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Research Article
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A real-time adaptive signal control method for multi-intersections in mixed connected vehicle environments

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Abstract: With the advancement of connected vehicle (CV) technology, an increasing number of CVs will appear on urban roads. Data collected by CVs can be used to optimize signal parameters at intersections, thus improving traffic efficiency. In this study, we design a real-time adaptive signal control method for an arterial road with multiple intersections with low penetration rates. By utilizing vehicle arrival information collected by CVs, our method rapidly determines optimal signal phasing and timing (SPaT). The proposed adaptive signal control method was tested with the Simulation of Urban Mobility (SUMO) software, and was found to reduce total travel delay in the network better than a fixed coordination control method. The performance of the proposed method in reducing travel delay is expected to improve as CV detection range increases.

Key words: Adaptive traffic signal control; Connected vehicle (CV); Travel delay; Arterial road control

1 Introduction

Signal lights effectively distribute the right-of-way of traffic flow in different directions, thereby reducing traffic conflicts and enhancing safety (Lo, 2006). Control strategies for traffic signals can be divided into three main categories: fixed-time control, actuated control, and adaptive control.

The fixed-time signal control method is suitable for intersections with relatively stable traffic flows, and its operation is heavily reliant on historical traffic volume data (Little et al., 1981). Fixed-time signal control programs are made based on historical traffic data at different times of day, such as the morning or evening rush hours. Thus, they are applied at the same corresponding periods of different days. When there is a significant change in traffic volume, the effectiveness of the fixed-time signal control method can deteriorate. This is often the case in the real world, where traffic volume may fluctuate irregularly with time. The actuated signal control method and the adaptive signal control method can overcome this issue. Actuated signal control dynamically adjusts the signal timing by monitoring traffic flow in real time, using roadside infrastructure-based sensors such as loop detectors, video cameras, infrared sensors, or acoustic sensors. By using the collected traffic volume data, the green light durations, phase splits, etc., can be adjusted. The adaptive signal control method also uses real-time traffic information to adjust the signal control parameters. As such, it strives to find a solution that minimizes a certain objective and optimizes traffic flow. Classical adaptive control methods, such as Sydney coordinated adaptive traffic system (SCATS) (Sims and Dobinson, 1980) and split-cycle-offset optimization technique (SCOOT) (Bing and Carter, 1995), have long been used in real traffic management.

Traditional adaptive signal control depends on real-time traffic data collected by infrastructure-based sensors; however, the traffic data is reliant on the accuracy of the sensors. When detectors are broken, adaptive signal control becomes ineffective, for example, if a group of detectors fails to collect traffic flow information in a certain direction. Moreover, detectors are very expensive to maintain, which is a common shortcoming of traditional adaptive signal control. As computer, sensor, and communication technology have progressed, intelligent transportation systems

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have developed remarkably in recent years (Wu and Waterson, 2022). Additionally, more connected vehicles (CVs) are present today, providing more real-time traffic information such as vehicle speed and location.

The primary purpose of managing road traffic is to enhance the efficiency of vehicle operation and improve the safety of traffic flow. On this foundation, the goal is to reduce vehicle energy consumption and improve driver comfort. With the development of intelligent transportation systems, we are being offered increasingly precise and timely traffic information that was previously inaccessible. Compared with traffic information collected from infrastructure-based sensors, the information collected by CVs can be more accurate and timely. This is because sensors onboard CVs can detect a wider range of vehicles and gather more types of data (Wang JD et al., 2021). Furthermore, the wireless communication equipment on CVs can send data to control centers in real time; infrastructure-based sensors require a detection cycle to output results, such as average speed or vehicle counts, which can result in traffic information that is slightly out of date. In other words, traditional traffic management methods may have limitations in handling the new characteristics of traffic flow. Thus, it is important to make full use of the real-time information collected by CVs or road side units (RSU) to effectively manage traffic flow.

Current adaptive signal control methods focus on optimizing the signal parameters of single intersections (Guo et al., 2019). Little research has extended adaptive signal control methods to multi-intersections. In this study, we design a real-time adaptive signal control method for multi-intersections in a mixed traffic flow environment, which can operate for various CV penetration rates. The proposed method will utilize the real-time traffic information collected by CVs (vehicle speed, location, acceleration, etc.) for all input traffic flow at the intersection. Then, the method will update the signal control parameters with the goal of minimizing the total travel delay of all vehicles. Finally, we use simulation of urban mobility (SUMO) software to test our signal control method and analyze its performance. The main contributions of this paper can be summarized as follows:

(1) We designed a real-time adaptive signal control method that dynamically optimizes the signal parameters of intersections, potentially reducing travel delays on both major and minor roads.

(2) The proposed signal control method only uses data collected by CVs. It does not need other roadside sensors to detect the speed and location of human-driven vehicles.

(3) The proposed signal control method can reduce travel delay even at a lower penetration rate. Moreover, should the detection range of CVs increase in the future, the performance of the proposed method in terms of reducing delays will improve.

2 Literature review

Several studies have focused on optimizing signal control parameters at intersections to improve the efficiency of traffic flow. This includes traditional signal control approaches using infrastructure-based sensors (Zheng et al., 2010; Zheng and Recker, 2013; Yang et al., 2015) and more advanced techniques such as optimization methods (Das et al., 2023) and reinforcement learning methods (Wan and Hwang, 2018; Mo et al., 2022; Huang and Qu, 2023; Fu et al., 2024; Li YS et al., 2024; Yang and Fan, 2024). Although reinforcement learning methods are increasingly being used for optimizing traffic signal control schemes and have demonstrated superiority in optimizing regional signal control plans, there are some drawbacks to these methods, such as inadequate generalization and reliability of the models. These methods also require a large amount of training data, and their applicability may be poor when traffic rules or road conditions differ (Zhang et al., 2024).

Some research has emphasized optimizing signal parameters, such as the signal phasing and timing (SPaT) data message for single intersections in a CV environment. For example, Feng et al. (2015) proposed an algorithm that optimized the phase sequence and duration of a single intersection in a CV environment, solving a two-level optimization problem minimizing the total vehicle delay and queue length. Different studies have focused on different optimization targets, such as maximizing the vehicle throughput at the intersection (Mohammadi et al., 2021) and minimizing the queue length (Li and Peng, 2024). Alternatively, Xu et al. (2019) utilized certain traffic-state information (elapsed time, vehicle stops, or queue length) for each traffic phase to reveal current traffic conditions. Accordingly, they developed a rule-based adaptive signal control method that outperformed an optimal fixed control scheme. Instead of optimizing vehicle trajectories (Li JQ et al., 2024), Yang and Fan (2024) designed a transit signal priority control strategy utilizing CV data that performed better than conventional methods. Optimizing phase sequences and green light durations using CV data has been found to improve operational efficiency of single intersections and reduce vehicle travel delay (Kodi et al., 2024). However, only optimizing the SPaT of single intersections could not improve the operational efficiency of multi-intersection arterial roads.

A few studies have focused on optimizing the signal control schedules of arterial roads in a CV environment. For instance, Wang QZ et al. (2021) proposed an adaptive multi-path progression signal control method for multi-intersections in a CV environment. Their method reduced the travel delay at intersections and improved the green bandwidth of all critical paths along the arterial roads. This approach involved two optimization objectives: one minimizing the total delay at the intersection, and the other maximizing the green bandwidth of all critical paths along the arterial roads. Ma et al. (2024) proposed an arterial road signal timing method that used a probe vehicle with a low penetration rate, allowing adjustments of the offset and green splits at intersections to reduce vehicle travel delays. Similarly, Zhao et al. (2024) used partial CV data to prevent overflow. Liang et al. (2023) optimized the signal parameters of intersections on arterial roads, considering pedestrian delays in addition to vehicle delays. With this background literature in mind, our proposed adaptive signal control method aims to determine the SPaT of arterial intersections in a timelier manner; in this way, the SPaT will be set at a pre-time horizon to effectively reserve the green phase and green time duration for approaching vehicles.

3 Problem statement

Fig. 1 illustrates the adaptive signal control scenario along an arterial with three signalized intersections in a mixed CV and human-driven vehicle (HDV) traffic environment. The arterial runs in the east-west direction, with lanes from the right to the left of the edge being straight-right, straight, and left, respectively. The major road consists of three lanes in the East-West direction, while the minor road contains two lanes in the south-north direction.

There are two types of vehicles in this system, HDVs and CVs, as shown in Fig. 1. In the proposed adaptive signal control strategy, the goal is to minimize the total travel delay of vehicles going through the intersections. Instead of vehicle speed (Ji et al., 2023), in this study, we focus on optimizing the SPaT according to real-time vehicle data to reduce travel delay. The framework of the proposed adaptive signal control strategy is shown in Fig. 2.

It is essential to note that our work focuses on optimizing the SPaT of intersections. To quantify the potential benefits while modeling the system, the following assumptions are made:

(1) All CVs in this system are equipped with on-board sensors, which can record the speeds, positions, accelerations, etc. of themselves. These sensors can also detect the speeds and positions of HDVs within a certain distance.

(2) All CVs are V2X enabled (V2V denotes vehicle to vehicle communication, and V2I denotes vehicles to infrastructure communication), allowing communication with the other CVs and the roadside units. The roadside units can share the signal phase and timing information. Moreover, CVs can share their information, such as speed, position, and acceleration.

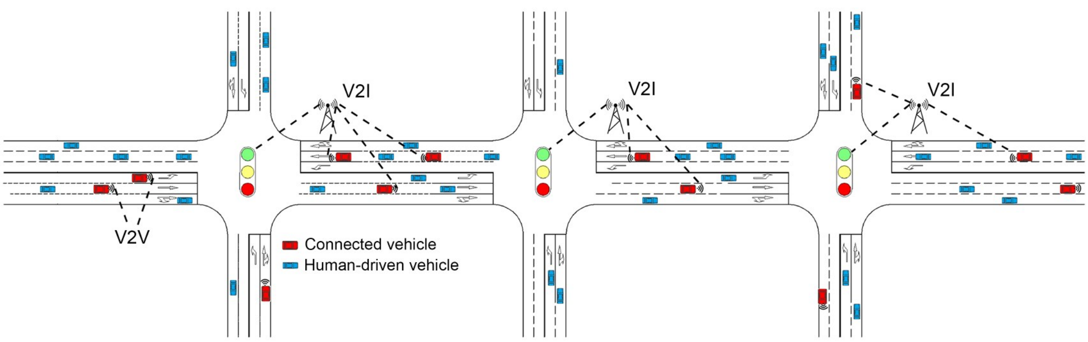

Fig. 1 Illustration of adaptive signal control for an arterial with three signalized intersections. References to color refer to the online version of this figure

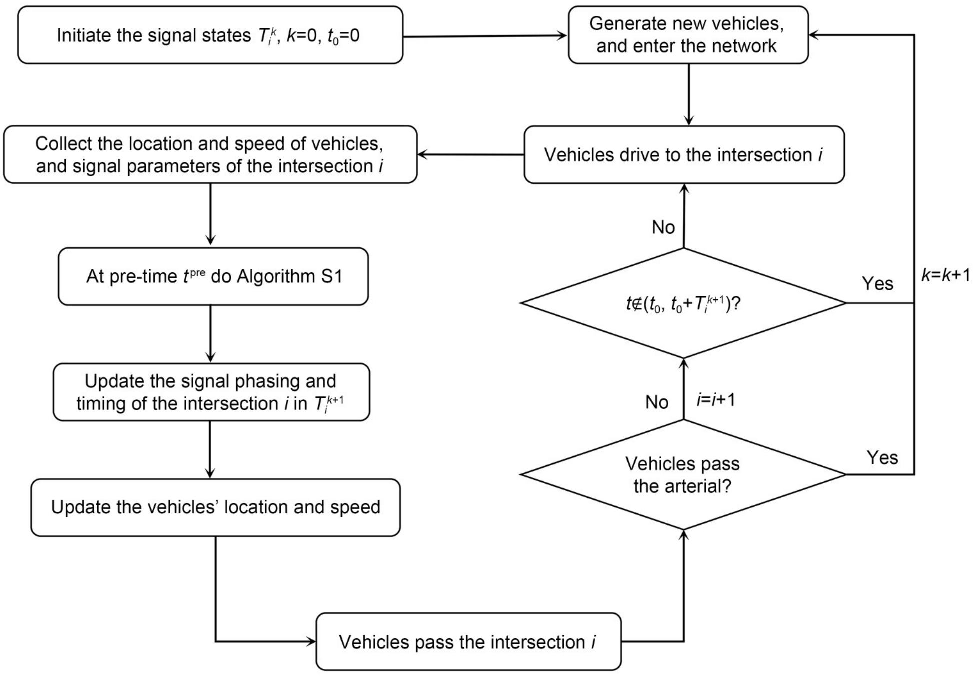

Fig. 2 Framework of the proposed adaptive signal control method

Additionally, there are assumed to be no packet losses or delays during information transmission.

4 Methodology

The framework of the proposed adaptive signal control strategy is shown in Fig. 2. In this section, formulas and models are given to illustrate how the control strategy works in detail. Initially, according to vehicles' arrival information, the adaptive signal control model outputs Signal Phase and Timing (SPaT) to minimize the total travel delay of all vehicles travelling through the intersection.

The proposed cooperative control strategy includes an adaptive signal control model which can determine the SPaT based on vehicle demands to fully utilize green time and minimize delays. This section introduces the design of an adaptive signal control method that decides whether the existence of a certain phase is necessary, or whether the green time should be extended based on vehicle data.

In the adaptive signal control (Fig. 2), T_i^k denotes the kth cycle length of intersection i, and t denotes the time elapsed since the signal light started running. An initial SPaT is set to control the vehicles driving toward the intersection i. Then the CVs and road side devices, such as detectors, will collect the arriving vehicles' speeds and locations. The adaptive signal control module will reserve the SPaT of the (k+1)th cycle at t^{pre}, while t^{pre} is defined as a pre-time horizon before the (k+1)th cycle begins. After deciding the SPaT of the (k+1)th cycle at the pre-time horizon t^{pre}, the trajectory control module plans the trajectories of CVs that will enter the intersection i in the (k+1)th cycle. Algorithm S1 (in the electronic supplementary materials) is the core of the adaptive signal control method, as it determines the SPaT of the intersection i in the (k+1)th cycle. After vehicles travel through the intersection i, they will drive to the next intersection i+1. When the real time t exceeds the cycle time T_i^{k+1}, or equivalently when the kth cycle is set for vehicles traveling across intersection i, the adaptive signal control method will handle vehicles arriving in the upcoming cycle.

The adaptive signal control model is formulated to minimize the total travel delay of vehicles that will travel through the intersection i, and is summarized as follows:

$$\min d_i^k, \tag{1}$$

$$d_i^k = \sum_{j=1}^{M}\sum_{n=1}^{N}(t_{i,j}^n - t_{i,j}^{n,\mathrm{opt}}), \tag{2}$$

$$\phi_{i,j}^k = \begin{cases} 1, & \text{if } \mathrm{num}_{i,j}^k \neq 0, \\ 0, & \text{otherwise}, \end{cases} \tag{3}$$

$$\sum_{j=1}^{M}(\phi_{i,j}^{k}G_{j}) = T_{i}^{k}, \tag{4}$$

$$G_{j,\min} \leqslant G_{j}' + \Delta G_{j} \leqslant G_{j,\max}. \tag{5}$$

The optimization objective is given in Eq. (1), where d_i^k denotes the total travel delay of intersection i in the kth cycle. The travel delay of a single vehicle could be defined as the difference between $t_{i,j}^{n}$ and $t_{i,j}^{n,\mathrm{opt}}$, where $t_{i,j}^{n}$ is the travel time of the nth vehicle away from it to be detected passing the stop line in the lane using phase j of intersection i, while $t_{i,j}^{n,\mathrm{opt}}$ is the ideal corresponding travel time. In Eq. (3), $\phi_{i,j}^{k}$ is the jth phase of intersection i in the kth cycle ($\phi_{i,j}^{k}=1$ indicates that the jth phase will be implemented, while $\phi_{i,j}^{k}=0$ will be ignored). In Eq. (4), G_j represents the implemented green time of the jth phase. In Eq. (5), G_j' is the preset green time of the jth phase; ΔG_j denotes the extended green time of the jth phase; $G_{j,\min}$ and $G_{j,\max}$ are the minimum and maximum green times, respectively.

5 Simulation and analysis

To evaluate the effectiveness of the proposed adaptive signal control method, we conducted simulation experiments using SUMO (Simulation of Urban Mobility) and Python. SUMO is a microscopic continuous traffic simulation software, and the control algorithm is written in Python using the Traffic Control Interface (Traci) to control the objects in SUMO, such as signal light parameters. In this section, we test the proposed control method for different traffic volumes, and verify its advantages compared to solely signal control or trajectory control.

5.1 Simulation parameter settings

The simulation scenario is an arterial containing three intersections, with the parameters of the links, initial signal phasing, and timing of the intersection shown in Fig. 3. The length of every minor road linked with the intersection is 400 m, and 600 m for the major road. As mentioned in Section 2, the major road contains three lanes, and the minor road contains two lanes. There are four signal phases for each intersection, and the preset green time of every phase is 30 s for the E-W direction, 6 s for the El-Wl direction, 15 s for the N-S direction, and 6 s for the Nl-Sl direction. In this study, adaptive signal control is implemented for all traffic flow that is involved in these four phases of the intersections, including the vehicles traveling on the minor road.

Table 1 presents the parameter settings for the simulations. We set the simulation period as 4200 s to assess the effectiveness of the cooperative control

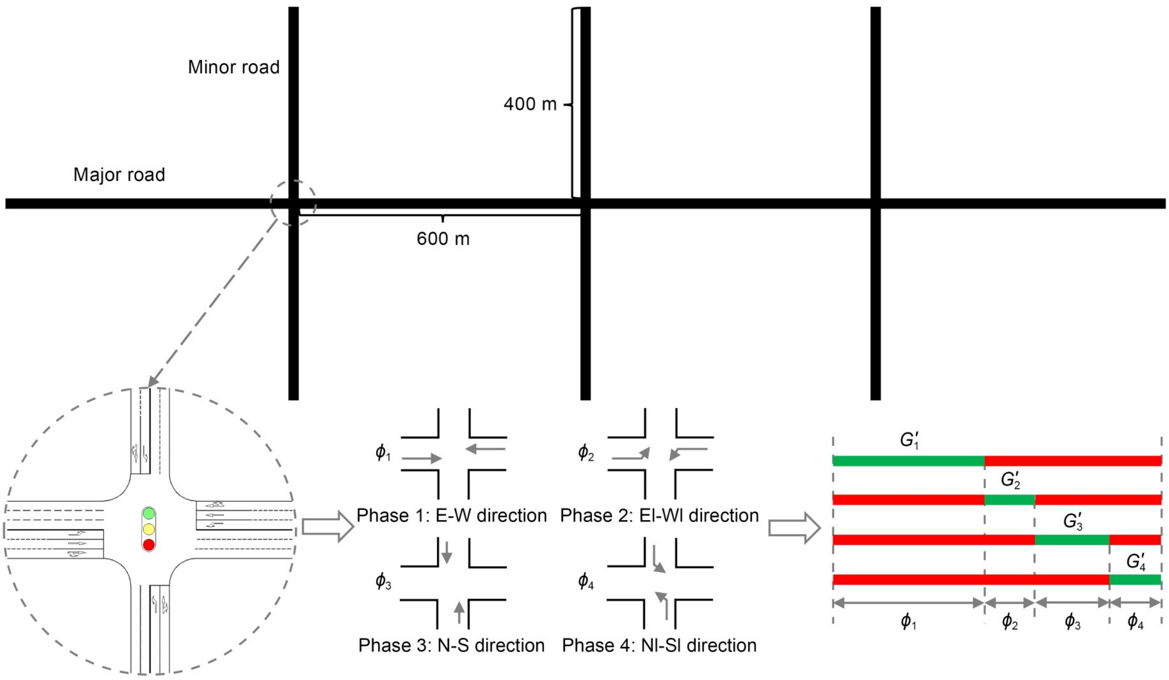

Fig. 3 Arterial scenario and signal settings in the simulation. References to color refer to the online version of this figure

Table 1 Parameter settings for the simulations

Item	Description
Simulation period (s)	4200.0
Simulation step (s)	1.0
Minimum time headway of CV (s)	1.0
Minimum time headway of HDV (s)	1.1
Minimum gap of CV (m)	1.0
Minimum gap of HDV (m)	2.0
Maximum allowed speed (m/s)	15.0
CFM of HDV	Krauss
CFM of CV	IDM
Arrival of vehicle	Poisson distribution
Maximum acceleration (m/s^2)	0.8
Maximum deceleration (m/s^2)	4.5

CFM: car-following model; IDM: intelligent driver model

strategy in servicing certain traffic volumes for approximately one hour. Time headway denotes the time interval between following vehicles, and different time headways are set for CVs and HDVs to differentiate them while driving. Human-driven vehicles enter the network in compliance with a Poisson distribution, while CVs occur in the mixed traffic flow randomly. We do not designate the order in which CVs appear in the traffic flow, to be more realistic. The maximum acceleration and maximum deceleration in the simulations are 0.8 and 4.5 m/s^2, respectively.

5.2 Analysis of results

In this section, we present simulation results of mixed traffic flow at a macroscopic scale. We test our proposed adaptive signal control method at a 500 pcu/(h·lane) level for different penetration rates. The unit "pcu/(h·lane)" represents the traffic flow level per lane per hour. The performance of the proposed method is compared with fixed-time signal control and fixed coordination control methods, as shown in Tables 2–4. The fixed-time signal control method without setting the offset of adjoined intersections served as the baseline. The fixed coordination control method was selected to compare with the proposed adaptive signal control method.

The performance in reducing average travel delay on the major road is shown in Table 2, with the results indicating that both the fixed coordination control method and the proposed adaptive signal control method reduce the travel delay of vehicles on the major road. The fixed coordination control method acts upon vehicles traveling on the major road by setting a fixed offset that creates a green wave; in these simulation experiments, the green wave bandwidth is 16 s. With our proposed adaptive signal control method, the performance in reducing travel delay on major roads will

Table 2 Reduction of average travel delay on the major road for different methods

Method	Average travel delay (s)				
	PR=10%	PR=20%	PR=30%	PR=40%	PR=50%
FT (baseline)	36.25	36.88	36.49	36.26	36.97
FCC	32.23 (−11.09%)	30.43 (−17.49%)	33.71 (−7.62%)	29.46 (−18.75%)	33.67 (−8.93%)
ASC (60 m)	34.45 (−4.97%)	35.68 (−3.25%)	34.10 (−6.55%)	33.64 (−7.23%)	35.92 (−2.84%)
ASC (70 m)	32.70 (−9.79%)	34.48 (−6.51%)	33.75 (−7.51%)	32.84 (−9.43%)	33.15 (−10.33%)
ASC (80 m)	32.70 (−9.79%)	33.46 (−9.27%)	32.71 (−10.36%)	30.55 (−15.75%)	32.67 (−11.63%)

The average delay is measured in seconds; FT is the fixed time signal control method that does not set the offset; FCC denotes the fixed coordination control method; ASC denotes the proposed adaptive signal control method; (60 m), (70 m), and (80 m) denote CV detection ranges of 60, 70, and 80 m, respectively; PR is the penetration rate

Table 3 Reduction of average travel delay on minor roads for different methods

Method	Average travel delay (s)				
	PR=10%	PR=20%	PR=30%	PR=40%	PR=50%
FT (baseline)	35.06	39.26	34.15	36.71	38.39
FCC	33.48 (−4.51%)	48.59 (+23.76%)	35.29 (+3.34%)	39.06 (+6.40%)	40.36 (+5.13%)
ASC (60 m)	27.21 (−22.39%)	29.34 (−25.27%)	26.93 (−21.14%)	29.71 (−19.07%)	27.95 (−27.19%)
ASC (70 m)	25.63 (−26.90%)	28.95 (−26.26%)	27.58 (−19.24%)	26.78 (−27.05%)	27.67 (−27.92%)
ASC (80 m)	25.72 (−26.64%)	30.35 (−22.69%)	27.16 (−20.47%)	27.53 (−25.01%)	28.02 (−27.01%)

The average delay is measured in seconds; FT denotes the fixed time signal control method that does not set the offset; FCC is the fixed coordination control method; ASC denotes the proposed adaptive signal control method; (60 m), (70 m), and (80 m) denote CV detection ranges of 60, 70, and 80 m, respectively; PR is the penetration rate

Table 4 Reduction of total average travel delay on the network (including major and minor roads)

Method	Average travel delay (s)				
	PR=10%	PR=20%	PR=30%	PR=40%	PR=50%
FT (baseline)	35.47	38.45	34.95	35.88	37.91
FCC	33.23 (−6.32%)	42.41 (+10.30%)	34.75 (−0.57%)	35.79 (−0.25%)	38.08 (+0.45%)
ASC (80 m)	28.09 (−20.81%)	31.41 (−18.31%)	29.05 (−16.88%)	28.56 (−20.40%)	29.60 (−21.92%)

The average delay is measured in seconds; FT denotes the fixed time signal control method that does not set the offset; FCC is the fixed coordination control method; ASC denotes the proposed adaptive signal control method; (80 m) means the CVs' detection range is 80 m; PR is the penetration rate

improve as CV detection range increases. For instance, at a 20% penetration rate, when the CVs' detection range was 60 m, the average travel delay was reduced by 3.25%. Moreover, when the CVs' detection range rises to 70 m, the reduction ratio of average travel delay improves to 6.51%. Finally, for an 80 m detection range, the reduction ratio of average travel delay was 9.27%. From Table 2, we can see that the performance of the fixed coordination control method in reducing average travel delay on major roads is better than that of the proposed adaptive signal control method. This is because the fixed coordination control focuses on designing a green wave for vehicles traveling on major roads, without considering the operational efficiency of vehicles traveling on minor roads. Nevertheless, attention should be paid to the operational efficiency of the entire traffic system when managing traffic.

Our proposed adaptive signal control method thus reduced vehicles' travel delays on both major and minor roads, as observed in Tables 3 and 4. Compared with the baseline, the fixed coordination control method tended to increase the vehicles' travel delay on minor roads; for example, at a 20% penetration rate level, the fixed coordination control method increased the vehicles' travel delay by 23.76%. In contrast, our proposed adaptive signal control method reduced the travel delay on the minor road by 22.69%. Moreover, our method could reduce the travel delay on the minor road at various penetration rates under 50%.

From Table 4, we can see that the fixed coordination control method may result in greater average travel delay for the network, as observed in the performance of the fixed coordination control method at a 20% penetration rate. This suggests that the fixed coordination control method may undermine traffic efficiency on the minor road in order to improve traffic efficiency on the major road. In contrast, the proposed adaptive signal control method could significantly reduce the total travel delay for the network, for both the major and minor roads at various penetration rates. For instance, the total average travel delay of the entire network was reduced by 20.81% when the penetration rate was 10%.

We also present spatiotemporal traffic speeds for different CV penetration rates in Fig. 4. These results illustrate the speed and position of the mixed traffic flow during the simulation period. Different colors represent different speed values: when the speed is near zero, the color is more red, and when the speed is higher, the color is more green. In Figs. 4a and 4b, where the spatiotemporal trajectories are shown for a 10% penetration rate, the speeds of the traffic flow through the intersection using our proposed adaptive signal control method were generally higher compared to the fixed coordination control method. The results in Figs. 4c–4f had similar trends, indicating that our method enables mixed traffic flow to travel through intersections at higher speeds.

6 Conclusions

We designed a real-time adaptive signal control method that uses data collected by CVs to dynamically optimize the SPaT at intersections along an arterial road. The proposed method only uses the data collected by CVs; it does not require road-side units to record the speeds and locations of human-driven vehicles. Additionally, the proposed method considers the traffic efficiency of both major and minor roads. Through testing of the proposed adaptive signal control method in SUMO, we demonstrated that our approach outperforms a fixed coordination control method in reducing the total travel delay of the arterial network. This novel strategy may provide insights into formulating signal control plans that enhance traffic efficiency. Future work might include designing adaptive signal control methods for regional traffic networks using CV data.

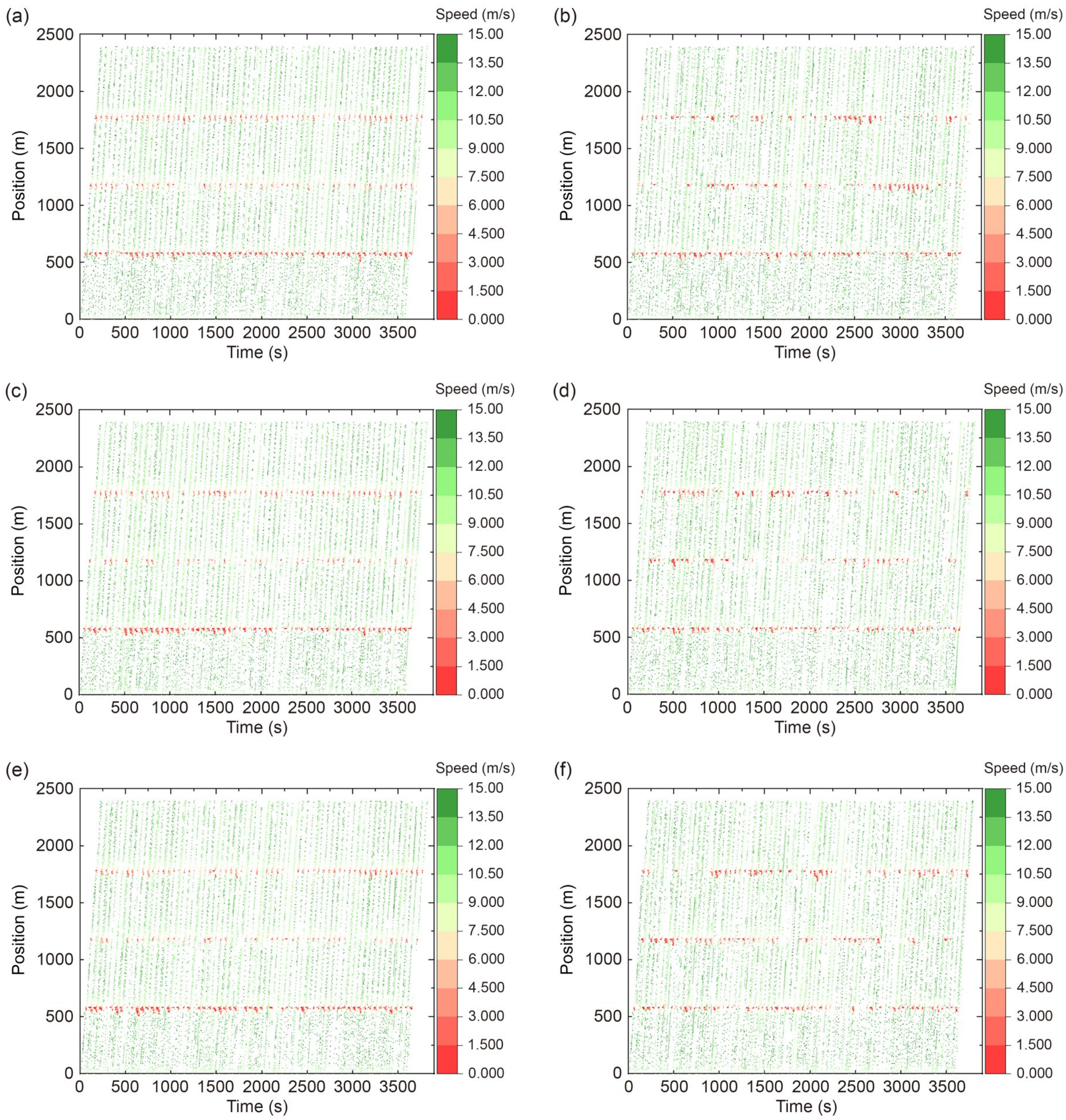

Fig. 4 Spatiotemporal trajectories of the mixed traffic flow at various penetration rates: (a) PR of 10% with the fixed time control method; (b) PR of 10% with the proposed adaptive signal control method; (c) PR of 30% with the fixed time control method; (d) PR of 30% with the proposed adaptive signal control method; (e) PR of 50% with the fixed time control method; (f) PR of 50% with the proposed adaptive signal control method

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Author contributions

Jianqi LI processed the corresponding data, wrote the first draft of the manuscript, and revised and edited the final version. Rongjun CHENG designed the research and helped to organize the manuscript.

Conflict of interest

Jianqi LI and Rongjun CHENG declare that they have no conflict of interest.

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Electronic supplementary materials

Algorithm S1