Research on the Platoon Speed Guidance Strategy at Signalized Intersections in the Connected Vehicle Environment

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The development of connected vehicle (CV) technology has created conditions for improving the traffic efficiency of intersections and provided support for more effective speed guidance at signalized intersections. First, this paper proposes a platoon speed guidance strategy to reduce the fuel consumption and delay of the platoon passing through the intersection and smooth traffic oscillation, which includes constant speed guidance, deceleration guidance, acceleration guidance, and stop guidance. Then, the optimal speed calculation method is designed, including the calculation of the platoon’s passable period and maximum number of passing vehicles, the platoon restructure method, the analysis of the trajectory of the vehicles, and the calculation of the optimal trajectory of the platoon based on the goal of minimum fuel consumption and delay. Finally, eight different intersection scenarios are designed to simulate the proposed platoon speed guidance strategy. The results show that the platoon speed guidance strategy can effectively reduce the fuel consumption and delay of the platoon passing through the intersection and smooth traffic oscillation. In addition, the influences of queue length and CV penetration rate on the platoon speed guidance strategy are also discussed. The results show that when the queue length affects the passable period, the improvement in fuel consumption, drive time, and delay will decrease as the queue length increases. And as the penetration rate increases, the strategy becomes increasingly effective in reducing the delay and fuel consumption of the platoon in general.

1. Introduction

As an important node of the urban road network, intersections are the key to causing urban road traffic congestion [1]. At the intersection, the traffic flow from all directions converges here, which can easily cause traffic congestion [2]. At the same time, intersection signals will also block the traffic flow, and the resulting delays will sometimes affect the road or even the running state of the road network in the surrounding area [3]. In order to alleviate the problem of traffic congestion at intersections, conventional measures such as road widening, canalization, and construction have been adopted [4]. However, due to the limitations of land resources and environment, the expansion of road traffic facilities has been greatly restricted, and conventional means cannot meet the growing traffic needs. In recent years, the CV technology has brought a new direction to solve this problem [5–8]. It uses advanced communication technology to create connections between vehicles and vehicles (V2V) and vehicles and roads (V2I) and to realize information sharing and utilization. The technology can be used to predict traffic flow [9, 10], predict trajectories [11, 12], optimize signal control [13–16], and guide vehicles, etc.

Using the CV technology to guide vehicle speed at intersections has become the focus of research to solve the
problem of intersection congestion [9, 17, 18]. CVs can obtain information including the queuing status of intersections and the status of signal control facilities through V2I and can also obtain information such as the position and speed of surrounding vehicles through V2V. These technologies provide the possibility for speed guidance. The vehicle can adjust the speed in advance through the speed guidance and pass the intersection at the optimized speed, which can reduce the unnecessary queue and stop. Speed guidance can be optimized for different objectives, such as safety, fuel economy, and traffic efficiency [19]. In the CV environment, it is easier for vehicles to form a platoon, and it is more common for vehicles to travel in a platoon [20–23]. In this context, this paper proposes a platoon speed guidance strategy at signalized intersections, which enables platoons to pass through the intersection with the minimum delay and fuel consumption, considering the impact of queuing vehicles at intersections. The contributions of this paper are mainly related to the following four aspects:

1. A platoon speed guidance strategy considering the influence of the queue at signalized intersections in the CV environment is proposed, including constant speed guidance, deceleration guidance, acceleration guidance, and stop guidance.

2. The optimal speed calculation method is given for the platoon speed guidance strategy, which includes calculation of the platoon’s passable period and its maximum number of vehicles that can pass, platoon restructure, and optimization of the trajectory of the leading vehicle and the following vehicles.

3. The platoon speed guidance strategy and method are simulated, and the results show that the proposed strategy can effectively reduce platoon fuel consumption and delay and smooth the traffic oscillation.

4. The influence of the CVs’ penetration rate on the proposed strategy is discussed. The simulation results show that the platoon speed guidance strategy can reduce the delay and fuel consumption under mixed traffic flow, and the higher the penetration rate, the better the effect.

The rest of this paper is organized as follows. Section 2 briefly introduces the existing related studies. Section 3 proposes the platoon speed guidance strategy. In Section 4, we present a method to obtain the optimal speed. Section 5 presents the simulation analysis. Section 6 analyzes influences of different queue lengths and penetration rates on the strategy, and the conclusion and future prospects are in Section 7.

2. Literature Review

Vehicle speed guidance at an intersection is an important means to optimize intersection traffic, and many works have been achieved.

In terms of speed guidance at unsignalized intersections, Lee and Park [24] proposed a cooperative vehicle intersection control algorithm to control the movement of a single vehicle so vehicles can safely pass through the intersection. The results show that the algorithm improves the intersection performance. Chai et al. [25] proposed a slot preassigning method. When vehicles enter the status-adjusting area, the management center begins to calculate the target status and generate suggestions. Simulation results show that the proposed method performs better than signal-based intersections. Zhao and Li [26] proposed a car-following model to explore the impact of V2V communication on driving behavior with two cross-flows. The results show that by extending the guidance space range and increasing the maximum speed limit, the benefit of the guidance strategy can be improved, and it is more suitable for medium-low traffic density and small safe separation conditions. Chen and Liu [27] proposed a gap-based automatic speed control algorithm for eco-driving. The algorithm considers acceptable clearance as green time and unacceptable clearance and vehicle length as red time. The results show that the proposed algorithm can effectively prevent conflicts while minimizing vehicle fuel consumption, travel time, and emissions. Huang et al. [28] proposed a guidance strategy and built a simplified iterative behavior model to predict the behavior of potentially conflicting vehicles. The results show that the guidance strategy can effectively improve the safety and efficiency of drivers passing through the intersection at different compliance rates. Bifulco et al. [29] proposed a novel cooperative fully-distributed control algorithm for connected automated vehicles (CAVs), considering the safe crossing problem of an unsignalized intersection for mixed traffic flows. The simulation results show that, the proposed algorithm can strongly improve the safety and mobility performances of the intersection.

In terms of speed guidance at signalized intersections, Chen [30] developed an eco-driving optimization model to analyze the optimal eco-driving trajectory of vehicles. The results show that eco-driving can reduce substantial emissions without significantly increasing driving time. Chen et al. [31] proposed a dynamic eco-driving speed guidance strategy, aiming to optimize the fuel consumption emission curve of vehicles approaching signalized intersections. The results showed that the strategy significantly reduced the number of stops, reducing fuel consumption and emissions. Liu et al. [32] proposed a speed guidance model that considers the mixed traffic flow of electric vehicles and diesel vehicles to achieve the goals of reducing travel delays and reducing emissions and energy consumption. The results show that the proposed model has good performance, and increasing the proportion of electric vehicles can reduce energy consumption and emissions. Wang et al. [33] proposed a speed guidance model under the green light phase. The results show that there is a significant difference in the time interval distribution with and without speed guidance, and speed guidance can improve the coordination of time interval without reducing the travel efficiency. Tang et al. [34] proposed a speed guidance model to explore the impact of driver’s bounded rationality on vehicle fuel consumption and emissions during the entire process of vehicles passing
through signalized intersections. The results show that the driver’s bounded rationality has a significant impact on the vehicle’s fuel consumption and emissions, but its impact directly depends on the parameters of the driver’s bounded rationality. Wang et al. [35] proposed a speed guidance model to provide different guidance strategies for different signal phases and timings. Simulation results show that the proposed model can reduce delays, total stop time, and number of stops, and improve traffic efficiency at intersections. Yao et al. [36] proposed a trajectory smoothing method based on a single variable speed limit and position optimization, which makes the trajectory of each approaching vehicle run smoothly without stopping according to real-time traffic demand and signal timing information. The results show that this method can improve traffic efficiency and reduce fuel consumption. Ci et al. [37] proposed a V2I-based car-following model at signalized intersections, which considered the impact of V2I on intelligent vehicle operation on the basis of the full velocity difference (FVD) model. Simulation results show that the model can better reflect the impact of V2I on vehicle operation at intersections. Ding et al. [38] proposed a comprehensive platoon formation and trajectory optimization method for low-visibility environments. The simulation results show that the proposed method can avoid overlapping vehicle trajectories and reduce delays. Sun et al. [39] proposed a speed guidance model for buses to improve the level of bus service and maintain a stable headway. The simulation results show that the variance coefficient of headway and the average waiting time are significantly reduced. Wu et al. [40] proposed an integrated control strategy for transit signal priority and speed guidance in the CV environment. The simulation results show that the strategy reduces the delay of the bus and improves the punctuality of the bus. Liang and Wei [41] proposed a single-intersection bus speed guidance and signal priority control method, and the simulation results show that this method can reduce the average passenger delay. Namazi and Taghavipour [42] proposed a speed guidance method under the CV environment. Combined with real data, the simulation results show that the proposed method can reduce waiting time, fuel consumption, and emissions. Mintsis et al. [43] proposed an enhanced velocity planning algorithm. Simulation results show that the algorithm can reduce CO₂ emissions and improve the comfort and safety of speed recommendations. Wu et al. [44] proposed a cooperative hierarchical eco-driving strategy for CV platoons that combine the advantages of hierarchical driving techniques and platoon control through an efficient hierarchical framework. Simulation results show that the strategy has good adaptability under random traffic signals and vehicle states, reduces delays through intersections, and improves energy economy.

Furthermore, since the driving behavior of the preceding vehicle affects the following vehicle, the effect of speed guidance for a single vehicle at an intersection is limited, and some scholars began to research on the multiple vehicle speed guidance. Wu et al. [45] proposed a multivehicle speed guidance strategy at signalized intersections. Compared with the single-vehicle speed guidance strategy, multivehicle guidance can significantly reduce delay and stop times and improve traffic control efficiency. Liu et al. [46] proposed a multivehicle speed guidance strategy in the CV environment with the optimization objective of minimizing travel time. And the research results show that a multivehicle speed guidance strategy can significantly improve the traffic efficiency of intersections and is more effective than a single one.

On the basis of multivehicle guidance at intersections, some scholars have begun to study platoon speed guidance. Chen et al. [47] proposed an eco-driving speed control algorithm suitable for platoons at signalized intersections. The results show that when the platoon needs to accelerate through the intersection, a smaller headway leads to less fuel consumption, and if it needs to slow down, a smaller headway results in more fuel consumption. Wu et al. [48] proposed an improved cooperative eco-driving model for platoons passing two consecutive traffic signals at green time. Simulation results show that the proposed model saves fuel significantly. Yu et al. [49] proposed a consistent optimal speed advisory model for platoons with unconnected vehicles mixed in signal intersections. Numerical results show that the proposed model can improve the safety and fuel economy of mixed traffic flows. Wang et al. [50] proposed a joint control model that simultaneously optimizes the speed of CVs and coordinates signals along the arterial line. Experiments show that the model can reduce delays and eliminate platoon queues. Ye et al. [51] proposed a signalized intersection optimization model based on the vehicle platoon guidance strategy. The results show that it has significant fuel-saving potential without increasing travel time. Wang et al. [52] proposed a multi-priority control method for CV platoon trajectories, which assigns different priorities to throughput, efficiency, and fuel consumption emissions. The results show that the method can significantly improve traffic and energy efficiency while ensuring the safety of connected and autonomous vehicles at urban signalized intersections. Chen et al. [53] proposed the concept of a "1 + n" mixed platoon, consisting of a leading CAV and n following human-driven vehicles, and formulated a platoon-based optimal control framework for CAV control at signalized intersections. The results show that mixed platoon control has greater advantages compared to the traditional trajectory optimization approach for a single CAV. Chen et al. [54] proposed a hierarchical eco-driving control strategy for a hybrid platoon of CAVs and human-driven vehicles (HDVs), which minimizes fuel consumption in trajectory optimization and considers the time-varying powertrain efficiency of hybrid vehicles to improve the energy economy at signalized intersections. Simulation results show that the strategy can improve fuel economy. Liu et al. [55] proposed a joint control method to simultaneously optimize intersection traffic signals and CAV platoon trajectories by optimizing signal phase length and acceleration to maximize comfort and minimize delays during the signal cycle. Simulation results show that the method has advantages in terms of delay, fuel consumption, and throughput compared to the control of a two-level structure. Ma et al. [56] proposed the ecological cooperative adaptive cruise
control (Eco-CACC) to minimize the energy consumption of the CAV platoon. The results show that the proposed strategy enhances the energy economy.

In summary, scholars have conducted extensive research on the speed guidance at intersections, including speed guidance at different types of intersections, single vehicle speed guidance, multiple vehicle speed guidance, and platoon speed guidance, and have achieved a series of results. However, most of them do not consider the impact of queuing vehicles at intersections, and the platoons use a fixed headway. In the CV environment, the headway in the platoon can be changed, and reducing the headway can improve the traffic efficiency [57]. Based on this, the paper proposes a platoon speed guidance strategy at signalized intersections in the CV environment to reduce the delay and fuel consumption. The strategy considers the influence of queuing vehicles at intersections and sets different headways to improve the passing efficiency.

### 3. Platoon Speed Guidance Strategy

In order to realize the speed guidance for platoons entering the intersection, the guidance area is set based on the V2I communication distance. The roadside unit (RSU) that realizes real-time information exchange with CVs has been widely used in urban intersections [58]. RSU can obtain real-time platoon information, such as speed, acceleration, position, etc., as well as queuing platoon information and signal phase and timing (SPaT) information. The RSU can transmit the acquired information to the cloud control center. The cloud control center calculates the optimal platoon speed guidance strategy by analyzing the acquired information and transmitting it to the platoon. The platoon changes its driving speed according to the strategy and passes the intersection. Taking a straight lane at an intersection as an example, the schematic diagram of the platoon speed guidance is shown in Figure 1.

In the process of platoon speed guidance, the effects of longitudinal traffic on the strategy are focused on, and some assumptions are made: (a) the driver is completely obedient to the guidance; (b) conflicting traffic at intersections is ignored [59]; (c) message transfer delays and strategy calculation times are ignored.

We firstly calculate the passable period \([t_{\text{in}}, t_{\text{out}}]\) for platoons according to the phase information of signal lights, the passing time of the queuing platoon, and the entering speed of the incoming platoon. The guided platoon can pass the intersection within the passable period. Then, calculate \(n_{\text{max}}\), the maximum number of vehicles that can pass through the intersection in the period. If the length of the platoon is not greater than \(n_{\text{max}}\), the whole platoon will be guided through the intersection; otherwise, the platoon cannot pass through the intersection and must be guided to restructure. Vehicles that can pass are organized into one platoon, the others which cannot pass are organized into another platoon, called the first incoming platoon and the second incoming platoon, respectively.

Since the entry speed \(v_r\), the length of the platoon \(n\), and the phase of the signal lights are all random when the platoon reaches the guidance area, in order to make the platoon pass the intersection more efficiently, four different platoon guidance strategies are designed.

1. **Constant speed guidance strategy**
   - If the whole platoon can pass the intersection in the passable period at the speed \(v_r\), then guide the platoon to drive at \(v_r\).

2. **Deceleration guidance strategy**
   - If the platoon travels at speed \(v_r\) will lead the platoon to accelerate according to the optimal deceleration and guide the platoon to decelerate according to the optimal deceleration.

3. **Accelerate the guidance strategy**
   - If the platoon drives at speed \(v_r\) will lead the last vehicle of the platoon cannot pass before \(t_{\text{out}}\), then calculate the optimal acceleration, and guide the platoon to accelerate according to the optimal acceleration.

4. **Stop guidance strategy.**

When the platoon neither through the intersection after \(t_{\text{in}}\) by deceleration nor through the intersection before \(t_{\text{out}}\) by acceleration, then calculate the optimal deceleration and guide the platoon to stop according to the optimal deceleration.

After the platoon speed guidance strategy is determined, the driving trajectory of the platoon is calculated. Finally, according to the trajectory optimization model, the optimal trajectory can be obtained, and thus the optimal guidance speed is obtained. The process of the platoon speed guidance is shown in Figure 2.

### 4. Method

#### 4.1. Calculation of the Passable Period \([t_{\text{in}}, t_{\text{out}}]\)

The passable period can be calculated by the entry speed, the SPaT, and the time of the queuing platoon to pass through the intersection. According to these parameters, a schematic diagram of the passable period can be obtained, as shown in Figure 3.

In Figure 3, \(t_{cg}\) is the length of time from the platoon entry time to the start time of the nearest green light time, which can be a negative number. \(t_{arr}\) is the shortest time for the leading vehicle of the platoon to pass through the intersection, which accelerates to the maximum speed with the maximum acceleration. \(t_{wp}\) is the length of time for the last vehicle of the queuing platoon to pass through the intersection. \(t_{safe}\) is the safe headway between the incoming platoon and the queuing platoon.

According to Figure 3, the passable period start time \(t_{\text{in}}\) can be obtained, and its calculation formula is as follows:

\[
t_{\text{in}} = \begin{cases} t_{cg} + t_{wp} + t_{safe}, & t_{arr} \leq t_{cg} + t_{wp} + t_{safe}, \\ t_{arr}, & t_{arr} > t_{cg} + t_{wp} + t_{safe}, \\ t_{cg} + T, & t_{arr} > t_{cg} + t_{green}, \end{cases}
\]

where \(T\) is the signal period and \(t_{green}\) is the green time.
The calculation formula of $t_{\text{arr}}$ is as follows:

$$t_{\text{arr}} = \frac{S_{\text{lead}} - v_r (v_{\text{max}} - v_r)}{v_{\text{max}}} = \frac{2a_{\text{max}} v_{\text{max}}}{v_{\text{max}}},$$

where $S_{\text{lead}}$ is the distance from the stop line to the guidance boundary, $v_{\text{max}}$ is the maximum speed of the vehicle, and $a_{\text{max}}$ is the maximum acceleration of the vehicle.

The calculation of the end time $t_{\text{out}}$ is as follows:
4.2. Calculation of \( n_{\text{max}} \). \( n_{\text{max}} \) refers to the maximum number of vehicles that can pass through the intersection within \([t_{\text{in}}, t_{\text{out}}]\), which is determined by the length of the passable period and the headway of the platoon. The headway may not be consistent due to the driver’s factors, but CV provides support for the consistency of the headway. In the CV environment, the following vehicle can respond faster to the behavior of the front one, so the headway can be reduced. Reducing the headway can increase the number of passable vehicles in the platoon. Assuming that the minimum headway of the platoon is \( h_{\text{t, min}} \), so \( n_{\text{max}} \) can be obtained as follows:

\[
\begin{align*}
 t_{\text{out}} &= \begin{cases} 
 t_{\text{cg}} + t_{\text{green}}, & t_{\text{arr}} \leq t_{\text{cg}} + t_{\text{green}}, \\
 t_{\text{cg}} + T + t_{\text{green}}, & t_{\text{arr}} > t_{\text{cg}} + t_{\text{green}},
\end{cases} \\
n_{\text{max}} &= \frac{t_{\text{out}} - t_{\text{in}}}{h_{\text{t, min}}}. 
\end{align*}
\]

where \( t_{\text{req}} \) is the red time.

4.3. Platoon Restructure Method. If \( n > n_{\text{max}} \), the platoon cannot completely pass through the intersection, and it needs to be reformed. The first \( n_{\text{max}} \) vehicles are organized into a new platoon, which is the first incoming platoon, and its headway is adjusted to \( h_{\text{t, min}} \). The \( n_{\text{max}} + 1 \) th vehicle and vehicles behind are organized into another platoon, which is the second incoming platoon.

Else, the platoon adjusts the headway according to \( n \), which is assumed as \( h_{\text{t}} \). If \( t_{\text{out}} - t_{\text{in}}/h_{\text{t}} < n < n_{\text{max}} \), the platoon travels at \( h_{\text{t, min}} \) to ensure that all vehicles can pass through the intersection, else the platoon travels at \( h_{\text{t}} \) to reduce the fuel consumption.
4.4. Analysis of the Leading Vehicle Trajectory. Since the behavior of the leading vehicle in the platoon will affect the following ones, the driving trajectory of the leading vehicle is calculated first. Different trajectories can be formed for the leading vehicle with different guided speeds, so we need to get the trajectories of the leading vehicle that can pass the intersection with the guidance. The calculation methods for the leading vehicle trajectory under different platoon guidance strategies are as follows:

(1) Constant speed strategy

Set \( S_{\text{last}} \) be the distance from the tail of the platoon to the stop line. When \( v_r \times t_{\text{in}} \leq S_{\text{lead}} \) and \( v_r \times t_{\text{out}} \geq S_{\text{last}} \), the platoon driving at \( v_r \) can make the whole platoon pass the intersection within the passable period. In this case, the leading vehicle is guided to drive at a constant speed \( v_r \) by using the constant speed guidance strategy. The leading vehicle trajectory constraint is as follows:

\[
v_G = v_r, \quad 0 < t \leq t_{\text{out}}.
\]  

(2) Deceleration guidance strategy

When \( v_r \times t_{\text{in}} > S_{\text{lead}} \) and \( v_r \times t_{\text{out}} + (v_r^2 - v_{\text{min}}^2)/(2a_{G1}v_{\text{min}}^2)) > S_{\text{lead}} \), the leading vehicle can pass through the intersection before \( t_{\text{in}} \) by entry speed \( v_r \), and also can drive with a speed not less than \( v_{\text{min}} \) to through the intersection after \( t_{\text{in}} \). In this case, the leading vehicle needs to use the deceleration guidance strategy.

If there is no queuing vehicle ahead, first, we guide the leading vehicle to decelerate to the guidance speed \( v_r \) with the guidance deceleration \( a_{G1} \) and then travel through the intersection with \( v_r \). At this situation, the leading vehicle trajectory needs to meet the following constraints:

\[
\begin{align*}
t_{\text{in}} &\leq \frac{S_{\text{lead}}}{v_r} + \frac{v_r^2 - v_r v_{\text{G}}}{2a_{G1}v_r} \leq t_{\text{out}}, \\
v_{\text{min}} &\leq v_r < v_{\text{G}}, \\
a_{\text{min}} &\leq a_{G1} < 0,
\end{align*}
\]

where \( a_{\text{min}} \) is the minimum acceleration.

If there is a queued vehicle ahead, first, we guide the leading vehicle to slow down to ensure that it can cross the intersection within the passable period, and then travel at a constant speed. After that, an acceleration process is added before the leading vehicle passes through the intersection in order to reduce the traffic oscillation of the platoon merging into the queuing platoon. The speed of the last queue vehicle in queue through the intersection is used as the target speed for the acceleration process, which is set as \( v_{wp} \).

In the above process, set the guidance deceleration as \( a_{G1} \), the guidance acceleration as \( a_{G2} \), and the guidance constant speed as \( v_r \). At this situation, the leading vehicle trajectory needs to meet the following constraints:

\[
\begin{align*}
t_{\text{in}} &\leq \frac{S_{\text{lead}}}{v_r} + \frac{(v_r - v_{\text{G}})^2}{2a_{G1}v_r} + \frac{(v_{wp} - v_r)^2}{2a_{G2}v_r} \leq t_{\text{out}}, \\
v_{\text{min}} &\leq v_r < v_{\text{G}}, \\
a_{\text{min}} &\leq a_{G1} < 0, \\
0 &< a_{G2} \leq a_{\text{max}}.
\end{align*}
\]  

(3) Acceleration guidance strategy

When \( v_{\text{max}} \times (t_{\text{out}} - (v_r^2 - v_{\text{max}}^2)/(2a_{\text{max}}v_{\text{max}}^2)) < S_{\text{last}} \), the leading vehicle can pass through the intersection but the last one cannot. In this case, the leading vehicle needs to use the acceleration guidance strategy.

If there is no queuing vehicle ahead, first guide the leading vehicle to accelerate to the guidance speed \( v_r \) with the guidance acceleration \( a_{G1} \), then travel through the intersection with \( v_r \). At this situation, the leading vehicle trajectory needs to meet the following constraints:

\[
\begin{align*}
t_{\text{in}} &\leq \frac{S_{\text{lead}}}{v_r} + \frac{v_r^2 - v_{\text{G}} v_{\text{wp}}}{2a_{G1}v_r} \leq t_{\text{out}}, \\
v_r &\leq v_r < v_{\text{G}} \leq v_{\text{max}}, \\
0 &< a_{G1} \leq a_{\text{max}}.
\end{align*}
\]  

If there are vehicles queuing up ahead, first guide the leading vehicle to accelerate to ensure that the leading vehicle can cross the intersection within the passable period, then travel at a constant speed. After that, as the deceleration guidance strategy, a deceleration process is added before the leading vehicle passes through the intersection. The speed of the last queue vehicle in queue through the intersection is used as the target speed for the acceleration process, which is set as \( v_{wp} \). In the above process, set the guidance deceleration as \( a_{G1} \), the guidance deceleration as \( a_{G2} \), and the guidance constant speed as \( v_r \). At this situation, the leading vehicle trajectory needs to meet the following constraints:
\[
\begin{align*}
&\forall i,\quad t_{in} \leq \frac{S_{lead}}{v_G} + \frac{(v_G - v_i)^2}{2a_{G1}v_G} + \frac{(v_{wp} - v_G)^2}{2a_{G2}v_G} \leq t_{out}, \\
&v_r < v_G \leq v_{max}, \\
&0 < a_{G1} \leq a_{max}, \\
&a_{min} \leq a_{G2} < 0.
\end{align*}
\]  
(9)

(4) Stop guidance strategy

When \( v_{min} \times (t_{in} + (v_r^2 - v_{min}v_i)/(2a_{max}v_{min})) > S_{lead} \), the leading vehicle of the platoon cannot decelerate through the intersection at a speed greater than \( v_{min} \). In order to reduce the idling time of the platoon, guide the vehicle to stop with a constant guidance deceleration \( a_G \). At this situation, the leading vehicle trajectory needs to meet the following constraint:

\[
a_G = \frac{v_r^2}{S_{stop}},
\]
(10)

where \( S_{stop} \) is the distance from leading vehicle to the stop position. If there is no queued vehicle, it is the distance to the stop line, else is the distance to the position \( h_0 \) behind the last queued vehicle.

4.5. Analysis of the Trajectory of the following Vehicle.

After the trajectory of the leading vehicle is obtained, the trajectory of the following vehicle can be calculated using the car-following model. Since the speed of the preceding vehicle can be obtained in real time in CV environment, we chose the FVD model [60] to analyze the trajectory of the following vehicles, and its formula is as follows:

\[
a_i(t) = \alpha(V(\Delta x_i(t)) - v_i(t)) + \beta(v_{i-1}(t) - v_i(t)),
\]
(11)

where \( \Delta x_i(t) \) is the headway between the \( i^{th} \) vehicle and the preceding vehicle at time \( t \), \( i = 2, 3, \ldots N; v_i(t) \) is the speed of the \( i^{th} \) vehicle at time \( t \); \( \alpha \) is the sensitivity; and \( \beta \) is the speed difference coefficient. The values of \( \alpha \) and \( \beta \) are as follows:

\[
\alpha = 0.41, \\
\beta = \begin{cases} 0, & \Delta x_i > 100, \\ 0.5, & \Delta x_i \leq 100, \end{cases}
\]
(12)

\[
V(\Delta x_i) = \frac{v_{max}}{2} (\tan h(\Delta x_i - h_0) - \tan h(h_i)),
\]
(13)

where \( h_0 \) is the headway of the platoon.

The set of trajectories of the leading vehicle obtained needs to meet the requirement that the following vehicles pass through the intersection before \( t_{out} \), and its formula is as follows:

\[
\int_0^{t_{out}} v_i^2 dt \geq S_i.
\]
(14)

where \( v_i \) is the speed of the \( i^{th} \) vehicle at time \( t \) and \( S_i \) is the distance from the \( i^{th} \) vehicle to the stop line.

According to formula (14), the trajectories of the whole platoon are obtained, which is set as \( M \).

4.6. Calculation of the Optimal Trajectory. The delay and fuel consumption are used as indicators to optimize the platoon trajectory. The calculation of fuel consumption and delay for each vehicle trajectory is as follows.

(1) Delay

The delay of a vehicle is the difference between the time it takes to pass the intersection after guidance and the time it takes to pass at \( v_{max} \). The total delay of the platoon is calculated as follows:

\[
t_d^m = \sum_{i=1}^{N} (t_{pass}^{m} - t_{free}^{m}),
\]
(15)

where \( t_d^m \) is the total delay of the \( m^{th} \) trajectory, \( m \in M; t_{pass}^{m} \) is the time for the \( i^{th} \) vehicle to pass the intersection under the \( m^{th} \) trajectory, and \( t_{free}^{m} \) is the time for the \( i^{th} \) vehicle to pass through the intersection at \( v_{max} \) under the \( m^{th} \) trajectory.

(2) Fuel consumption

The VT-micro model [61] is used to calculate the fuel consumption, and the formula is as follows:

\[
\text{MOE} = \sum_{e=0}^{s} \sum_{j=0}^{s} \left( C_{aj} x_{aj} (dv_{aj}/dt) \right),
\]

\[\text{MOE} = \left\{ \begin{array}{l} \sum_{e=0}^{s} \sum_{j=0}^{s} \left( M_{aj} x_{aj} (dv_{aj}/dt) \right), \quad a < 0, \\ \sum_{e=0}^{s} \sum_{j=0}^{s} \left( M_{aj} x_{aj} (dv_{aj}/dt) \right), \quad a \geq 0, \end{array} \right.\]
(16)

where \( \text{MOE} \) is the instantaneous fuel consumption of the vehicle, \( L; C_{aj} \) is the coefficient during acceleration when the powers of speed and acceleration are \( i \) and \( j \), and \( M_{aj} \) is the coefficient during deceleration when the powers of speed and acceleration are \( i \) and \( j \).

The fuel consumption of the whole platoon is the sum of the fuel consumption of each vehicle from the moment of guidance to the moment of passing intersection. The formula is as follows:

\[
f_{\text{pass}}^m = \sum_{i=1}^{N} \int_0^{t_{pass}^m} \text{MOE}_{i}(t) dt,
\]
(17)

where \( f_{\text{pass}}^m \) is the total fuel consumption of the \( m^{th} \) trajectory.

(3) Optimization model considering fuel consumption and delay

According to formula (15) and (17), a trajectory optimization model with the goal of minimizing the
sum of the fuel consumption and delay of the platoon is established, and the formula is as follows:

$$\min Z = \sum_{i=1}^{N} \left( f_{\text{pass}}^{\text{i}} - f_{\text{free}}^{\text{i}} \right) + \frac{1}{\sum_{i=1}^{N} t_{\text{free}}^{\text{i}}} + \frac{\int_{0}^{t_{\text{g}}} \text{MOE}_{\text{g}}(t) \, dt - f_{\text{free}}^{\text{i}}}{\sum_{i=1}^{N} t_{\text{pass}}^{\text{i}}}$$

s.t. $m \in M$,  

(18)

where $f_{\text{free}}^{i}$ is the fuel consumption of the $i^{th}$ vehicle driving with $v_{\text{max}}$.

5. Simulation Analysis

MATLAB is used to build the simulation scenes, and the proposed strategy is simulated, in which the genetic algorithm is used to solve the optimization model. Since the speed under constant speed strategy is not changed, we only simulate the scenarios under a deceleration guidance strategy, acceleration guidance strategy, and stop guidance strategy. The simulation scene is set to a straight lane at speed under constant speed strategy is not changed, we only use the algorithm to solve the optimization model. Since the proposed strategy is simulated, in which the genetic algorithm is used to build the simulation scenes, and the relevant parameters are shown in Table 1.

### 5.1. Simulation of Deceleration Guidance Strategy

According to whether there are queued vehicles at the intersection when the platoon enters the guidance area, the simulation of the deceleration guidance strategy is divided into two scenarios, namely, scenario A1 and scenario A2. In scenario A1, there are no queued vehicles at the intersection, while in scenario A2 there are queued vehicles. Furthermore, in order to analyze the influence of the headway adjustment on the incoming platoon, the simulation is also carried out for the scenario where the length of the incoming platoon is $n_{\text{max}}$, for which when there are queued vehicles the scenario is set as scenario A3. In these three scenarios, the deceleration guidance strategy is simulated. Trajectories and velocities of the platoon are obtained, as shown in Figures 4–6. At the same time, the fuel consumption, travel time, and delay of the platoon are obtained, as shown in Figures 7–9. In addition, in order to verify the effectiveness of the deceleration guidance strategy, the simulation results of three scenarios without guidance are added in Figures 4–9. Improvements in fuel consumption, driving time, and delays in the deceleration guidance strategy are shown in Table 2.

It can be seen from Figures 4(a) and 4(c) that the guided platoon does not stop at the intersection, while the unguided platoon stops at the intersection. It can be seen from figure 4(b) and 4(d) that the guided platoon remains stable after decelerating to the optimal speed, while the unguided platoon has traffic oscillations due to stop behavior. These show that in this scenario, the guided platoon can pass through the intersection with no stopping and smaller traffic oscillations.

Furthermore, it can be seen from Figure 7 and Table 2 that, compared with the unguided platoon, the total fuel consumption, travel time, and delay of the guided platoon are all reduced, and the reduction in fuel consumption is the most significant. This is the reason that the strategy allows the platoon to avoid stops and start-up delays.

It can be seen from Figures 5(a) and 5(c) that under the guidance of the strategy, the platoon passes through the intersection without stopping and then merges into the previous queuing platoon. Without guidance, the platoon stops before the intersection and merges into the queuing platoon. In Figures 5(b) and 5(d), it can be found that the guided platoon decelerates to the optimal speed, then drives at a constant speed, and then starts to accelerate when near the queuing platoon. The speed changes smoothly during the merge process under guidance, while the unguided platoon has a significant slowdown when it merges into the queue. This shows that in this scenario, the incoming platoon can pass through the intersection without stopping after being guided by the deceleration strategy and merge into the previous queuing platoon with small traffic oscillations.

Furthermore, it can be seen from Figure 8 and Table 2 that, compared with the unguided platoon, the total fuel consumption of the guided platoon is significantly reduced, but the drive time and delay are slightly increased. This is because the strategy guidance makes the platoon avoid stopping, but in order to ensure safety when merging into the queue, the safety distance between the leading vehicle and the last one in the queue is slightly increased.

It can be seen from Figures 6(a) and 6(c) that the guided platoon adjusts the headway to $h_{\text{min}}$; passes through the intersection without stopping, and merges into the previous queuing platoon. There are 4 vehicles that cannot pass the intersection during the green time in the unguided platoon. In Figures 6(b) and 6(d), it can be seen that the guided platoon drives at a constant speed after decelerating to the optimal speed, then accelerates through the intersection and smoothly merges into the queuing platoon. Without guidance, the part that can pass through the intersection stops, merges into the queuing platoon, and then passes through the intersection. The part that cannot pass first slows down with the preceding vehicles, then speeds up with them. Since this part cannot pass, it stops at the stop line and then accelerates when the green light turns on. This part had multiple acceleration and deceleration with the speed fluctuating greatly. This shows that the strategy can guide the incoming platoon through the intersection without stopping.

### Table 1: Related parameter settings.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{\text{max}}$</td>
<td>16.67 m/s</td>
</tr>
<tr>
<td>$v_{\text{min}}$</td>
<td>5 m/s</td>
</tr>
<tr>
<td>$a_{\text{g}}$</td>
<td>12 m/s</td>
</tr>
<tr>
<td>$a_{\text{h}}$</td>
<td>6 m</td>
</tr>
<tr>
<td>$a_{\text{max}}$</td>
<td>3 m/s</td>
</tr>
<tr>
<td>$a_{\text{min}}$</td>
<td>-3 m/s</td>
</tr>
</tbody>
</table>
increasing the number of vehicles passing through and merging into the previously queued platoon with a small traffic oscillation.

Furthermore, it can be seen from Figure 9 and Table 2 that under the guidance of the deceleration strategy and adjustment of headway, the total fuel consumption, travel time, and delay of the platoon are all reduced, and the reduction in fuel consumption is the most significant. The significant reduction in travel time and delay is due to the fact that reducing the headway increases the number of vehicles passing through the intersection.

In summary, under the deceleration guidance strategy, the platoon avoids stopping at intersections and reduces the total fuel consumption significantly. In terms of travel time and delay, it increases slightly in the scene with queuing vehicles but decreases without queuing vehicles. Especially when the length of the platoon is \( n_{\text{max}} \), the delay of the platoon can be significantly reduced by adjusting the headway.

5.2. Simulation of Acceleration Guidance Strategy. Similar to the deceleration guidance strategy, the simulation of the acceleration guidance strategy is divided into two scenarios, namely, scenario B1 and scenario B2. In scenario B1, there are no queued vehicles at the intersection, while in scenario B2 there are queued vehicles. In order to analyze the influence of headway adjustment on the incoming platoon, the
simulation is also carried out for the scene where the length of the platoon is $n_{\text{max}}$ and there are queued vehicles at the intersection, which is named as scenario B3. In these three scenarios, the acceleration guidance strategy is simulated, and the trajectories and speeds of the platoon are obtained, as shown in Figures 10–12, respectively. At the same time, the fuel consumption, travel time, and delay of the platoon are obtained, as shown in Figures 13–15. Similarly, in order to verify the effectiveness of the acceleration guidance strategy, the simulation results of three scenarios without guidance strategy are added to Figures 11–15. Improvements of fuel consumption, driving time, and delays in the acceleration guidance strategy are shown in Table 3.

It can be seen from Figures 10(a) and 10(c) that under the guidance strategy, the whole platoon passed through the intersection, while 2 vehicles could pass in the unguided platoon. In Figures 10(b) and 10(d), it can be seen that the guided platoon accelerates to the optimal speed and then drives at a constant speed, while the part of the unguided platoon that passes through drives at a constant speed, and the two vehicles that cannot pass cause traffic oscillations. These show that the incoming platoon increases the number of vehicles passing through the intersection in this scenario, which benefits from the acceleration guidance. Furthermore, it can be seen from Figure 13 and Table 3 that under the acceleration guidance, the total fuel consumption slightly increases but the driving time and delay of the platoon are
greatly reduced. The delay is greatly reduced because, under the acceleration guidance strategy, the platoon not only improves its average speed but also enables it to pass within the passable period without stopping.

While without guidance, the platoon passed without a merge behavior, and 3 vehicles could not pass the intersection. In Figures 11(b) and 11(d), it can be seen that under the strategy guidance, the platoon accelerates to the optimal speed and then slows down to merge into the previous queued platoon. While without guidance, the platoon drives at a constant speed, but 3 vehicles need to stop. These show that the incoming platoon can pass through an intersection with a small traffic oscillation and merge into the previous queueing platoon after being guided by the acceleration strategy. Furthermore, it can be seen from Figure 14 and Table 3 that, compared with no strategy guidance, the acceleration strategy guidance makes the platoon’s fuel

Figure 6: Simulation results in scenario A3. (a, b) trajectories and speeds of the guided platoon, respectively. (c, d) trajectories and speeds of the unguided platoon, respectively.
consumptions slightly increase, but the travel time and delay are greatly reduced.

It can be seen from Figures 12(a) and 12(c) that under the guidance of the strategy, the whole platoon passed the intersection and merged into the queuing platoon, while without the strategy guidance, 6 vehicles did not pass. It can be seen from Figures 12(b) and 12(d) that under the guidance of the strategy, the platoon has the same small traffic oscillation as scene B2, while under the guidance of no strategy, the 6 vehicles that did not pass and had an obvious traffic oscillation due to the stopping behavior. These show that in this scenario, the incoming platoon can be guided by the acceleration strategy and adjust the headway guidance to increase the number of vehicles passing through the intersection and merging into the queuing platoon with a small oscillation. Furthermore, it can be seen from Figure 15 and Table 3 that, under the acceleration strategy guidance, the platoon fuel consumption increases slightly, but the travel time and delay decrease.

In summary, under the acceleration guidance strategy, the number of vehicles passing through the intersection increases, the platoon fuel consumption increases slightly, but the travel time and delay decrease significantly. When the length of the platoon is $n_{\text{max}}$, adjusting the headway can further reduce the platoon delay.

5.3. Simulation of the Stop Guidance Strategy. When the platoon can neither pass through the intersection after $t_{\text{pass}}$ by decelerating nor pass through the intersection before $t_{\text{stop}}$ by accelerating, the stop guidance strategy should be used. Since the red phases of the signalized intersection set in the simulation scenarios are short, the strategy can only be applied when there are secondary queued vehicles at the intersection. Therefore, it is assumed that there are 3 secondary queued vehicles at the intersection, which is set as scenario C. In this scenario, the stop guidance strategy is simulated, and the trajectory and velocity of the platoon passing through the intersection are obtained, as shown in Figure 16, and the fuel consumption, travel time, and delay of the platoon are shown in Figure 17. In addition, in order to verify the effectiveness of the stop guidance strategy, the simulation results without strategy are added to Figure 16 and Figure 17, respectively.

It can be seen from Figures 16(a) and 16(c) that the guided platoon merged into the queuing platoon more smoothly than the one without guidance. In Figures 16(b) and 16(d), it can be seen that the guided platoon decelerates with a constant deceleration, and the curve is smoother than that of the unguided one, avoiding a large deceleration. This

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Fuel consumption (%)</th>
<th>Drive time (%)</th>
<th>Delay time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>−18.5</td>
<td>−2.6</td>
<td>−6.4</td>
</tr>
<tr>
<td>A2</td>
<td>−14.5</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>A3</td>
<td>−8.5</td>
<td>−22.3</td>
<td>−38.9</td>
</tr>
</tbody>
</table>
shows that in this scenario, the incoming platoon can be more safely merged into the queuing platoon through the stop strategy guidance. It can be seen from Figure 17 that the total fuel consumption of the guided platoon is reduced by 3.5%. This is because the stop-guidance strategy avoids large decelerations.

5.4. Simulation of Platoon Restructure. In order to explore the impact of the platoon restructure on the platoon, the strategy under the platoon restructure is simulated, set as scenario D, and the trajectory and velocity of the platoon under the strategy guidance are obtained through simulation, as shown in Figure 18. Fuel consumption, travel time, and delays are shown in Figure 19. In addition, the simulation results without strategy are added to Figures 18 and 19, respectively.

6. Influence of Queue Length and CV Penetration Rate on the Platoon Speed Guidance Strategy

6.1. Influence of Different Queue Lengths. Since the queue length at intersections has an influence on platoon speed guidance strategies, it is analyzed through scenario A2 and scenario B2, which are typical deceleration scenario and acceleration scenario, respectively. Referring to the analysis method in reference [62], different queue lengths in two scenarios are set and simulated. The results are obtained and...
shown in Table 4 and Table 5. In addition, the improvements to the strategy under different lengths are calculated and shown in Tables 6 and 7.

It can be seen from Table 4 that, as the queue length increases, the fuel consumption, driving time, and delay of the incoming platoon all increase. Table 6 shows that fuel consumption improvement roughly tends to decrease as queue length increases, and drive time and delay both increase slightly.

It can be seen from Tables 5 and 7 that, at queue lengths of 0, 3, 5, fuel consumption, drive time, and delay are the same. The reason is that the queue length has no influence on the platoon speed guidance strategy when the queue dissipates before $t_{in}$. However, at the queue length of 7, the fuel consumption is
increased, and the improvement in drive time and delay is reduced. This is because when the queue length increases and the $n_{\text{max}}$ decreases accordingly, different strategies will be used as a result, such as guiding the platoon with a small headway.

In summary, when the queue length affects the passable period, the improvement of the fuel consumption, drive time, and delay will decrease as the queue length increases, and even different strategies will be used.
6.2. Influence of Different CV Penetration Rates. With the rapid development of the CV technology, CVs have gradually appeared on the actual roads, and the number of them is increasing. However, for a long time in the future, the vehicles on the road will still be mix of CVs and unconnected vehicles [63, 64]. Therefore, it is necessary to explore the influence of the penetration rate of CVs on the platoon speed guidance strategy.

Four typical scenarios are selected for analysis, which are scenarios A2, A3, B1, and D. According to different penetration rates, the scenarios of CVs in each position in the platoon are simulated. The average fuel consumption and delay in different positions under the same penetration rate are obtained, which are shown in Figure 20. It should be noted that in the simulation of scenario D, the headway is reduced only when two connected vehicles are adjacent to each other.

It can be seen from Figure 20(a) that in scenario A2, as the penetration rate increases, the average delay of the platoon keeps on slightly increasing; however, the average fuel consumption of the platoon gradually decreases, especially when the penetration rate is 20%. The average fuel consumption dropped the fastest and then declined more slowly as the penetration rate increased.

It can be seen from Figure 20(b) that in scenario A3, with the increase in the penetration rate, the average fuel consumption decreases gradually, especially when the penetration rate is at 16.67%. But it has a slight increase at 83.34%. The average delay decreases gradually with the increase of the penetration rate, and the decrease becomes increasingly larger. It reaches a maximum value in the range of 83.34% to 100%, the decrease of which can reach 51.22% of the total decrease.

As can be seen from Figure 20(c), as the penetration rate increases, the average fuel consumption first decreases slightly and then increases slightly in scenario B1. This is because when the lead vehicle is not a CV, the platoon can only pass 3 vehicles. At this time, if the next vehicle is a CV, it will be separated from the preceding vehicle. Then, the deceleration guidance strategy is used, which reduces fuel consumption. With the increase in the penetration rate, the number of vehicles with the acceleration guidance strategy increases, and the fuel consumption increases. The average delay decreases rapidly with the increase of the penetration rate. This is because when the lead vehicle is a CV, the entire platoon can pass, and the delay is the lowest. As the penetration rate increases, the probability of the lead vehicle being a CV gradually increases.

Table 3: Improvements of fuel consumption, driving time, and delays in the acceleration guidance strategy.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Fuel consumption (%)</th>
<th>Drive time (%)</th>
<th>Delay time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>−0.9</td>
<td>41.9</td>
<td>90.0</td>
</tr>
<tr>
<td>B2</td>
<td>−1.7</td>
<td>43.2</td>
<td>87.9</td>
</tr>
<tr>
<td>B3</td>
<td>1.89</td>
<td>50.89</td>
<td>97.13</td>
</tr>
</tbody>
</table>

Figure 13: Total fuel consumption, travel time, and delays for scenario B1.

Figure 14: Total fuel consumption, travel time, and delays for scenario B2.

Figure 15: Total platoon fuel consumption, travel time, and delays for scenario B3.
It can be seen from Figure 20(d) that under scenario D, the average delay decreases with the increase in the penetration rate, and the magnitude of the decrease becomes increasingly larger. The average fuel consumption decreases first, then slightly increases, and then decreases with increasing penetration. Because after the penetration rate reaches a certain level, the penetration rate will allow more vehicles in the platoon to reduce the headway, but not enough to increase the number of passing vehicles, so the fuel consumption will increase slightly at this stage. However, as the penetration rate continues to increase, the number of passing vehicles increases, reducing the number of vehicles queuing or slowing down, so the fuel consumption begins to decline.

In summary, the average delay and average fuel consumption of the platoon decrease gradually as the penetration rate increases. Although the average delay or average fuel consumption has increased slightly in some scenarios, the corresponding average fuel consumption or average delay has decreased significantly in the same scenario. This
Figure 17: Total fuel consumption, travel time, and delays for scenario C.

Figure 18: Continued.
Figure 18: Simulation results in scenario D. (a, b) driving trajectories and speed of the guided platoon. (c, d) driving trajectories and speeds of the unguided platoon, respectively.

Figure 19: Total fuel consumption, travel time, and delays for scenario D.

Table 4: Simulation results of different queue lengths in scenario A2.

<table>
<thead>
<tr>
<th>Queue lengths</th>
<th>Fuel consumption (mL)</th>
<th>Drive time (s)</th>
<th>Delay time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Guidance</td>
<td>No guidance</td>
<td>Guidance</td>
</tr>
<tr>
<td>0</td>
<td>164.22</td>
<td>201.6</td>
<td>176.67</td>
</tr>
<tr>
<td>3</td>
<td>189.64</td>
<td>219.47</td>
<td>215.82</td>
</tr>
<tr>
<td>5</td>
<td>202</td>
<td>232.06</td>
<td>237.64</td>
</tr>
<tr>
<td>7</td>
<td>225.9</td>
<td>257.26</td>
<td>267.12</td>
</tr>
</tbody>
</table>
Table 5: Simulation results of different queue lengths in scenario B2.

<table>
<thead>
<tr>
<th>Queue lengths</th>
<th>Fuel consumption (mL)</th>
<th>Drive time (s)</th>
<th>Delay time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Guidance</td>
<td>No guidance</td>
<td>Guidance</td>
</tr>
<tr>
<td>0</td>
<td>304.42</td>
<td>299.44</td>
<td>182.79</td>
</tr>
<tr>
<td>3</td>
<td>304.42</td>
<td>299.44</td>
<td>182.79</td>
</tr>
<tr>
<td>5</td>
<td>304.42</td>
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<td>182.79</td>
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<tr>
<td>7</td>
<td>320.15</td>
<td>299.44</td>
<td>192.05</td>
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</table>

Table 6: Improvements of fuel consumption, drive time, and delay with different queue lengths in scenario A2.

<table>
<thead>
<tr>
<th>Queue lengths</th>
<th>Fuel consumption (%)</th>
<th>Drive time (%)</th>
<th>Delay time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>−18.5</td>
<td>−2.6</td>
<td>−6.4</td>
</tr>
<tr>
<td>3</td>
<td>−13.6</td>
<td>0.1</td>
<td>1.3</td>
</tr>
<tr>
<td>5</td>
<td>−14.5</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>7</td>
<td>−12.2</td>
<td>0.4</td>
<td>0.6</td>
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</table>

Table 7: Improvements of fuel consumption, drive time, and delay with different queue lengths in scenario B2.

<table>
<thead>
<tr>
<th>Queue lengths</th>
<th>Fuel consumption (%)</th>
<th>Drive time (%)</th>
<th>Delay time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.7</td>
<td>−43.2</td>
<td>−87.9</td>
</tr>
<tr>
<td>3</td>
<td>1.7</td>
<td>−43.2</td>
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</tr>
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<td>1.7</td>
<td>−43.2</td>
<td>−87.9</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
<td>−40.3</td>
<td>−82.1</td>
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</tbody>
</table>

Figure 20: Continued.
indicates that the guidance strategy is increasingly effective in reducing delays and fuel consumption in general with the penetration rate increasing.

7. Conclusion

This paper proposes a platoon speed guidance strategy at signalized intersections in the CV environment to optimize the fuel consumption and delay of the platoon. The strategy includes constant speed guidance, deceleration guidance, acceleration guidance, and stop guidance. At the same time, the calculation method for the optimal speed of the platoon is given, which includes determining the passable period and the maximum number of passing vehicles according to the intersection information, calculating the driving trajectory of the leading vehicle and the following vehicle, respectively, based on different guidance strategies of the platoon, and determining the optimal trajectory of the platoon based on an optimization model of fuel consumption and delay.

Eight scenarios of intersections are designed, and the speed guidance strategy of the platoon is simulated. The results show that the deceleration guidance strategy significantly reduces the total fuel consumption of the platoon, the acceleration guidance strategy significantly reduces the total delay of the platoon, and reducing the headway of the platoon can increase the number of vehicles passing through the intersection and further reduce the platoon delay. Furthermore, the incoming platoon guided by the stop guidance strategy merges into the queued platoon more safely and reduces fuel consumption. The platoon restructure method increased the number of vehicles passing through the intersection in the platoon, significantly reducing delays and avoiding vehicle stops.

In addition, two typical scenarios are selected to simulate the impact of different queue lengths on the platoon speed guidance strategy. The results show that when the queue length affects the passable period, the improvement in fuel consumption, drive time, and delay will decrease as the queue length increases, and even different strategies will be used. Four typical scenarios are selected to simulate the impact of the penetration rate of CVs on the platoon speed guidance strategy. The results show that as the penetration rate increases, the average delay and average fuel consumption of the platoon gradually decrease, and the guidance strategy is generally increasingly effective in reducing the delay and fuel consumption.

This paper studies the speed guidance strategy of Platoons at signalized intersections in the CV environment and verifies the effectiveness of the strategy. However, the proposed strategy is only for a single signalized intersection and does not consider multiple intersections, so that the guidance of the vehicle speed of the platoon may be locally optimal. In addition, this paper only considers the speed guidance of the vehicle and does not combine the signal control. If the two are combined, the effect of the guidance can be further improved.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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