

Research Article

An Intersection Platoon Speed Control Model Considering Traffic Efficiency and Energy Consumption in CVIS

Wenhao Ren, Junyou Zhang , Li Li, and Qian Zhou

College of Transportation, Shandong University of Science and Technology, Qingdao 266590, China

Correspondence should be addressed to Junyou Zhang; junyouzhang@sdust.edu.cn

Received 27 September 2021; Accepted 23 November 2021; Published 18 December 2021

Academic Editor: Yunfeng Hu

Copyright © 2021 Wenhao Ren et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper proposed an intersection platoon speed control model considering traffic efficiency and energy consumption in the cooperative vehicle-infrastructure systems (CVIS) environment. This model divides the control situation in detail according to the different state of signal lights at the intersection and splits the platoon that cannot pass the intersection completely. The optimization model is established by taking the traffic delay and energy consumption of the platoon as the control objectives, and the model is solved by using a genetic algorithm (GA). Finally, the simulation platform is built by SUMO traffic simulation software, MATLAB, and Python to verify the model. The simulation results show that the total number of queued vehicles, the maximum number of queued vehicles, and the mean travel time of vehicles decreased by 77.81%, 33.33%, and 10.95%, respectively. Besides, the total fuel consumption is reduced by 19.95%, the total emissions of CO₂, CO, HC, NO_x, and PM_x decreased by 19.96%, 58.55%, 51.33%, 23.81%, and 37.51%, respectively. It indicates that the proposed platoon speed control model can effectively improve traffic efficiency while reducing energy consumption and pollutant emissions.

1. Introduction

With the rapid growth of car ownership, the existing urban traffic infrastructure construction level cannot meet the growing demand for traffic travel, and urban traffic problems are increasingly serious [1, 2]. As the key node of urban road traffic, the traffic efficiency of the intersection is getting worse and worse [3]. In the traditional “go-stop” type transport operation mode, the collaboration between the vehicles is less, and the vehicle just passively accept intersection signal control, which leads to the vehicle in the process of the intersection of frequent deceleration or start-stop, thus reducing the efficiency of intersection, increasing energy consumption and pollutant emissions of the vehicle at the same time, and causing traffic congestion, environmental pollution, and a series of problems [4, 5].

Researchers have carried out a large number of studies on improving the efficiency of intersections. In the traditional sense, the improvement of intersection efficiency mostly focuses on the optimization of intersection signal control. Tan et al. [6] studied the continuous-time and discrete-time signal timing models for the classical isolated

signalized intersection with only two one-way vehicle flows and proposed a gradient descent algorithm. Wu et al. [7] established a cellular automata model with greedy algorithm for the traffic control of intersections in autonomous vehicle environment. Jin et al. [8] proposed a multiobjective agent-based framework for road traffic controls to tackle the challenges of increasing traffic congestion and other negative impacts. Rafter et al. [9] proposed a new traffic signal control algorithm, multi-mode adaptive traffic signals (MATS), which combines information from existing fixed-time plans and loop detectors, and position data from connected vehicles to perform decentralized control on signalized intersections. Wu et al. [10] proposed a novel multiagent recurrent deep deterministic policy gradient (MARDDPG) algorithm based on deep deterministic policy gradient (DDPG) algorithm for traffic light control (TLC) in vehicle networks.

At present, with the rapid development of artificial intelligence and wireless communication technology, cooperative vehicle-infrastructure system (CVIS) is increasingly mature [11, 12]. Vehicles are equipped with advanced sensors, controllers, actuators, and other devices and integrated vehicle

positioning technology and modern communication technologies such as 5G to realize the transmission and sharing of traffic information between vehicles, roadside facilities, pedestrians, and the cloud. Under the environment of CVIS, the intersection control centre can obtain the information of surrounding vehicles and signal lights in real time and control the speed of intelligent vehicle through data fusion and data processing technology, so as to better improve the efficiency of the intersection [13–15]. In the research of speed control, Lee and Li [16] proposed an eco-driving advisory system (EDAS) that reduces CO₂ emissions and energy consumption by letting the vehicle continuously pass through multiple intersections with the minimum possibilities of stops. Mintsis et al. [17] used a detailed microscopic simulation model of a city network in Thessaloniki, Greece, as a test bed to evaluate the performance of dynamic eco-driving for different penetration rates of the dynamic eco-driving technology and varying traffic conditions. Yang et al. [18] conducted real-world vehicle driving measurements to directly study the effectiveness of SG-ITS in terms of driving behaviour, time savings, fuel consumption, and pollutant emissions by driving vehicles on the same routes with and without SG-ITS speed guidance. Considering the queuing effect and the driver's actual tracking error, Zhang et al. [19] proposed a vehicle queuing length estimation method based on V2I technology to predict the effective green time and developed a hierarchical GLOSA system. Shen et al. [20], considering the velocity plan and longitudinal dynamics control of the vehicle, proposed a control framework for connected and automated vehicles (CAVs), and the effectiveness of these converters was verified by the cosimulation of CarMaker-Simulink. Lin et al. [21] considered more realistic powertrain dynamics, including the engine and the transmission as well as aerodynamic resistance, rolling resistance, etc., explicitly describing dynamic behaviour and fuel characteristics at acceleration, deceleration, and constant speed. Wu et al. [22] simultaneously optimized signal timing and vehicle speed and dynamically adjusted vehicle arrival time through speed guidance.

Most of the above studies are carried out on the speed control of vehicles traveling alone. Platoon can maintain a smaller distance between vehicles than if the vehicles were traveling alone on the road, thus allowing the road to accommodate more vehicles, increasing the capacity and the throughput of the road [23]. At the same time, platoon can reduce the resistance of each vehicle, so as to reduce the energy consumption of vehicles. The wireless communication between vehicles in the CVIS environment improves the safety of platoon [24–26]. At present, most of the researches on the platoon are focused on the control and stability of a single platoon. Some scholars also consider the actual road intersection environment and study the platoon in terms of improving the traffic efficiency of the intersection. Ma et al. [27] proposed ecological cooperative adaptive cruise control (Eco-CACC) based on V2X communication, combining the advantages of eco-driving and car following to minimize the energy consumption of connected automated vehicle platoon. Feng et al. [28] transformed the problem of intersection capacity maximization into how to minimize the intersection arrival time of vehicles in the green phase, and

designed a composite trajectory planning strategy architecture for platoon trajectory optimization. Faraj et al. [29] proposed an effective and complete platoon-based speed optimization scheme to minimize idle time near signalized intersection. Wang et al. [30] considered longitudinal safety and designed a intersection platoon control algorithm, which takes maximizing the efficiency of the intersection capacity within a given green time as the main priority and minimizing emissions as the second priority. Bisht and Shet [31] prioritized platoons according to their proximity to intersection and designed and evaluated an intersection platoon collaboration algorithm based on V2X communication. However, there are fewer studies on the combination of platoon and intersection speed control, and most of them do not consider the impact of platoons that fail to pass the intersection and need to slow down and stop.

Therefore, in order to improve the operation efficiency of intersections and reduce energy consumption, this paper combines the platoon and speed control under the CVIS environment. First of all, on the basis of defining the intersection speed control area, taking the travel delay of the platoon as the control target, the overall speed control of the platoon is carried out, so that more platoons can pass the intersection during the green light. At the same time, considering the platoon that cannot pass the intersection to carry on the split control, so that as many vehicles in the platoon as possible through the intersection and with the minimum energy consumption as the control target to guide the vehicles that cannot pass through the intersection to slow down and stop. Based on this, an optimization model considering traffic efficiency and energy consumption is established and solved by genetic algorithm (GA) that has better convergence and faster solving speed compared to traditional optimization methods.

The organizational structure of this paper is as follows: Section 2 introduces the intersection scenario and the assumptions of the research content. Section 3 introduces the methodology of the intersection platoon speed control model considering traffic efficiency and energy consumption in CVIS proposed in this paper. Section 4 uses SUMO, MATLAB, and Python to design a comparative simulation experiment. Section 5 discusses and analyses the experimental results. Finally, the conclusion and research perspectives are drawn in Section 6.

2. Problem Statement and Assumptions

This paper studies a typical symmetrical signal intersection with four entrance lanes. As shown in Figure 1, each entrance lane includes three directions: left turning, straight going, and right turning. The four entrance roads and four exit roads of the intersection are represented by E1–E8, respectively. Therefore, without considering the turn back of vehicles, the traffic flow of the intersection is the following 12 direction: $L_{ab} \in \{L_{14a} = (E1 \rightarrow E4), L_{16} = (E1 \rightarrow E6), L_{18} = (E1 \rightarrow E8), L_{36} = (E3 \rightarrow E6), L_{38} = (E3 \rightarrow E8), L_{32} = (E3 \rightarrow E2), L_{58} = (E5 \rightarrow E8), L_{52} = (E5 \rightarrow E2), L_{54} = (E5 \rightarrow E4), L_{72} = (E7 \rightarrow E2), L_{74} = (E7 \rightarrow E4), \text{ and } L_{76} = (E7 \rightarrow E6)\}$.

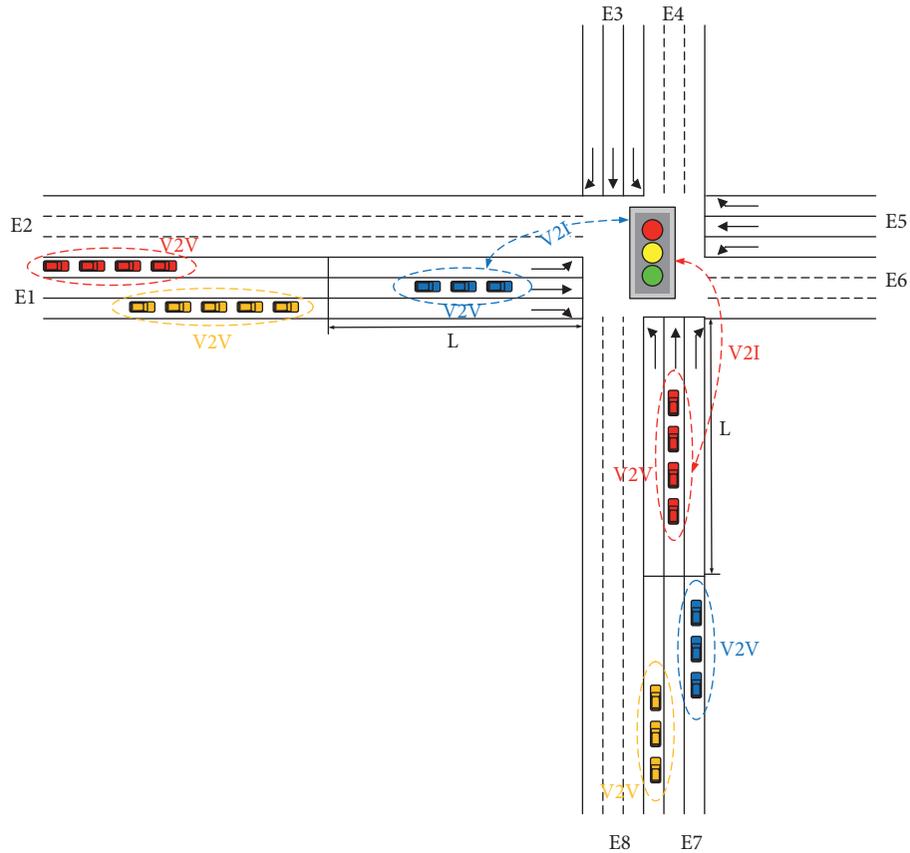


FIGURE 1: The intersection scene studied in this paper.

The intersection adopts a fixed period signal control scheme, with a period duration of C , according to the flow direction of traffic flow, and it is divided into the following four phases (as shown in Table 1): west-east straight travel (WES), west-east left turn (WEL), north-south straight travel (NSS), and north-south left turn (NSL). Since the right turning vehicle has little influence on the traffic flow of the intersection, the research in this paper does not consider the impact of right turning. The control range of the intersection control centre is the road L meters away from the intersection stop line on each entrance road. When the platoon reaches the control range, the platoon realizes the intersection traffic information interaction through vehicle-to-vehicle and vehicle-to-road communication and adjusts the speed.

In order to specify the research object, the research of this paper is also based on the following basic assumptions: (1) the vehicles running on the road are all intelligent connected vehicles that can realize vehicle-to-vehicle and vehicle-to-infrastructure communication. The vehicles arrive at the intersection in the form of a platoon, and the platoon will drive according to the speed calculated by the control center. (2) The intersection control center can obtain all kinds of traffic operation information at the intersection, and the packet loss or delay of communication between vehicles and between vehicles and infrastructures is ignored. (3) The road surface is flat, and the influence of slope on vehicles is ignored. (4) There is

TABLE 1: Intersection signal phase

Phase	Routes	Phase diagram
PHASE1 (WES)	L_{16}, L_{52}	
PHASE2 (WEL)	L_{14}, L_{58}	
PHASE3 (NSS)	L_{38}, L_{74}	
PHASE4 (NSL)	L_{36}, L_{72}	

no position conflict with the side platoons when each platoon passes through an intersection.

3. Materials and Methods

In this paper, the intersection platoon speed control model considering traffic efficiency and energy consumption in CVIS includes three parts: determination method of control area, platoon overall speed control strategy, and platoon split speed control strategy, as shown in Figure 2.

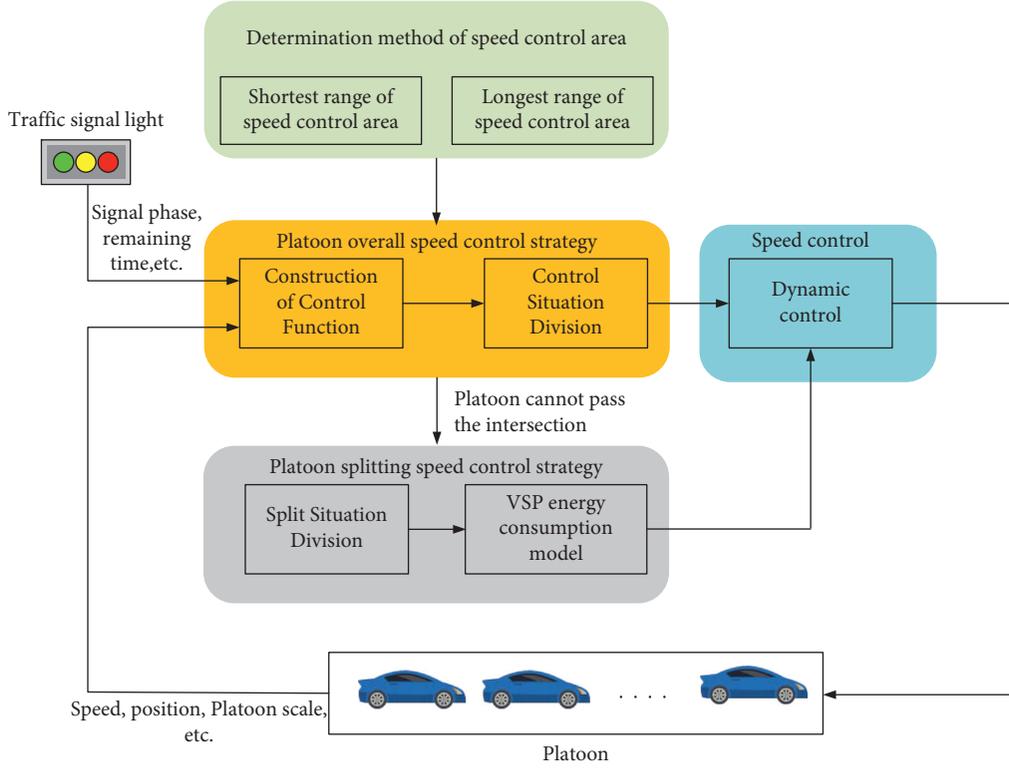


FIGURE 2: Flow chart of the intersection platoon speed control model considering traffic efficiency and energy consumption in CVIS.

- The length of the control area is defined according to the information of the platoon scale, the maximum and minimum speed limit of the vehicles, and the maximum acceleration and deceleration of the vehicles, so as to achieve the optimal control effect.
- This model divides and analyses the state of traffic lights at the intersection in detail and gives the judgment conditions and constraint conditions of each situation. Taking the minimum travel delay as the control goal, the platoon overall speed control strategy is constructed.
- The platoon split control strategy is built, and the basis of the platoon split is given. For the platoon that needs to slow down and stop at the intersection, the control function of the energy consumption of the platoon is built according to the VSP vehicle fuel consumption model, and the control goal is to minimize the energy consumption.

3.1. Determination Method of the Control Area. In this paper, the intersection speed control area is defined. The shortest range of speed control area is to ensure that no matter what speed the platoon enters the control area, it has enough time to adjust its speed. Therefore, the length of the speed control area of the platoon should not be less than the distance for the whole platoon to adjust its speed, namely,

$$L \geq \max \left\{ \frac{v_{\max}^2 - v_{\min}^2}{2a_{\max}}, \frac{v_{\max}^2 - v_{\min}^2}{2d_{\max}} \right\}, \quad (1)$$

where v_{\max} is the maximum speed limit of vehicles on the road; v_{\min} is the minimum speed limit of vehicles on the road; a_{\max} is the absolute value of the maximum acceleration of vehicles on the road; d_{\max} is the absolute value of the maximum deceleration of vehicles on the road.

To ensure that the platoon can pass the intersection as soon as possible and reduce the interference to downstream platoons, the longest control range is that even if the platoon enters the intersection control area at the beginning of the current green light at the minimum speed, the platoon can still completely pass the intersection at the end of the next green light, namely,

$$v_{\min} (C + G) \geq L + L_{p\max}, \quad (2)$$

where G is the green light duration of the signal light; $L_{p\max}$ is the maximum length of the platoon on the road and can be calculated using equations (3) and (4):

$$L_{p\max} = \max(L_{p,i,j}), \quad (3)$$

$$L_{p,i,j} = N_{i,j} \cdot l + (N_{i,j} - 1) \cdot \Delta l, \quad (4)$$

where $L_{p,i,j}$ is the length of the j th platoon arriving at the intersection control area in the i th traffic flow direction; $N_{i,j}$ is the platoon scale of the j th platoon arriving at the intersection control area in the i th traffic flow direction; l is the length of the vehicles in the platoon; Δl is the spacing between vehicles in the platoon.

From the above analysis, it can be seen that the defined range of the length L of the intersection speed control area is as follows:

$$L \subset \left[\max \left\{ \frac{v_{\max}^2 - v_{\min}^2}{2a_{\max}}, \frac{v_{\max}^2 - v_{\min}^2}{2d_{\max}} \right\}, v_{\min} (C + G) - L_{p\max} \right]. \quad (5)$$

3.2. Platoon Overall Speed Control Strategy. In the CVIS environment, through wireless communication between vehicles and between vehicles and infrastructures, when the platoon reaches the speed control area of the intersection, the control centre of the intersection obtains the traffic information such as the position, speed, scale of the platoon, and the current phase of the signal light at the intersection and builds an optimization model to calculate the optimal speed of the platoon through the obtained traffic information, so as to control the overall speed of the platoon.

3.2.1. Construction of Control Function. The purpose of platoon overall speed control is to improve the operational efficiency of transport system, the operational efficiency of the transport system can be expressed by the travel delay of the platoon, and the travel delay of the platoon can be expressed as the difference between the time it takes for the platoon to actually arrive at the intersection and the time it takes for the platoon to arrive at the intersection at free flow speed. In this study, in order to avoid road traffic flow have great speed fluctuation, the platoon reaches the intersection stop line at a uniform speed after the platoon is adjusted to the optimal speed. Then, the actual time of the platoon arriving at the intersection stop line includes the time of speed adjustment and the time of the platoon driving at uniform speed. Then, the calculation equation of the travel delay of the platoon is as follows:

$$d_{i,j}(v_{t,i,j}, a_{i,j}) = \left| \frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} \right| + \left| \frac{L - \left(|v_{t,i,j}^2 - v_{0,i,j}^2| / 2a_{i,j} \right)}{v_{t,i,j}} \right| - \frac{L}{v_f}, \quad (6)$$

where $v_{0,i,j}$ is the initial speed of the j th platoon arriving at the intersection speed control area in the i th traffic flow direction; $v_{t,i,j}$ is the optimized speed of the j th platoon arriving at the intersection speed control area in the i th traffic flow direction; $a_{i,j}$ is the acceleration used to adjust the speed of the j th platoon arriving at the intersection speed control area in the i th traffic flow direction; v_f is the speed of free flow on the road.

Therefore, the control goal of the platoon overall speed control strategy is to minimize the travel delay of the platoon, namely,

$$f_1 = \min(d_{i,j}(v_{t,i,j}, a_{i,j})). \quad (7)$$

3.2.2. Control Situation Division. According to the signal light state when the platoon reaches the control area of the intersection, the control situation is divided in detail. The signal light status when the platoon reaches the control area

is divided into green and red. Based on the remaining signal light duration and other information, the judgment conditions and the restriction conditions that the platoon can pass the intersection without stopping are given on the basis of calculation and analysis of each situation.

(1) Calculation of Relevant Important Parameters. In order to facilitate the description and the construction of the strategy, the important parameters needed in the strategy are firstly calculated:

- (1) The maximum time required of a platoon to reach the stop line at the intersection

The maximum time required of a platoon to reach the stop line at the intersection is the time required by the platoon to slow down to the minimum speed and maintain the minimum speed to reach the stop line at the intersection at a uniform speed. The calculation equation is as follows:

$$t_{\max} = \left| \frac{v_{\min} - v_{0,i,j}}{d_{\max}} \right| + \left| \frac{L - \left(|v_{\min}^2 - v_{0,i,j}^2| / 2d_{\max} \right)}{v_{\min}} \right|. \quad (8)$$

- (2) The minimum time required for all vehicles in a platoon to pass the intersection

The minimum time required for all vehicles in a platoon to pass the intersection is the time required for the platoon to accelerate to the maximum speed at the maximum acceleration and maintain the maximum speed to uniformly pass the intersection. The calculation equation is as follows:

$$t_{\min} = \left| \frac{v_{\max} - v_{0,i,j}}{a_{\max}} \right| + \left| \frac{L + L_{p,i,j} - \left(|v_{\max}^2 - v_{0,i,j}^2| / 2a_{\max} \right)}{v_{\max}} \right|. \quad (9)$$

- (3) The maximum time required for all vehicles in a platoon to pass the intersection

In order to ensure the traffic efficiency of the intersection, in this paper, for the platoon that decelerates through the intersection, after the first vehicle in the platoon reaches the stop line of the intersection, the platoon immediately recovers to the initial speed with the maximum acceleration. Therefore, the maximum time required for all vehicles in a platoon to pass the intersection is the time required for the platoon to slow down to the minimum speed and maintain the minimum speed to reach the stop line at the intersection and then accelerate to the initial speed so that all vehicles in the platoon completely pass the intersection. The calculation equation is as follows:

$$t_{\max 1} = t_{\max} + \left| \frac{L_{p,i,j} - \left(|v_{0,i,j}^2 - v_{\min}^2| / 2a_{\max} \right)}{v_{0,i,j}} \right| + \left| \frac{v_{0,i,j} - v_{\min}}{a_{\max}} \right|. \quad (10)$$

(2) *Platoon Speed Control under Green Light Situation.* Suppose that $T_{0,i,j}$ is the time when the j th platoon arrives at the intersection control area in the i th traffic flow direction, and $T_{g,i,j}$ is the end time of the current green phase when the j th platoon arrives at the intersection control area in the i th traffic flow direction. When the platoon arrives at the intersection control area and the intersection signal light is green, the speed control of the platoon can be divided into the following three situations:

(1) Uniform passage situation

When $T_{g,i,j} - T_{0,i,j} \geq (L + L_{p,i,j})/v_{0,i,j}$, it indicates that if the platoon keeps the current speed after arriving at the intersection control area, the signal light is still green when arriving at the intersection, and the remaining green time is long, which can make all the vehicles in the platoon pass the intersection. At this time, in order to avoid the large speed fluctuation of the platoon, the platoon should adopt uniform speed control strategy to make the vehicles in the platoon keep the current speed.

(2) Accelerated passage situation

When $t_{\min} \leq T_{g,i,j} - T_{0,i,j} < (L + L_{p,i,j})/v_{0,i,j}$, it indicates that if the platoon keeps the current speed after arriving at the intersection control area, there will be two situations: one is that the signal light will turn red when the platoon reaches the stop line at the intersection, so that none of the vehicles in the platoon can pass the intersection; the other is that the signal light is still green when the platoon reaches the stop line at the intersection, but the remaining green time is short, so only some vehicles in the platoon can pass the intersection. But in both cases, if the platoon accelerates with maximum acceleration and reaches the maximum speed limit on the road, it can pass the intersection in the remaining green time. Therefore, in order to avoid unnecessary start-stop and parking waiting of vehicles in the platoon, the platoon should pass the intersection at the current green phase as much as possible, so the acceleration control strategy should be adopted for the platoon, as shown in Figure 3, the constraint is shown in the following equation:

$$\frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} + \frac{L + L_{p,i,j} - ((v_{t,i,j}^2 - v_{0,i,j}^2)/2a_{i,j})}{v_{t,i,j}} \leq T_{g,i,j} - T_{0,i,j}. \quad (11)$$

(3) Cannot passage situation

When $0 < T_{g,i,j} - T_{0,i,j} < t_{\min}$, it indicates that if the platoon keeps the current speed after reaching the control area of the intersection, the signal light will turn red when it reaches the stop line of the intersection, or it will still be green but the remaining time is very short, which can only make part of the vehicles in the platoon pass the intersection or make all the vehicles in the platoon unable to pass the intersection. In addition, even if the platoon speeds up to the maximum speed with maximum acceleration,

it cannot completely pass the intersection in the current green phase. At this time, it is necessary to turn to the platoon split stage.

(3) *Platoon Speed Control under Red Light Situation.* Suppose that $T_{r,i,j}$ is the end time of the current red light phase when the j th platoon in the i th traffic flow direction arrives at the intersection control area; $T_{g,i,j,1}$ is the end time of the green phase when the j th platoon in the i th traffic flow direction arrives at the intersection control area under red light situation; t_q is the queuing dissipation time at the current intersection, $t_q = H/v_q + t_l$, where H is the queue length at the current intersection, v_q is the dissipation speed of the queue at the current intersection, and t_l is the start-up loss time of the vehicle. Then, when the platoon reaches the intersection control area and the intersection signal light is red, the speed control of the platoon can be divided into the following four situations:

(1) Cannot passage situation

When $T_{r,i,j} - T_{0,i,j} + t_q > t_{\max}$, it indicates that if the platoon keeps the current speed after reaching the control area of the intersection, there will be two situations when it reaches the intersection: one is that the signal light will still be red, the other is that the signal light will turn green but there are long queue lengths at the intersection. And, even if the platoon slows down to the minimum speed limit with maximum deceleration, the platoon still unable to pass the intersection. At this point, it is necessary to turn into the platoon split stage.

(2) Decelerated passage situation

When $L/v_{0,i,j} < T_{r,i,j} - T_{0,i,j} + t_q \leq t_{\max}$ and $T_{g,i,j,1} - T_{0,i,j} \geq t_{\max,1}$, it indicates that if the platoon keeps the current speed after reaching the control area of the intersection, there will be two situations when it reaches the intersection: one is that the signal light will still be red, the other is that the signal light will turn green and there are queuing vehicles at the intersection. But if the vehicles in the platoon slow down to the minimum speed limit with maximum deceleration, they can pass the intersection within the next green time. Therefore, the deceleration control strategy should be adopted for the platoon, as shown in Figure 4, and the constraints are shown in equations (12) and (13):

$$\frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} + \frac{L - ((v_{t,i,j}^2 - v_{0,i,j}^2)/2a_{i,j})}{v_{t,i,j}} \geq T_{r,i,j} - T_{0,i,j} + t_q, \quad (12)$$

$$\begin{aligned} & \frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} + \frac{L - ((v_{t,i,j}^2 - v_{0,i,j}^2)/2a_{i,j})}{v_{t,i,j}} \\ & + \frac{v_{0,i,j} - v_{t,i,j}}{a_{\max}} + \frac{L_{p,i,j} - ((v_{0,i,j}^2 - v_{t,i,j}^2)/2a_{\max})}{v_{0,i,j}} \\ & \leq T_{g,i,j,1} \end{aligned} \quad (13)$$

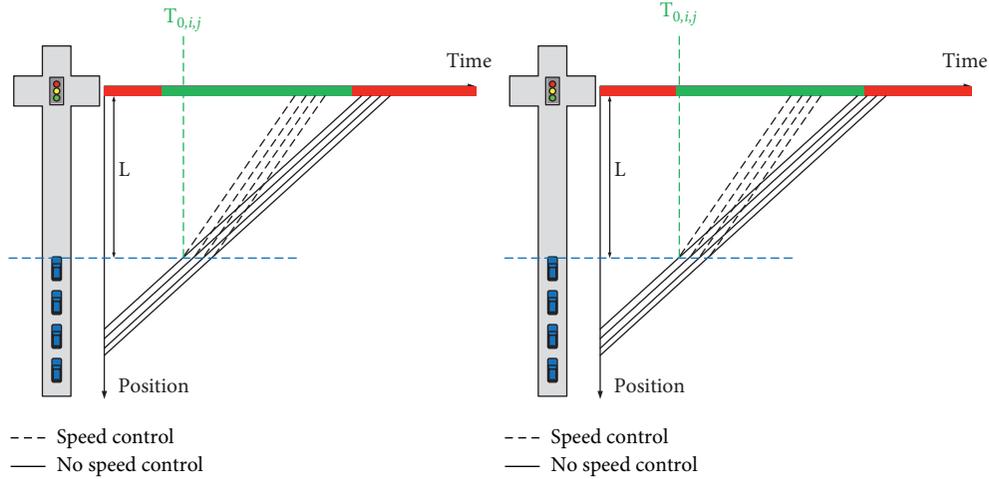


FIGURE 3: Schematic diagram of accelerated passage situation under green light.

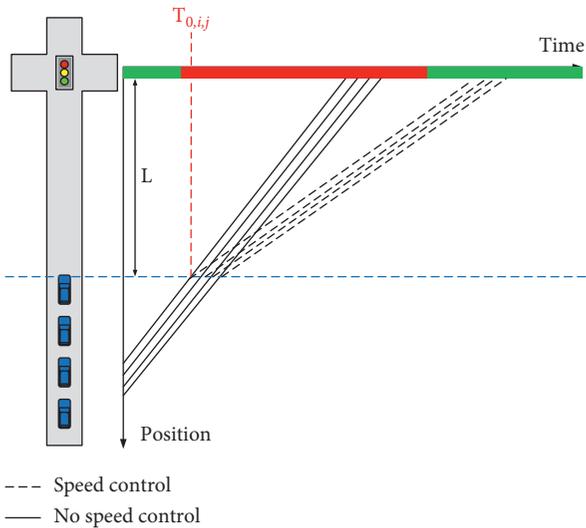


FIGURE 4: Schematic diagram of decelerated passage situation under red light.

(3) Uniform passage situation

When $0 < T_{r,i,j} - T_{0,i,j} + t_q \leq L/v_{0,i,j}$ and $T_{g,i,j,1} - T_{0,i,j} \geq (L + L_{p,i,j})/v_{0,i,j}$, it indicates that if the platoon keeps the current speed after reaching the control area of the intersection, the signal light will turn green and queues at the intersection have dissipated when arriving at the intersection, and the remaining green time is long, which can make all the vehicles in the platoon pass the intersection. At this time, the platoon should adopt uniform speed control strategy to make the vehicles in the platoon keep the current speed.

(4) Accelerated passage situation

When $0 < T_{r,i,j} - T_{0,i,j} + t_q \leq L/v_{0,i,j}$ and $t_{\min} < T_{g,i,j,1} - T_{0,i,j} \leq (L + L_{p,i,j})/v_{0,i,j}$, it indicates that if the platoon keeps the current speed after reaching the control area of the intersection, the signal light will be green, but the rest of the green time can only make the platoon some of the vehicles reach the

intersection. If the platoon speeds up to the maximum speed with maximum acceleration, it can completely pass the intersection in the green phase. Therefore, acceleration control strategy should be adopted for the platoon, as shown in Figure 5, and the constraints are shown in equations (14) and (15):

$$\frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} + \frac{L - ((v_{t,i,j}^2 - v_{0,i,j}^2)/2a_{i,j})}{v_{t,i,j}} \quad (14)$$

$$\geq T_{r,i,j} - T_{0,i,j} + t_q,$$

$$\frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} + \frac{L + L_{p,i,j} - ((v_{t,i,j}^2 - v_{0,i,j}^2)/2a_{i,j})}{v_{t,i,j}} \quad (15)$$

$$\leq T_{g,i,j,1} - T_{0,i,j}.$$

To sum up, the flow chart of control situation division is shown in Figure 6:

3.2.3. Constraints

(1) Speed constraint:

$$\begin{aligned} v_{\min} &\leq v_{t,i,j}, \\ v_{0,i,j} &\leq v_{\max}. \end{aligned} \quad (16)$$

(2) Acceleration constraint:

$$-d_{\max} \leq a_{i,j} \leq a_{\max}. \quad (17)$$

(3) The passing time constraint of the front and rear platoon:

In order to ensure traffic safety and avoid collisions between the platoons when crossing the intersection, the time when the first vehicle of the rear platoon reaches the stop line at the intersection should be greater than or equal to the time when the last vehicle

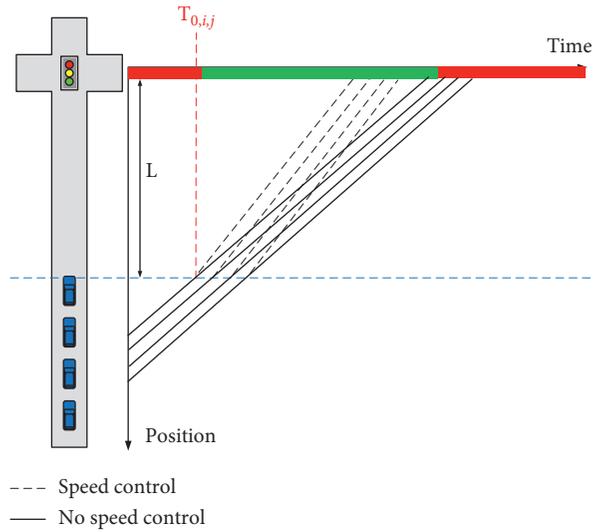


FIGURE 5: Schematic diagram of accelerated passage situation under red light.

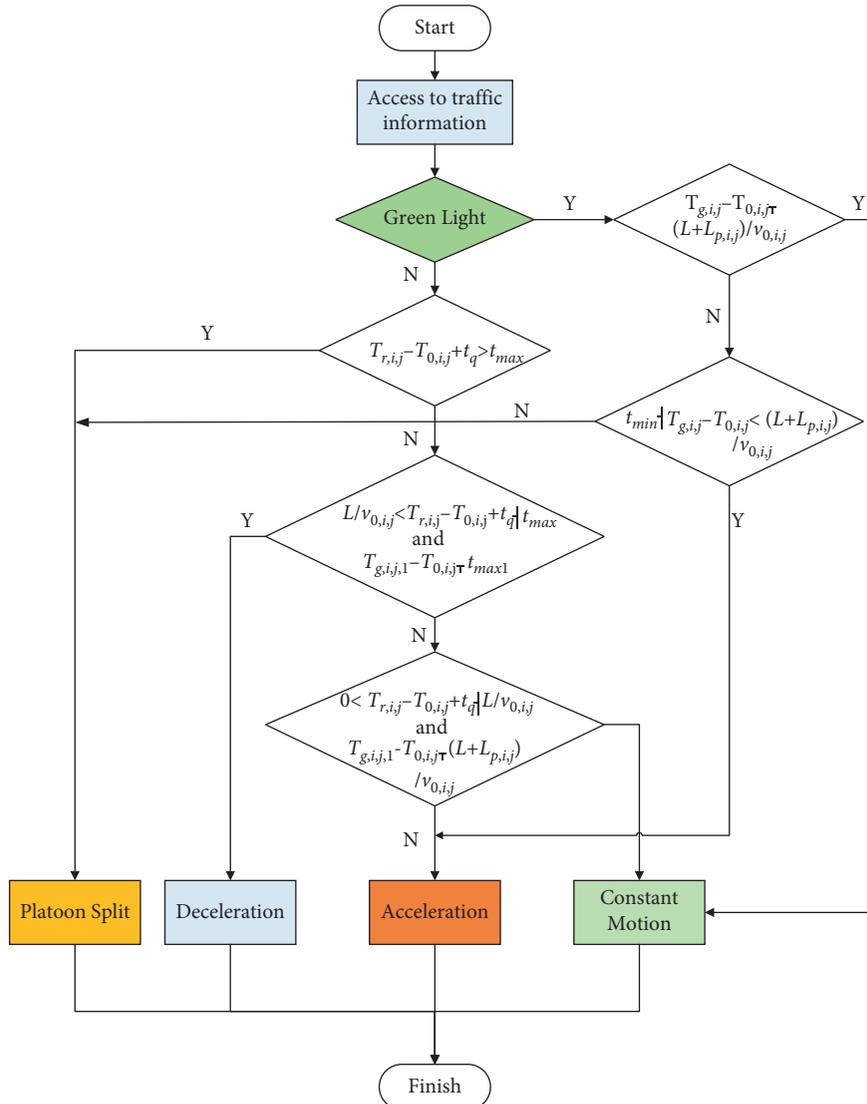


FIGURE 6: Flow chart of control situation division.

of the front platoon completely passes the stop line at the intersection, namely,

$$T_{N_{i,j-1},i,j-1} \leq T_{1,i,j} = T_{0,i,j} + \frac{v_{t,i,j} - v_{0,i,j}}{a_{i,j}} + \frac{L - ((v_{t,i,j}^2 - v_{0,i,j}^2)/2a_{i,j})}{v_{t,i,j}}, \quad (18)$$

where $T_{N_{i,j-1},i,j-1}$ is the time when the last vehicle of the $j-1$ th platoon in the i th traffic flow direction reaches the intersection stop line and $T_{1,i,j}$ is the time when the first vehicle of the j th platoon in the i th traffic flow direction reaches the intersection stop line.

3.3. Platoon Split Speed Control Strategy. In order to maximize the throughput of the intersection, improve the

operation efficiency of the traffic, and make more vehicles can pass the intersection without stopping during the green time, for the platoon that cannot pass the intersection through the platoon overall speed control strategy, the platoon split speed control strategy is transferred to, as shown in Figure 7. In this paper, the platoon split speed control strategy considers the following two situations:

- (a) For the platoon that still cannot pass the intersection through the acceleration control strategy, the platoon split speed control is carried out. First, the number of vehicles that can pass the intersection is calculated if the platoon accelerates to the maximum speed limit of the road with the maximum acceleration, and then the platoon is divided into P_1 and P_2 . Therefore, the number of vehicles in platoon P_1 and P_2 is calculated as shown in equations (20) and (21):

$$N_1 = \left\lfloor \frac{((v_{\max}^2 - v_{0,i,j}^2)/2a_{\max}) + v_{\max} \cdot (G_r - ((v_{\max} - v_{0,i,j})/a_{\max})) - L}{l + \Delta l} \right\rfloor, \quad (19)$$

$$N_2 = N_{i,j} - N_1, \quad (20)$$

where N_1 are the number of vehicles in the split platoon P_1 ; N_2 are the number of vehicles in the split platoon P_2 ; and G_r is the remaining green duration.

For P_1 , since the platoon accelerates to its maximum speed at maximum acceleration, it can pass the intersection at the current green time, it still accelerates through the intersection according to the platoon overall speed control strategy in Section 3.2, taking the minimum travel delay as the control objective function, and the constraints are the same as those in Section 3.2. For platoon P_2 , as the platoon is no longer able to pass the intersection, the platoon is controlled to slow down and stop with the control objective of minimum fuel consumption.

- (b) For the platoon that still cannot pass the intersection through the deceleration control strategy, the platoon has slowed down to the minimum speed limit and still cannot pass the intersection, so the platoon should be controlled to slow down and stop at the minimum fuel consumption.

In this study, for the control of the platoon with the minimum fuel consumption and stop, by VSP fuel consumption model to build the platoon's energy consumption model. VSP fuel consumption model is a fuel consumption model based on the specific power of the vehicle, which takes into account rolling resistance and aerodynamic drag as well as changes in the kinetic and potential energy of the vehicle [32]. The basic driving behaviour during the deceleration and stop process of the platoon is regarded as the process of driving at a uniform speed for a period of time and then slowing down and stopping, so the fuel consumption of the process can be calculated by the following equation:

$$e_{i,j}(t_1, t_2, a_{i,j}) = t_1 \cdot \text{VSP} + \int_0^{t_2} \text{VSP} dt, \quad (21)$$

where t_1 is the time of the platoon moving at uniform speed; t_2 is the time of uniform deceleration movement of the platoon; VSP can be calculated using the following equation:

$$\text{VSP} = v \cdot \left(a \cdot (1 + \varepsilon_i) + g \cdot \text{grade} + g \cdot C_R + \frac{1}{2} \rho_a \frac{C_D \cdot A}{m} (v + v_w)^2 \cdot v \right) + \int_0^{t_2} \text{VSP} dt, \quad (22)$$

where ε_i is the "mass factor," which is the equivalent translational mass of the rotating components (wheels, gears, shafts, etc.) of the powertrain, the

suffix i indicates that is gear-dependent.; grade is the vertical rise/slope length; g is the acceleration of gravity; C_R is the coefficient of rolling resistance

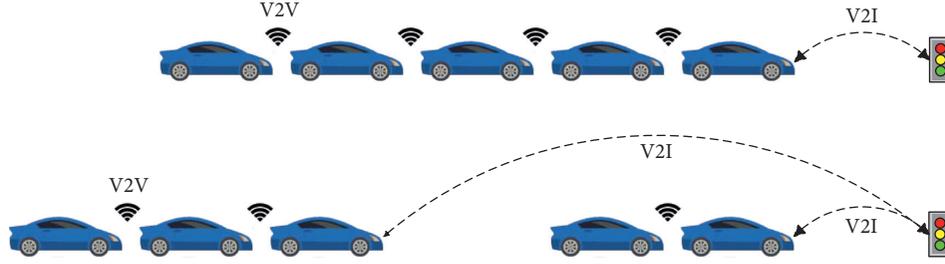


FIGURE 7: Schematic diagram of platoon split speed control strategy.

(dimensionless); C_D is the drag coefficient (dimensionless); A is the frontal area of the vehicle; ρ_a is ambient air density (1.207 kg/m^3 at $20^\circ\text{C} = 68^\circ\text{F}$); v_w is the headwind into the vehicle, m is the mass of the vehicle.

Since the vehicles studied in this paper are all light vehicles, the calculation equation of VSP can be simplified as follows [33]:

$$\text{VSP} = \frac{Av + Bv^2 + Cv^3 + mv_a}{m}, \quad (23)$$

where $A = 0.156461$, $B = 0.002002$, $C = 0.000493$, and $m = 1.4788$.

Therefore, the control function of platoon energy consumption built based on VSP model in this paper is shown as follows:

$$f_2 = \min(e_{i,j}(t_1, t_2, a_{i,j})). \quad (24)$$

The constraint conditions are

$$t_1 + t_2 \leq T_{r,i,j} - T_{0,i,j}, \quad (25)$$

$$v_{0,i,j}t_1 + \frac{v_0^2}{2a_{i,j}} = L_q - H, \quad (26)$$

$$-d_{\max} \leq a_{i,j} < 0. \quad (27)$$

In equation (26), L_q is the distance between the lead vehicle of the platoon that needs to slow down and the stop line of the intersection when the platoon reaches the control area of the intersection.

4. Simulation Experiment

In this study, the proposed control model is verified by using SUMO, MATLAB, and Python, and the overall flow of the simulation is shown in Figure 8. SUMO is used to build a typical intersection simulation environment, and the number of lanes, signal light cycle, signal light phase, traffic flow, and so on are set. The total cycle time of the signal light is 88 s, in which the west-east straight travel phase is 29 s, the west-east left turn phase is 15 s, the north-south straight travel phase is 25 s, and the north-south left turn phase is 19 s, as shown in Figure 9. The input traffic flow of each lane at the intersection and other simulation parameters are

shown in Table 2, and the input vehicles are randomly formed into the platoon. At the same time, the minGap parameter between vehicles is set to 1.5 m to ensure the traffic safety during the operation of the platoon. The car-following model during the operation of the platoon adopts the improved Krauss model [34]. The Traci interface of SUMO software is used to realize the interaction with Python. When the platoon reaches the control area of the intersection; various traffic information of the platoon and the signal light is obtained. In MATLAB, the optimization solution model is established through the genetic algorithm (GA), and the optimal solution is obtained through selection, crossover, mutation, and other operations based on the theory of biological evolution. The traffic information such as the speed and remaining time of signal light when the platoon enters the control area of the intersection is taken as input variables, and the optimal speed and acceleration values of the platoon were obtained, which were input into the SUMO software.

Since the model in this paper does not involve the change of signal light phase order, the speed control and result analysis are only carried out for the platoon running in the straight lane at the west entrance. In order to make a comparative analysis with the proposed intersection platoon speed control model, a comparative experiment was carried out in the case of no intersection platoon speed control. In the same intersection simulation environment, the two experiments were simulated with 3,600 steps in SUMO, and the platoon trajectory, the traffic efficiency information (number of queued vehicles at intersection, mean travel time), energy consumption, and emissions information (fuel, CO_2 , CO, HC, NO_x , and PM_x) of the platoon were obtained.

5. Results and Discussion

This paper discusses and analyses the experimental results from the following three aspects:

5.1. Platoon Trajectory Analysis. Figures 10–15 shows the comparison of platoon trajectory. It can be seen from the platoon trajectory of the platoon under various working conditions that, through the speed control model of the platoon in this paper, the platoon can make as many vehicles in the platoon pass through the intersection without stopping by accelerating, decelerating, and splitting, thus reducing the start-stop and idle speed of vehicles and thus

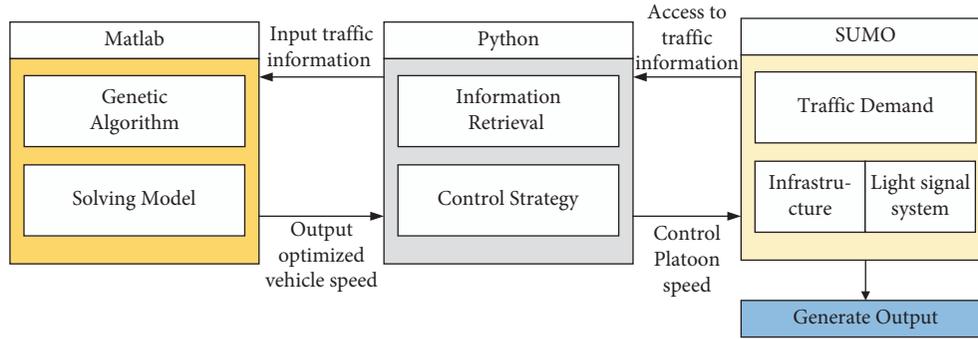


FIGURE 8: Overall flow chart of simulation experiment.

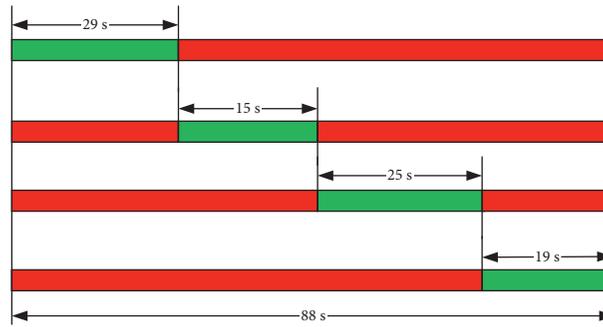


FIGURE 9: Signal light cycle diagram.

TABLE 2: Simulation parameters.

Parameter	Value
v_{max} (m/s)	19.44
v_{min} (m/s)	5.56
a_{max} (m/s ²)	3
d_{max} (m/s ²)	6
L_{16} (veh/h)	363
L_{14} (veh/h)	193
L_{52} (veh/h)	352
L_{58} (veh/h)	200
$N_{i,j}$	$\in [2, 9]$
$l(m)$	4
$L(m)$	300
minGap(m)	1.5
L_{38} (veh/h)	211
L_{36} (veh/h)	158
L_{74} (veh/h)	200
L_{72} (veh/h)	150

increasing the throughput of the intersection. At the same time, it can be seen from the platoon trajectory diagram that decelerates and stops that the paper takes the minimum fuel consumption as the control objective to control the vehicle to decelerate in advance, which makes the platoon trajectory smoother and the speed fluctuation smaller.

5.2. *Traffic Efficiency Analysis.* As can be seen from Table 3, the total number of queued vehicles at the intersection decreased by 77.81%, and the maximum number of queued

vehicles decreased by 33.33%. And, after speed control is implemented, the number of vehicles in queue is reduced in most cases as shown in Figure 16. Causing a decline in the number of queuing vehicles for two reasons, on the one hand, most of the platoon can undertake speed adjustment in advance by the platoon speed control model proposed in this paper and make as many vehicles through the intersection during the green light, thus reducing the intersection driveway lined up and vehicle parking waiting, reduce traffic congestion; on the other hand, as shown in Figure 15, take an example of the speed trajectory of a platoon that needs to slow down and stop; the speed trajectory graph of the platoon slowing down and stopping at the intersection shows that, as the platoon split speed control strategy controls the platoon that cannot cross the intersection at the green light time, slowing down and stopping with minimum fuel consumption makes the platoon slow down earlier, which to some extent also leads to a reduction in the number of vehicles queuing at the intersection and controls the platoon to slow down earlier; the speed trajectory of the vehicle is smoother and the speed fluctuation is smaller.

Meanwhile, the mean travel time of vehicles is reduced by 10.95%. As can be seen from the broken line in Figure 17, in most cases, the mean travel time curve with platoon speed control is below or near the mean travel time curve without platoon speed control and is relatively stable. Therefore, it can be seen that, on the basis of ensuring the stability of traffic operation, the speed control strategy proposed in this paper can reduce the average traffic time and improve the efficiency of traffic operation.

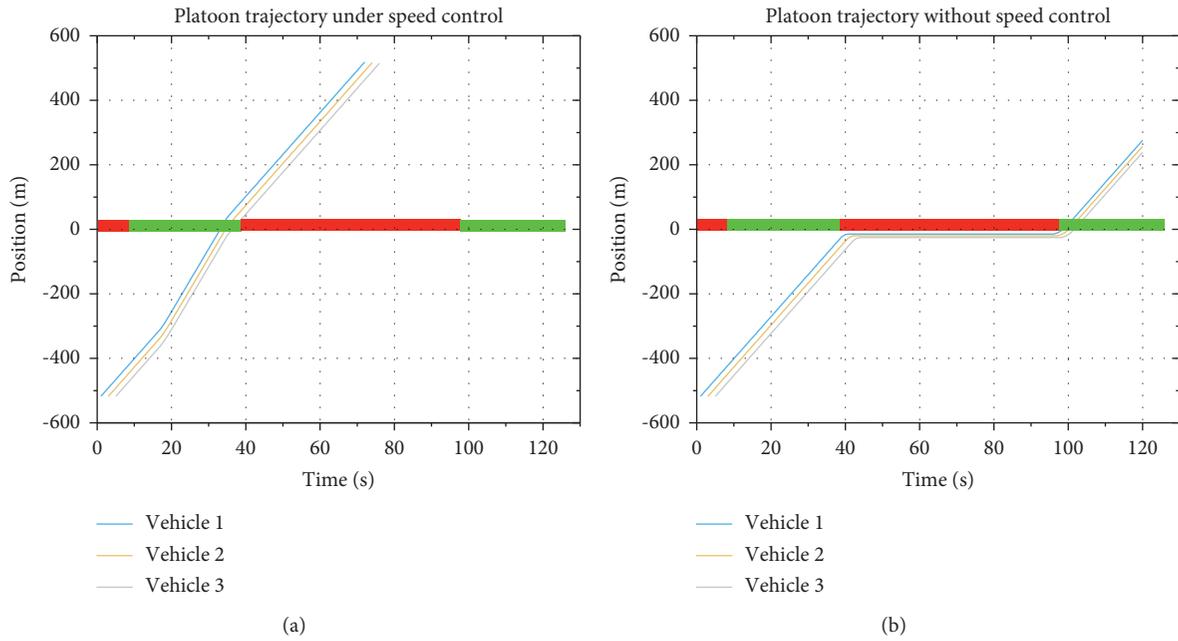


FIGURE 10: Accelerated passage situation under green light. (a) Platoon trajectory under speed control. (b) Platoon trajectory without speed control.

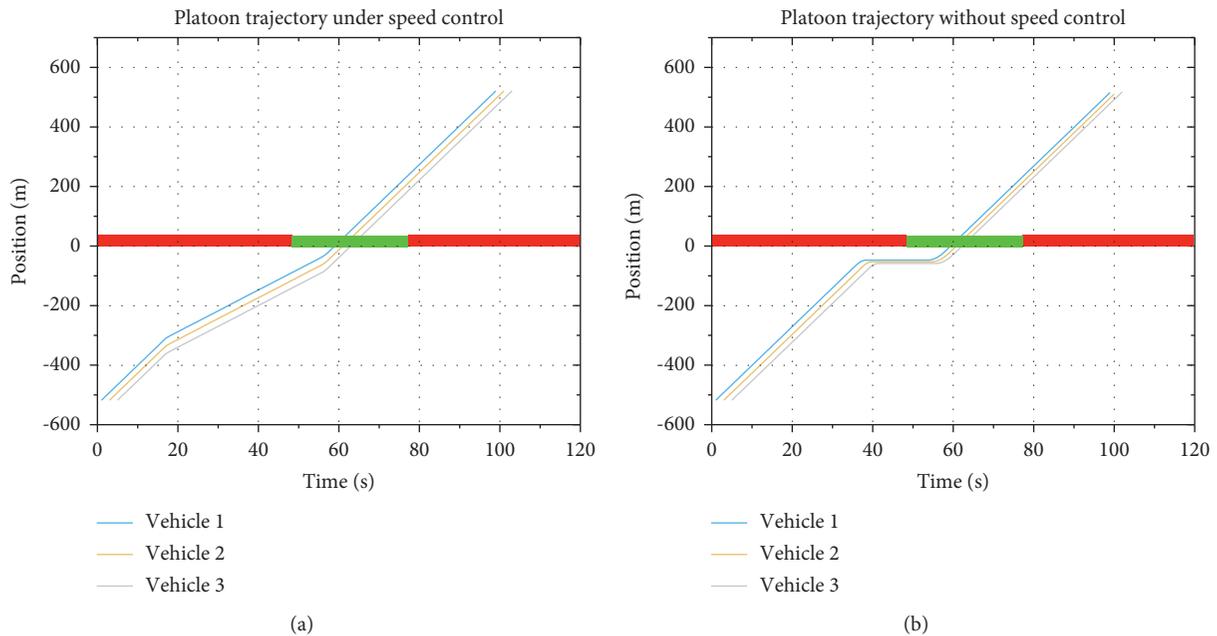


FIGURE 11: Decelerated passage situation under red light. (a) Platoon trajectory under speed control. (b) Platoon trajectory without speed control.

5.3. Analysis of Energy Consumption and Pollutant Emissions. In terms of energy consumption and pollutant emissions, it can be seen from Figure 18 that, after the proposed platoon speed control, the total fuel consumption is reduced by 19.95%, and the total emissions of CO₂, CO, HC, NO_x and PM_x are reduced by 19.96%, 58.55%, 51.33%, 23.81%, and 37.51%, respectively. On the one hand, the

overall speed control strategy proposed in this paper reduces the start-stop and idle speed of vehicles near the intersection. On the other hand, the proposed platoon split speed control strategy has carried out speed optimization treatment with minimum fuel consumption as the control objective for the platoon that fails to pass the intersection. This indicates that the speed control strategy

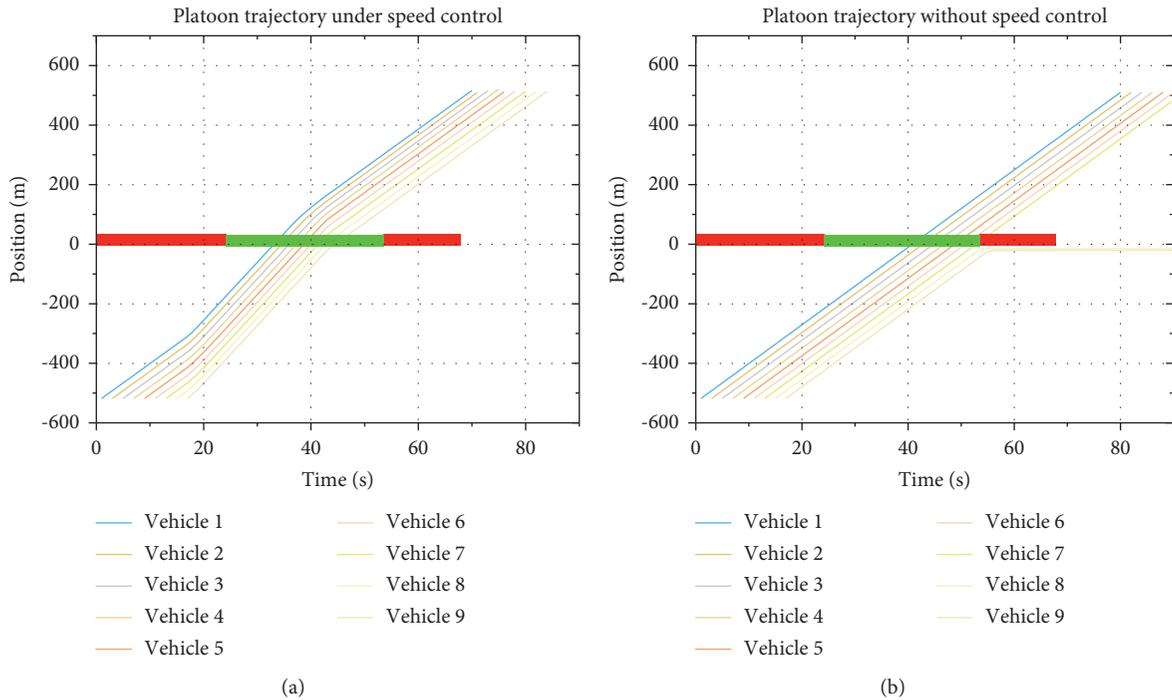


FIGURE 12: Accelerated passage situation under red light. (a) Platoon trajectory under speed control. (b) Platoon trajectory without speed control.

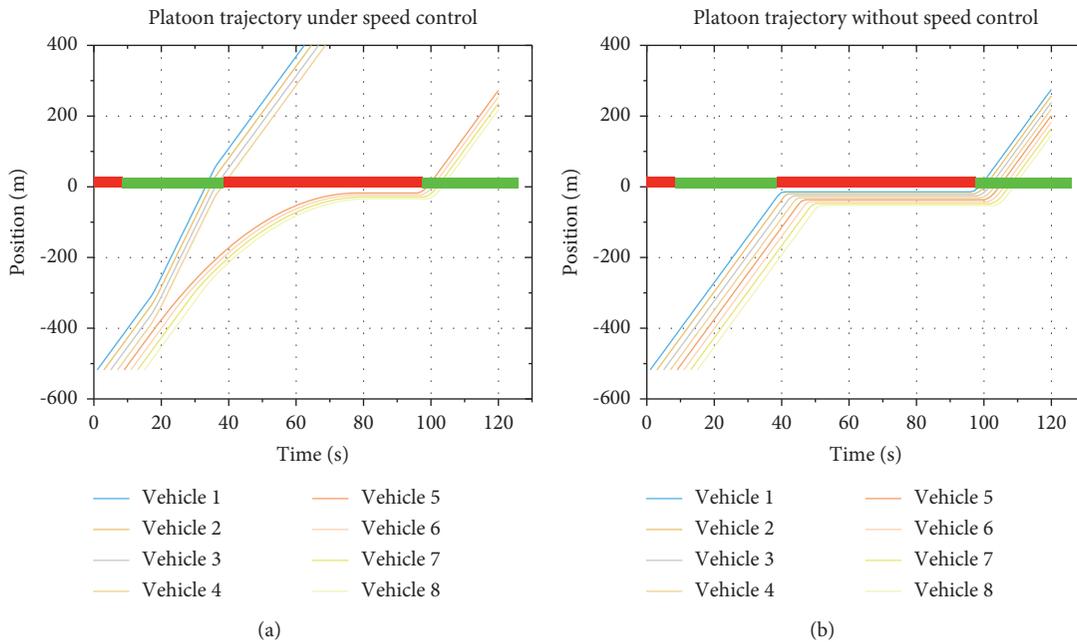


FIGURE 13: Platoon split situation. (a) Platoon trajectory under speed control. (b) Platoon trajectory without speed control.

proposed in this paper is effective in reducing energy consumption and pollutant emissions during traffic operation.

In conclusion, compared with no intersection platoon speed control, the intersection speed control model

proposed in this paper can reduce the number of queued vehicles and travel time while effectively reducing the energy consumption and total pollutant emissions in the process of traffic operation and ensure the energy saving and high efficiency in the process of traffic operation.

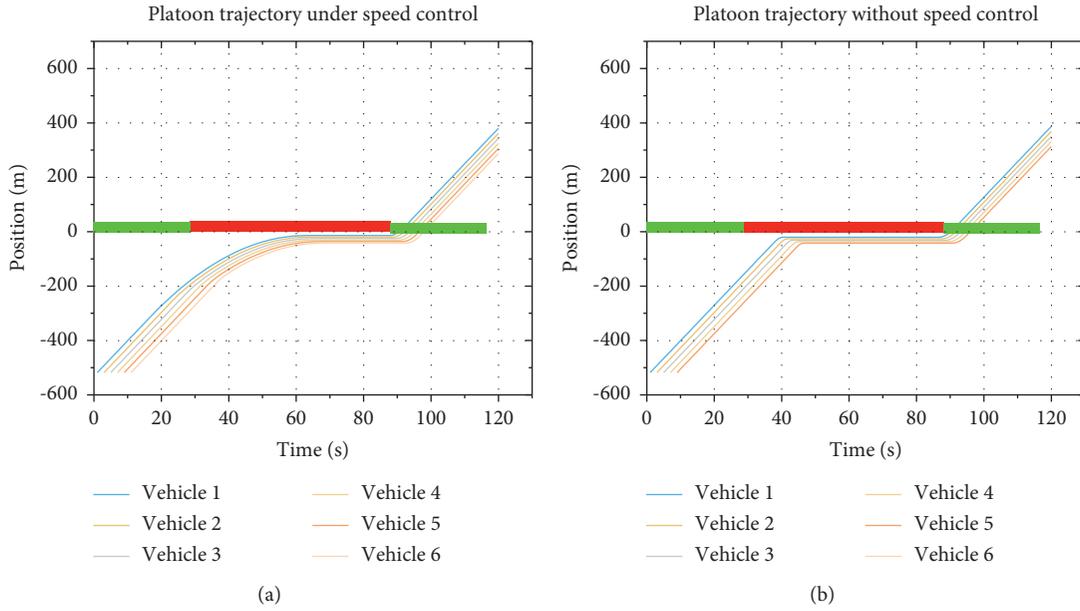


FIGURE 14: Platoon slow down and stop situation under green light. (a) Platoon trajectory under speed control. (b) Platoon trajectory without speed control.

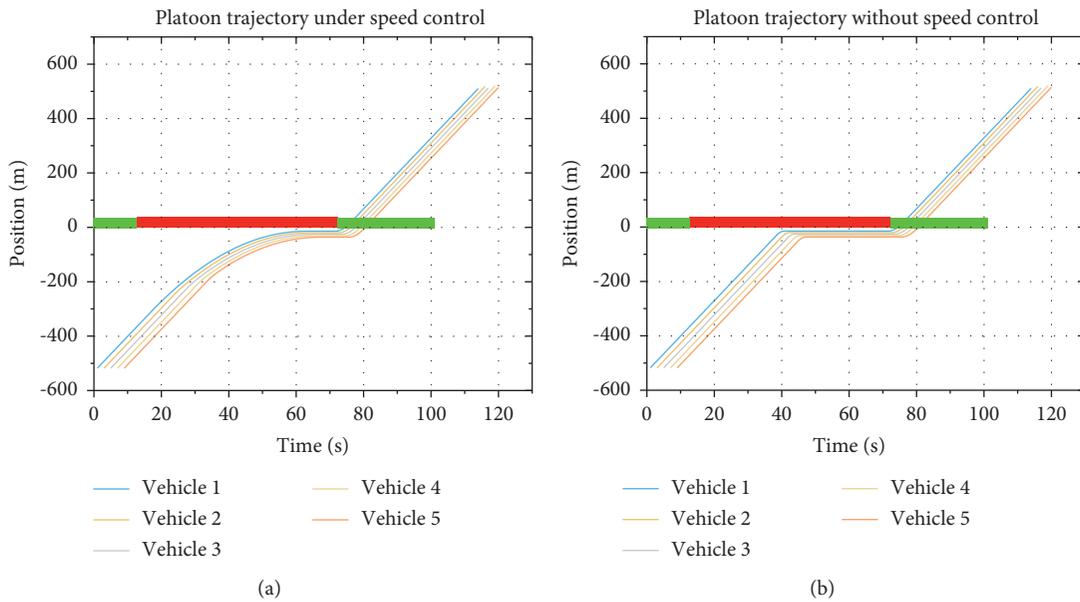


FIGURE 15: Platoon slow down and stop situation under red light. (a) Platoon trajectory under speed control. (b) Platoon trajectory without speed control.

TABLE 3: Traffic efficiency simulation results.

	Speed control	No speed control
Total number of queued vehicles (veh)	1921	8657
Maximum number of queued vehicles (veh)	8	12
Mean travel time (s)	95.72	107.49

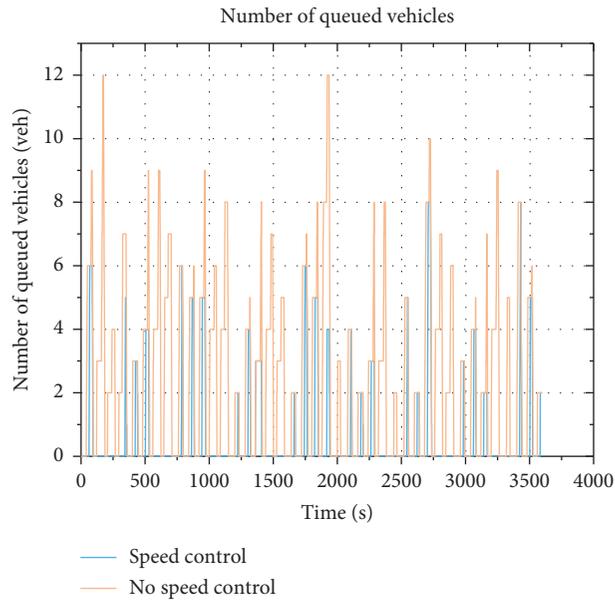


FIGURE 16: Number of queued vehicles of speed control and no speed control.

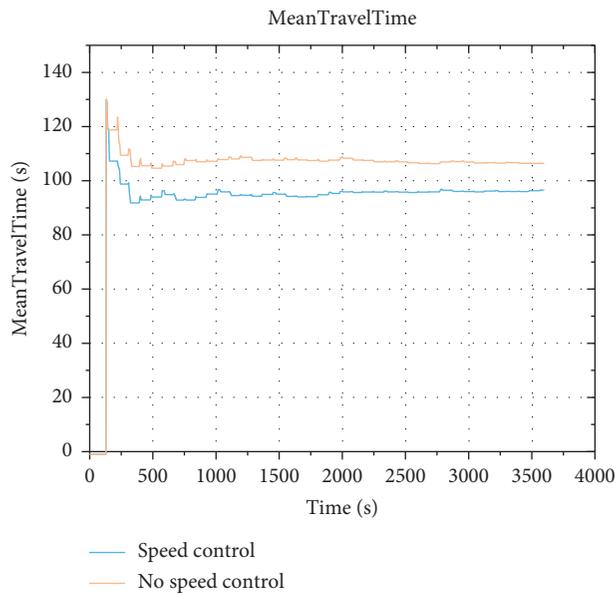


FIGURE 17: Mean travel time of speed control and no speed control.

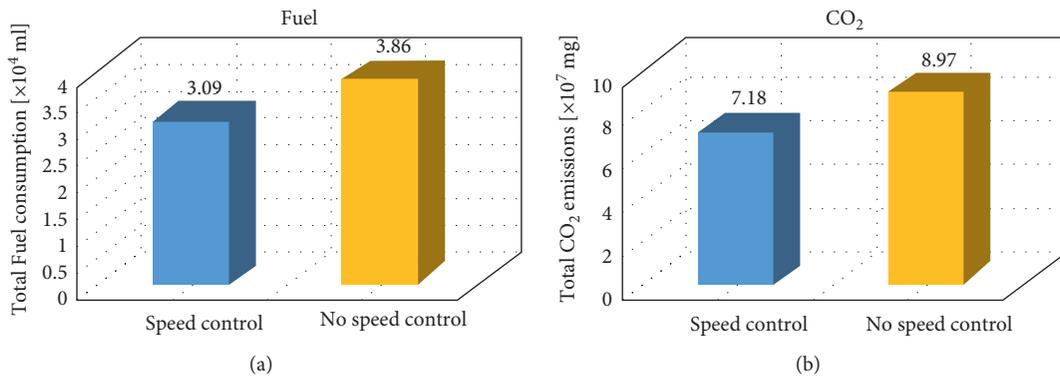


FIGURE 18: Continued.

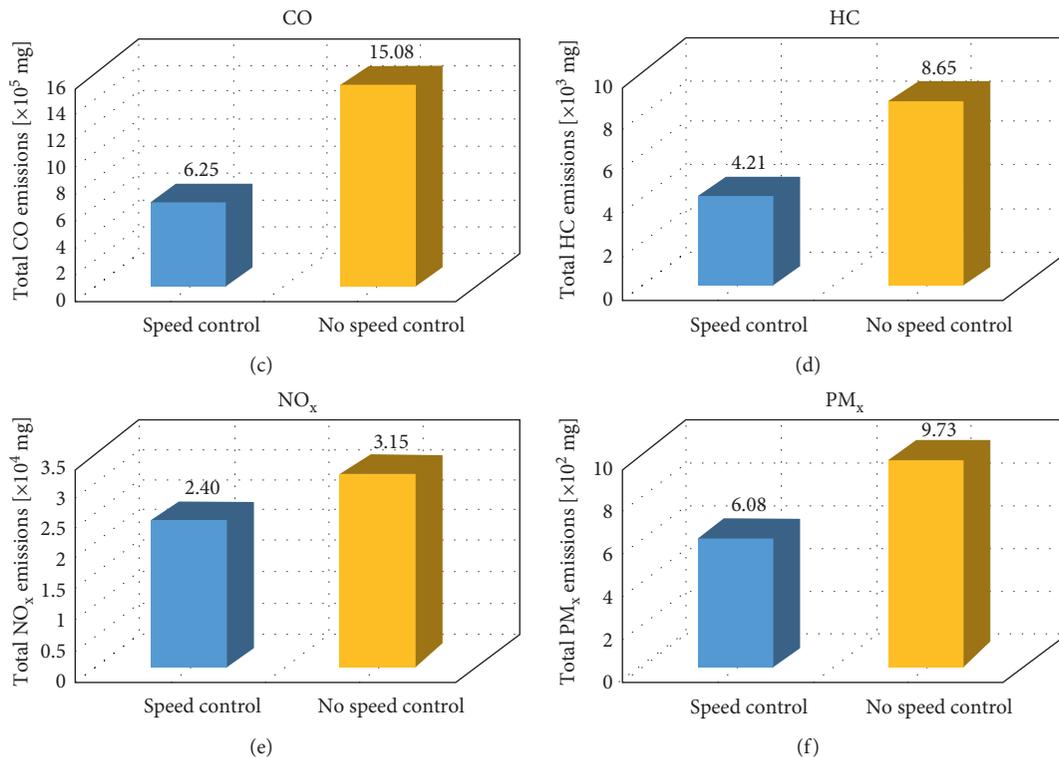


FIGURE 18: Energy consumption and pollutant emissions of speed control and no speed control. (a) Fuel. (b) CO₂. (c) CO. (d) HC. (e) NO_x. (f) PM_x.

6. Conclusions

In this paper, an intersection platoon speed control model considering traffic efficiency and energy consumption is proposed to improve traffic efficiency and reduce energy consumption and pollution gas emissions during traffic operation. Firstly, this paper constructs the platoon overall speed control strategy. On the basis of defining the speed control area of the intersection, the state of the signal light when the platoon arrives at the control area is divided in detail. Meanwhile, the judgment conditions of each situation and the corresponding restrictions that make the platoon pass the intersection without stopping are given. For the platoons that cannot pass the intersection in the green phase through the overall speed control strategy, a platoon split speed control strategy is constructed in order to allow as many vehicles as possible to pass the intersection and to minimize the fuel consumption of vehicles that cannot pass the intersection. The model is solved and verified by SUMO, MATLAB, and Python. Simulation results show that, compared with the no platoon speed control, under the intersection platoon speed control model considering traffic efficiency and energy consumption proposed in this paper, the total number of queued vehicles at the intersection decreased by 77.81%, the maximum number of queued vehicles decreased by 33.33%, and the mean travel time of vehicles is reduced by 10.95%. The total fuel consumption is saved by 19.95%, and the total emissions of CO₂, CO, HC, NO_x, and PM_x are reduced by 19.96%, 58.55%, 51.33%, 23.81%, and 37.51%, respectively. This indicates that the optimal control effect of the platoon speed control model proposed in this paper is good, which can ensure

the traffic efficiency and reduce the energy consumption and pollution gas emissions in the process of traffic operation.

For future work, we plan to further consider the traffic signal factors on the basis of the platoon speed control model proposed in this paper, so as to better improve the operational efficiency of traffic and environmental protection.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the Natural Science Foundation of Shandong Province (Grant no. ZR2019MF056).

References

- [1] Y. Du, W. ShangGuan, and L. Chai, "A coupled vehicle-signal control method at signalized intersections in mixed traffic environment," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 3, pp. 2089–2100, 2021.
- [2] K. Gao, F. Han, P. Dong, N. Xiong, and R. Du, "Connected vehicle as a mobile sensor for real time queue length at signalized intersections," *Sensors*, vol. 19, no. 9, p. 2059, 2019.

- [3] K. Long, C. Ma, Z. Jiang, Y. Wang, and X. Yang, "Integrated optimization of traffic signals and vehicle trajectories at intersection with the consideration of safety during signal change," *IEEE Access*, vol. 8, pp. 170732–170741, 2020.
- [4] S. Stebbins, M. Hickman, J. Kim, and H. L. Vu, "Characterising green light optimal speed advisory trajectories for platoon-based optimisation," *Transportation Research Part C: Emerging Technologies*, vol. 82, pp. 43–62, 2017.
- [5] Z. He, W. Zhang, and N. Jia, "Estimating carbon dioxide emissions of freeway traffic: a spatiotemporal cell-based model," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 5, pp. 1976–1986, 2020.
- [6] J. Tan, X. Shi, Z. Li et al., "Continuous and discrete-time optimal controls for an isolated signalized intersection," *Journal of Sensors*, vol. 2017, Article ID 6290248, 11 pages, 2017.
- [7] W. Wu, Y. Liu, Y. Xu, Q. Wei, and Y. Zhang, "Traffic control models based on cellular automata for at-grade intersections in autonomous vehicle environment," *Journal of Sensors*, vol. 2017, Article ID 9436054, 6 pages, 2017.
- [8] J. Jin and X. Ma, "A multi-objective agent-based control approach with application in intelligent traffic signal system," *IEEE Transactions on Intelligent Transportation Systems*, vol. 20, no. 10, pp. 3900–3912, 2019.
- [9] C. B. Rafter, B. Anvari, S. Box, and T. Cherrett, "Augmenting traffic signal control systems for urban road networks with connected vehicles," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 4, pp. 1728–1740, 2020.
- [10] T. Wu, P. Zhou, K. Liu et al., "Multi-agent deep reinforcement learning for urban traffic light control in vehicular networks," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 8, pp. 8243–8256, 2020.
- [11] X. Han, D. Tian, Z. Sheng et al., "Reliability-aware joint optimization for cooperative vehicular communication and computing," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 8, pp. 5437–5446, 2021.
- [12] C. Yu, Y. Feng, H. X. Liu, W. Ma, and X. Yang, "Integrated optimization of traffic signals and vehicle trajectories at isolated urban intersections," *Transportation Research Part B: Methodological*, vol. 112, pp. 89–112, 2018.
- [13] C. Sun, J. Guanetti, F. Borrelli, and S. J. Moura, "Optimal eco-driving control of connected and autonomous vehicles through signalized intersections," *IEEE Internet of Things Journal*, vol. 7, no. 5, pp. 3759–3773, 2020.
- [14] E. Zadorbrishi, L.-M. Cosovanu, and M. Dimian, "Traffic flow density model and dynamic traffic congestion model simulation based on practice case with vehicle network and system traffic intelligent communication," *Symmetry*, vol. 12, no. 7, p. 1172, 2020.
- [15] L. Hu, Y. Zhong, W. Hao et al., "Optimal route algorithm considering traffic light and energy consumption," *IEEE Access*, vol. 6, pp. 59695–59704, 2018.
- [16] W.-H. Lee and J.-Y. Li, "An eco-driving advisory system for continuous signalized intersections by vehicular ad hoc network," *Journal of Advanced Transportation*, vol. 2018, Article ID 5060481, 12 pages, 2018.
- [17] E. Mintsis, E. I. Vlahogianni, E. Mitsakis, and S. Ozkul, "Enhanced speed advice for connected vehicles in the proximity of signalized intersections," *European Transport Research Review*, vol. 13, no. 1, p. 2, 2021.
- [18] Z. Yang, J. Peng, L. Wu et al., "Speed-guided intelligent transportation system helps achieve low-carbon and green traffic: evidence from real-world measurements," *Journal of Cleaner Production*, vol. 268, Article ID 122230, 2020.
- [19] Z. Zhang, Y. Zou, X. Zhang, and T. Zhang, "Green light optimal speed advisory system designed for electric vehicles considering queuing effect and driver's speed tracking error," *IEEE Access*, vol. 8, pp. 208796–208808, 2020.
- [20] X. Shen, X. Zhang, T. Ouyang, Y. Li, and P. Raksincharoensak, "Cooperative comfortable-driving at signalized intersections for connected and automated vehicles," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6247–6254, 2020.
- [21] Q. Lin, S. E. Li, S. Xu, X. Du, D. Yang, and K. Li, "Eco-driving operation of connected vehicle with V2I communication among multiple signalized intersections," *IEEE Intelligent Transportation Systems Magazine*, vol. 13, no. 1, pp. 107–119, 2021.
- [22] W. Wu, L. Huang, and R. Du, "Simultaneous optimization of vehicle arrival time and signal timings within a connected vehicle environment," *Sensors*, vol. 20, no. 1, p. 191, 2019.
- [23] S. Karbalaieali, O. A. Osman, and S. Ishak, "A dynamic adaptive algorithm for merging into platoons in connected automated environments," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 10, pp. 4111–4122, 2020.
- [24] C. Hong, H. Shan, M. Song et al., "A joint design of platoon communication and control based on LTE-V2V," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 12, pp. 15893–15907, 2020.
- [25] N. Chen, M. Wang, T. Alkim, and B. van Arem, "A robust longitudinal control strategy of platoons under model uncertainties and time delays," *Journal of Advanced Transportation*, vol. 2018, Article ID 9852721, 13 pages, 2018.
- [26] D. Wu, J. Wu, and R. Wang, "An energy-efficient and trust-based formation algorithm for cooperative vehicle platooning," in *Proceedings of the 2019 International Conference on Computing, Networking and Communications (ICNC)*, pp. 702–707, Honolulu, HI, USA, February 2019.
- [27] F. Ma, Y. Yang, J. Wang et al., "Eco-driving-based cooperative adaptive cruise control of connected vehicles platoon at signalized intersections," *Transportation Research Part D: Transport and Environment*, vol. 92, Article ID 102746, 2021.
- [28] Y. Feng, D. He, and Y. Guan, "Composite platoon trajectory planning strategy for intersection throughput maximization," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 7, pp. 6305–6319, 2019.
- [29] M. Faraj, F. E. Sancar, and B. Fidan, "Platoon-based autonomous vehicle speed optimization near signalized intersections," in *Proceedings of the 2017 IEEE Intelligent Vehicles Symposium (IV)*, pp. 1299–1304, Los Angeles, CA, USA, June 2017.
- [30] C. Wang, Y. Dai, and J. Xia, "A CAV platoon control method for isolated intersections: guaranteed feasible multi-objective approach with priority," *Energies*, vol. 13, no. 3, p. 625, 2020.
- [31] N. Bisht and R. A. Shet, "Platoon-based cooperative intersection management strategies," in *Proceedings of the 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*, pp. 1–6, Antwerp, Belgium, May 2020.
- [32] J. L. Jiménez-Palacios, *Understanding and Quantifying Motor Vehicle Emissions with Vehicle Specific Power and TILDAS Remote Sensing*, Massachusetts Institute of Technology, Cambridge, MA, USA, 1999.
- [33] R. Liao, X. Chen, L. Yu, and X. Sun, "Analysis of emission effects related to drivers' compliance rates for cooperative vehicle-infrastructure system at signalized intersections," *International Journal of Environmental Research and Public Health*, vol. 15, no. 1, p. 122, 2018.
- [34] S. Krauss, P. Wagner, and C. Gawron, "Metastable states in a microscopic model of traffic flow," *Physical Review E*, vol. 55, no. 5, pp. 5597–5602, 1997.