehicle cooperation scenarios

scenarios	performance metrics	safety constraints	time constraints
formation control	deviation between actual formation and standard formation	avoid obstacles no collision	reach the target within specified time
convoy driving	connected vehicle number connectivity distance	no collision	driving: brake in time merging: join the convoy within specified time
intersection management	total number of passing vehicles in a period of time average passing time	no collision	pass the intersection area in finite time

In an intersection management scenario, the vehicles must safely pass the intersection and reach the target road in a limited timeframe. A non-signalized control mode generally exists in urban traffic, which means that large traffic volumes of traffic and complicated traffic situations will exist; therefore, V2I communication is required to establish connection with the control center while the vehicles pass through the intersection areas. This can help the control center to process a large amount of vehicle information clearly, and to send information to the vehicles in time to avoid traffic accidents. All types of wireless network exist in urban intelligent traffic systems however, and this may cause problems relating to limited resource availability and strong interference. To solve the above problems, an efficient allocation tactic is vital for non-signalized intersection management; this will both ensure traffic safety, and enhance efficiency at the intersection.

In conclusion, resource allocation in multi-vehicle cooperation communication is a significant issue. It can be modeled as a general solution; namely, to find an appropriate resource allocation scheme, whilst fulfilling the restricted constraints and achieving better performance.

Objective: resource allocation scheme
Optimize: performance metrics
Subject to: safety & time constraints

The performance metrics and constraints are different for different scenarios, as summarized in Tab. 2.

5 Resource allocation in cooperative intersection management

5.1 Scenario description

Consider an intersection formed by two one-way roads, named road A and road B, as shown in Fig. 6. Note that there is no traffic light, only a central controller. The red area represents the intersection, and the green areas represent the queue. Suppose that there are convoys driving on the road, and a separate vehicle is considered as a one vehicle convoy.

Figure 6 Intersection management scenario for platoon driving

The distance between vehicles in the same convoy is very small, whilst the distance between different con-

Figure 7 State diagram of a convoy

voys is relatively big. Thus, less time will be spent per vehicle if more vehicles are part of a convoy when passing the intersection.

Assume that the convoys are organized in platoon pattern, and that the vehicle at the front is the leader. If a convoy's leader is in the intersection area, its state will be defined as PASSING. However, if a convoy's leader is in the queue area, its state will be defined as WAITING. Only if all vehicles in a convoy are neither in the intersection area nor the queue area, will the convoy's state be defined as IDLE. The state diagram of a convoy is shown in Fig. 7.

When a convoy enters the boundaries of the queue area, the leader will send a message to the central controller requesting passage through the intersection area. Assume that only one convoy at a time will send the request, so the uplink access resources are sufficient.

Accidents may happen during the period the convoy passes through the intersection area, such as pedestrians suddenly appearing, or the front vehicle breaking down. To prevent accidents, the central controller must maintain a continuous communication connection with each vehicle in the convoy. Because communication resources are limited in the central controller however, it cannot connect to all vehicles in the waiting queue. Therefore, we must develop a communication allocation scheme to increase the number of vehicles that may pass in a period of time.

Suppose that the central controller owns L communication resource blocks, and there are N types of convoys on the road, which contain $1, 2, \dots, N$ vehicles respectively. When the central controller establishes connections with a convoy, the number of resource blocks used is proportional to the number of vehicles in the convoy.

5.2 Resource allocation schemes

In the scenario described above, two resource allocation schemes are proposed. When the central controller receives the request from a convoy, it will add the requested information to the waiting queue of road A or road B according to the convoy's destination. Fig. 8 shows a general flow chart of a convoy's behavior under these two schemes.

Figure 8 General flow chart of a convoy

In order to clarify the schemes, we define $s_p \in \{0, A, B\}$ as the state of the intersection area, where $s_p = 0$ represents no convoy driving in the intersection area, $s_p = A$ represents that the convoy driving in the intersection area is from road A, and $s_p = B$

represents that the convoy driving in the intersection area is from road B.

(1) Scheme A

Step 1. The central controller arranges all pending convoys in a QUEUE based on the obtained request time sent by each convoy.

Step 2. Check whether the QUEUE is vacant and the central controller possess remaining resources. If the QUEUE is not vacant and resources exist, then proceed to Step 3.

Step 3. If the current level of remaining resources exceeds the amount required by the first convoy in the QUEUE, resources should be allocated to that convoy; otherwise, resource allocation should not be conducted until the connected convoy releases resources.

Step 4. Remove the convoy from the QUEUE after allocating resources to it and return to Step 2.

(2) Scheme B

Step 1. The central controller arranges all pending vehicles in two queues, namely QUEUE_A and QUEUE_B, based on the request time sent by each convoy. Vehicles in QUEUE_A and QUEUE_B are from road A and B, respectively.

Step 2. Check if the queues are vacant and the central controller has remaining resources. If the queues are not simultaneously vacant and resources exist, then proceed to Step 3.

Step 3. Check whether the time required for the intersection area to maintain the same state exceeds the time constraints. (except $s_p = 0$)

i. If the maintenance time of $s_p = A$ exceeds the time constraints, resources should be allocated to vehicles in QUEUE_B, then proceed to Step 5.

ii. If the maintenance time of $s_p = B$ exceeds the time constraints, resources should be allocated to vehicles in QUEUE_A, then proceed to Step 5.

iii. If the maintenance time stays within time constraints, then proceed to Step 4.

Step 4. Check the state of the intersection area and allocate resources to the appropriate convoy, then proceed to Step 5.

i. If $s_p = 0$, after comparing the number of vehicles in the first convoy of QUEUE_A and QUEUE_B,

resources should be allocated to the convoy with more vehicles first. Random selection should be made if the number of vehicles is equal.

ii. If $s_p = A$ and the level of current remaining resources exceeds the required amount for the first convoy in QUEUE_A, resources should be allocated to convoys in QUEUE_A first.

iii. If $s_p = B$ and the current level of remaining resources exceeds the amount required by the first convoy in QUEUE_B, resources should be allocated to convoys in QUEUE_B first.

Step 5. Remove the convoy from QUEUE_A or QUEUE_B after allocating resources to it and return to Step 2.

5.3 Performance evaluation

In this scenario, performance metrics can be defined as follows. a) Average queue length: the average number of vehicles in the WAITING state; b) average waiting time: the average time taken for a convoy to change from the WAITING state to the PASSING state; c) system throughput: the number of passing vehicles per minute.

Taking system throughput as an instance, this paper establishes a simulation to quantitatively evaluate the two proposed resource allocation schemes. The simulation parameters are shown in Tab. 3. The simulation results in Fig. 9 illustrate that with large volumes of traffic, the scheme B system throughput exceeds that of scheme A.

Table 3 Simulation parameters

parameters	values
intersection size	50 m × 50 m
number of resource blocks	5
transition time	3 s (convoy of 1 vehicle) 4 s (convoy of 2 vehicles) 5 s (convoy of 3 vehicles)
traffic volume	8/min-40/min (convoy of 1 vehicle) 4/min-20/min (convoy of 2 vehicles) 2/min-10/min (convoy of 3 vehicles)
simulation time	1200 s

Figure 9 System throughput versus traffic volume

This paper also qualitatively evaluates the performance of the two proposed resource allocation strategies. Consider a convoy c with n vehicles, where $1 \leq n \leq N$. If convoy c attains the WAITING state at moment t_1 , then its waiting time T_w depends on two factors: moment t_2 when the central controller allocates resources to it, and state s_p of the intersection area at the moment the connections are established. If there is no connected convoy in the PASSING state, or if the connected convoy in the PASSING state has the same driving direction as c , the convoy can enter the intersection area directly after the connections are established; the waiting time is therefore $T_w = (t_2 - t_1)$. However, if the convoy in the PASSING state has a different driving direction to c , convoy c must wait until the connected convoy attains the IDLE state at moment t_3 ; the waiting time is therefore $T_w = t_3 - t_1 \leq t_2 - t_1$.

The above analysis can be summarized as follows. For scheme A, resource allocation is based entirely on the arrival sequence of the convoys. This scheme considers fairness a priority for each convoy, but does not attempt to minimize the average system waiting times. Scheme B takes the waiting time of the convoy into account, and optimizes driving efficiency from the perspective of the entire system, as well as considering fairness among convoys from different roads.

6 Conclusion

Multi-vehicle cooperation is driving future trends in modern transportation systems. In this paper, we

have introduced three typical multi-vehicle cooperation scenarios: formation control, convoy driving, and intersection management. Because communication plays a very important role in multi-vehicle cooperation systems, types of multi-vehicle communication were discussed. Requirements for communication systems and potential solutions to existing issues were also examined, and a communication resource allocation solution was generated for the three discussed scenarios. Focusing on the cooperative intersection management scenario, we proposed two schemes to allocate resources efficiently. Both quantitative and qualitative evaluation were used to comprehensively assess performance.

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