

A Simulation System and Speed Guidance Algorithms for Intersection Traffic Control Using Connected Vehicle Technology

Shuai Liu, Weitong Zhang, Xiaojun Wu, Shuo Feng, Xin Pei*, and Danya Yao

Abstract: In the connected vehicle environment, real-time vehicle-state data can be obtained through vehicle-to-infrastructure communication, and the prediction accuracy of urban traffic conditions can significantly increase. This study uses the C++/Qt programming language and framework to build a simulation platform. A two-way six-lane intersection is set up on the simulation platform. In addition, two speed guidance algorithms based on optimizing the travel time of a single vehicle or multiple vehicles are proposed. The goal of optimization is to minimize the travel time, with common indicators such as average delay of vehicles, average number of stops, and average stop time chosen as indexes of traffic efficiency. When the traffic flow is not saturated, compared with the case of no speed guidance, single-vehicle speed guidance can improve the traffic efficiency by 20%, whereas multi-vehicle speed guidance can improve the traffic efficiency by 50%. When the traffic flow is saturated, the speed guidance algorithms show outstanding performance. The effect of speed guidance gradually enhances with increasing penetration rate, and the most obvious gains are obtained when the penetration rate increases from 10% to 40%. Thus, this study has shown that speed guidance in the connected vehicle environment can significantly improve the traffic efficiency of intersections, and the multi-vehicle speed guidance strategy is more effective than the single-vehicle speed guidance strategy.

Key words: connected vehicle; intersection traffic control; simulation system; speed guidance

1 Introduction

The concept of cooperative driving was first introduced in the early 1990s. A cooperative driving vehicle can control its velocity and trajectory to optimize objectives of traffic efficiency, such as average delay and average stop time. In 2006, Li et al.^[1,2] proposed the concept of “safety driving patterns” to obtain

the allowable movement schedules of all vehicles entering an intersection via traffic lights and vehicle-to-infrastructure (V2I) communication. The connected vehicle technology has become one of the cutting-edge technologies in the field of intelligent transportation today. It is an effective way to improve traffic efficiency, increase road safety, and reduce traffic pollution^[3]. The connected vehicle system has obvious positive effects on improving the efficiency of traffic networks. When vehicles are connected to each other, the drivers’ reaction time and headway between vehicles are shortened, leading to high road occupancy and high road capacity^[4]. Under the connected vehicle environment, the full-time acquisition of vehicle state data can effectively improve the prediction accuracy of urban traffic conditions^[5]. Using real-time V2I communication instead of traditional detectors can improve the timely response ability of the road traffic

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Manuscript received: 2017-05-17; accepted: 2017-06-19

signal controller^[6]. In addition, monitoring the states of platoons can improve the accuracy of the control and coordination of traffic signals^[6].

Researchers have conducted several studies on speed guidance under the connected vehicle environment. Nekoui^[7] explored the issue of road traffic safety via mathematical models and field experiments. They revealed that introducing speed guidance under the connected vehicle environment can effectively relieve the problems of vehicle emergency avoidance and collision avoidance under different conditions. Malakorn and Park^[8] examined a cooperative transportation system, which allows vehicles to accept trajectory instructions from an intelligent traffic signal using the two-phase signal-timing plan, and they found that this system is highly beneficial in terms of mobility and fuel consumption. Abu-Lebdeh^[9] analyzed the feasibility of dynamic speed control and discussed its potential benefits in the field of traffic control.

Yang et al.^[10] studied main rural roads and proposed a speed guidance strategy considering factors such as the location of vehicles, status of signal controls, acceleration and deceleration time of vehicles, and drivers' acceptance. They employed the VISSIM software, a microscopic simulator, to simulate the connected vehicle environment for validating their speed guidance strategy. Chen et al.^[11] used roadside variable message signs as display terminals for speed guidance. Considering the locations of roadside speed guidance equipment and signal timing, they proposed a strategy that combines dynamic speed guidance and dynamic signal control to optimize the arterial coordinated signal control system. He^[12] used real-time traffic data from vehicle-to-vehicle (V2V) and V2I communication to establish a platoon recognition algorithm based on headways. In addition, an optimized signal-control model named platoon-based arterial multi-modal signal control with online data was proposed using mixed integer linear programming for coordination between several arterial intersections^[12]. Lee and Park^[13] proposed a cooperative vehicle control algorithm that minimizes the total length of overlapped trajectories to avoid potential collisions in an intersection. Jackline and Andreas^[14] proposed a close-form solution in a centralized fashion for cooperative-driving vehicles to merge at expressway on-ramps.

Given the limited deployment of Cooperative Vehicle Infrastructure Systems (CVISs), simulation studies are important. Mature commercial traffic simulation software, such as VISSIM, Paramics, and TransModeler, are widely used^[15]. However, they can realize neither V2V or V2I communication, nor real-time intervention of the running status of vehicles.

The smart CVIS of China is named intelligent Vehicle-Infrastructure Cooperation Systems (i-VICS), which is the result of related studies in the last ten years^[16–18]. Given the technical characteristics of i-VICS, the present study has designed an intersection simulation system in the CVIS environment, which realizes V2V and V2I communication and real-time intervention of the running status of vehicles. In addition, two speed guidance algorithms are proposed and tested in the self-developed simulation system.

The remainder of this paper is organized as follows. Section 2 describes the methodologies including the vehicle dynamics description and speed-guidance algorithms. Section 3 introduces the simulation system designed in this research. A simulation-based case study and corresponding results are presented in Section 4. Finally, concluding remarks are presented in Section 5.

2 Methodology

In this section, we use mathematical language to model the intersection traffic control problem in the connected vehicle environment. First, the vehicle dynamics model is provided. Second, the way vehicles move without speed guidance is described. Third, the two speed-guidance algorithms we designed, namely, single-vehicle speed guidance algorithm and multi-vehicle cooperative speed guidance algorithm, are introduced. Finally, the constraints of the system are listed.

2.1 Vehicle dynamics description and assumption

2.1.1 Definition of variables

For the convenience of expression, the main variables to be used are defined in Table 1.

From the above definition, the system state can be expressed as $i\{q, s\}$, with q and s defined as

$$q = \begin{bmatrix} z(1) \\ \vdots \\ z(N) \end{bmatrix}, s = \begin{bmatrix} s(1) \\ \vdots \\ s(N) \end{bmatrix} \quad (1)$$

In the above equations, N is the current total number of vehicles in the system.

Table 1 Definition of main variables.

Variable	Definition
i	System state, including the traffic condition and the controlled variables
q	Traffic condition, including the states of all the vehicles in the current system
r	Functional parameters
s	Controlled variables, including the guided speed and the information of the traffic light (Boolean variable, with 0 representing red light, and 1 representing green light)
z	Vector of the vehicle state, including three dimensions of current speed, location, and waiting time
a	Acceleration (assumed constant, positive when speeding up, and negative when slowing down)
l	Distance from the current position to the stop line
x	Travel time (the time interval between the current moment and the moment leaving the stop line)
v	Guided speed
v_0	Current speed
w	Total waiting time in the waiting area
α	Discount factor
$J(i)$	Real value of the optimization function
$g(\cdot)$	One-step cost function

The vehicle state (vector) z can be expressed as

$$z(n) = \begin{bmatrix} v_0 \\ l \\ w \end{bmatrix}, \quad n = 1, 2, \dots, N \quad (2)$$

The controlled variable s can be denoted as

$$s(n) = [r(n) \quad v(n)], \quad n = 1, 2, \dots, N \quad (3)$$

with

$$r(n) = \begin{cases} 1, & \text{the signal for vehicle } n \text{ is green;} \\ 0, & \text{the signal for vehicle } n \text{ is red} \end{cases} \quad (4)$$

The simple dynamic equation of a vehicle passing the stop line can be expressed as

$$l = \int_0^x (v_0 + at) dt \quad (5)$$

For a constant acceleration $\alpha = \text{const}$, the above equation can be written as follows:

$$l = \frac{1}{2}ax^2 + v_0x \quad (6)$$

Thus, we obtain

$$x = \frac{-v_0 + \sqrt{v_0^2 + 2la}}{a} \quad (7)$$

For a vehicle in the stop state, the travel time x can be calculated through the following equation:

$$x = \frac{-v_0 + \sqrt{v_0^2 + 2la}}{a} + w \quad (8)$$

with $v_0 = 0$.

2.1.2 Basic assumptions

To simplify the research process, the following basic assumptions are made in this research:

(1) The studied region is a single intersection, i.e., the influence of other intersections does not need to be considered.

(2) The length of guiding region is 100 m away from the stop line in every direction.

(3) The signal at the intersection is controlled using fixed-cycle strategies.

(4) The vehicles have changed lanes before entering the controlled region, i.e., the vehicles will not change lanes in the controlled region.

(5) The vehicles with on-board equipment will follow the speed-guidance strategies.

(6) When the vehicles pass the stop line and enter the intersection, they will return to the state of autonomous driving.

2.2 Driving behavior without speed guidance

In the absence of speed guidance, a vehicle's straight driving behavior can be classified into free driving and car following. We define 150 m as the distance of interaction between vehicles, which is similar to that of the VISSIM simulation system. Thus, the two driving behaviors are as follows:

(1) When the distance to the front vehicle is equal to or greater than 150 m, the driver chooses the free driving strategy and tries to reach the maximum speed (defined as 90% of the speed limit of the road) as soon as possible.

(2) When the distance to the front vehicle is less than 150 m, the driver chooses the car following strategy. The commonly used driving psychophysical model, namely, the Wiedemann model^[19], is adopted in this study.

$$a_n(t+T) = \frac{[\Delta v_{n,n-1}(t)]^2}{2[\Delta x_{n,n-1}(t) - S]} + a_{n-1}(t) \quad (9)$$

In the above equation, S represents the expected minimum safe-following distance. According to the regulations on safe distance in regulation on the implementation of the road traffic safety law of the People's Republic of China^[20], the linear correlation model of the minimum safe following distance and the speed of the front vehicle is used:

$$S_n(t) = \lambda v_{n-1}(t) + \beta \quad (10)$$

In the above equation, $\lambda = 0.7 \text{ m}\cdot\text{h}/\text{km}$ is a linear coefficient, and $\beta = 5 \text{ m}$ is the minimum headway when stopped. For instance, when the speed of the

front vehicle is 50 km/h, the minimum safe-following distance of the vehicle behind is 40 m.

2.3 Speed-guidance algorithms

2.3.1 Single-vehicle speed guidance algorithm

Currently, in the driving process, most vehicles cannot acquire the signal control information of the front intersection in real time, and the drivers cannot judge in advance whether they can pass the stop line in the current signal cycle or not. Therefore, the drivers can only rely on experience and driving habits to decide the speed of the vehicle. With the emergence of connected vehicle technology, vehicles can acquire the real-time information of traffic conditions and signal information, thereby allowing vehicle speed adjustment through speed guidance and increasing traffic efficiency. If we choose a vehicle as the object of speed guidance and set its minimum travel time as the optimization objective, the speed guidance process can be described as follows:

(1) When the vehicle enters the guiding region, the signal is green, and there is no vehicle in the queue.

At this time, our goal is to make the vehicle pass the stop line as soon as possible before the green light ends. Thus, the optimize function is

$$f = \min(x - T_g - t_g) \text{ and } f \leq 0 \quad (11)$$

T_g is the moment that the green light is turned on, and t_g is the duration of the green light.

In the absence of a feasible solution (i.e., $f > 0$), this vehicle cannot pass the stop line through speed guidance and has to enter the queue, which can be classified into the next situation.

(2) When the vehicle enters the guided region, the signal is red; or the signal is green, but the queue has not dissipated.

At this time, our goal is to make the vehicle arrive at the intersection when the queue has just dissipated. Thus, the optimize function is

$$f' = \min(x - T_g - e - \frac{d}{s}) \text{ and } f' \geq 0 \quad (12)$$

e is the loss of the first vehicle's boot time, d is the current number of vehicles in the queue, and s is the saturation flow rate of this lane.

By solving the above objective function, we can obtain the speed control strategy to be adopted, that is, the acceleration that should be accepted by the current vehicle.

2.3.2 Multi-vehicle cooperative speed guidance algorithm

According to the above description, the time that each

vehicle needs to pass the stop line can be expressed by mathematical functions. Thus, we can build the optimization function to minimize the total time needed by all vehicles to pass the stop line.

First, the one-step cost function $g(\cdot)$ is defined as follows:

$$g(i_t) = \sum_{n=1}^N x_n(t) \quad (13)$$

Its physical meaning is the difference of total time that all vehicles need to pass the stop line between the two calculation moments.

We can define the cost function $J(\cdot)$ as

$$J(i_t) = \min_{u_t \in U_t} [g(i_t) + \alpha J(i_{t+1})], \quad i \in I \quad (14)$$

In the above equation, α is the discount factor, which can help obtain the best effect as much as possible at the first step of optimization.

The optimization function of this optimization problem is

$$\min_{u_t \in U_t} \sum_{t=0}^{\infty} \alpha^t g(i_t) \quad (15)$$

Similarly, we can obtain the control strategy to be adopted, that is, the acceleration to be accepted by the current guided vehicle.

2.4 Constraints

The constraints of the system are listed as follows:

(1) The time constraint of the "head vehicle" (the first vehicle in the queue) to pass the stop line. After the green signal lights up, the time of the first vehicle behind the stop line to pass the stop line should be equal to or larger than the time that the green signal lights up:

$$x_1 \geq T_g \quad (16)$$

(2) The time constraint between the stop state and the booting process. After the green signal lights up, if the first vehicle behind the stop line is in the stop state, the time it passes the stop line should be equal to or larger than the sum of the time that the green light is turned on (T_g) and the loss of the first car's boot time (e):

$$x_1 \geq T_g + e \quad (17)$$

(3) The time constraint for two consecutive vehicles to pass the stop line. The time for the latter vehicle to pass the stop line should be equal to or larger than the sum of the time of the vehicle before it passes the stop line and the minimum headway (t_s):

$$x_i \geq x_{i-1} + t_s \quad (18)$$

(4) The constraint of optimized speed. The optimized speed calculated by the model should lie between the

low and high thresholds of speed. If the optimized speed is not in this range, the vehicle has to stop and wait:

$$v_{\min} \leq v \leq v_{\max} \tag{19}$$

(5) The constraint of the number of vehicles passing the stop line. The number of vehicles passing the stop line in one signal cycle should be smaller than or equal to the volume under saturated state:

$$\frac{s \cdot n_l \cdot g_e}{3600} \geq N \tag{20}$$

In the above equation, n_l is the number of lanes in the studied direction, and g_e is the effective green time.

3 Simulation System Design

3.1 Framework and design of the simulation system

We use the C++/Qt programming language and framework to build the simulation system. As shown in Fig. 1, the simulation system mainly consists of three modules: the signal control module, user strategy module, and core simulation module.

In the signal control module, an interface that can adjust the signal cycle and the states of the 12 traffic lights in four directions (as shown in Fig. 2) is provided. The signal cycle and each light's state change process can be preset before the simulation runs, thereby providing a traffic signal control plan for the whole simulation process.

In the user strategy module, users can have access to system information such as the location, velocity, and

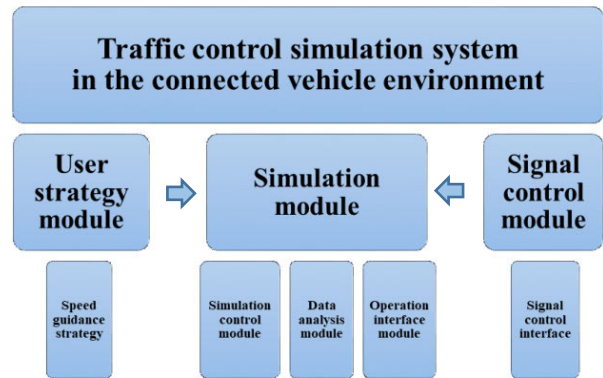


Fig. 1 Framework of the traffic control simulation system under the connected vehicle environment.

acceleration of a vehicle. As long as the control strategy of vehicle acceleration is transmitted to the simulation system, the control of vehicles in the simulation system can be realized.

In the simulation module, a graphical interface of the operation program (Fig. 3) is provided. The current phase of each signal at the intersection and both the number and real-time position of each vehicle are clearly displayed on the interface. The main parameters of the simulation control module can be adjusted on the interface, including the proportion of vehicles that are equipped with on-board equipment, traffic volume at each direction, and simulation speed. The preliminary statistics data provided by the data analysis module are also presented on the interface, e.g., the operation time of the program and the number of vehicles in each lane that have passed the stop line. By contrast, the

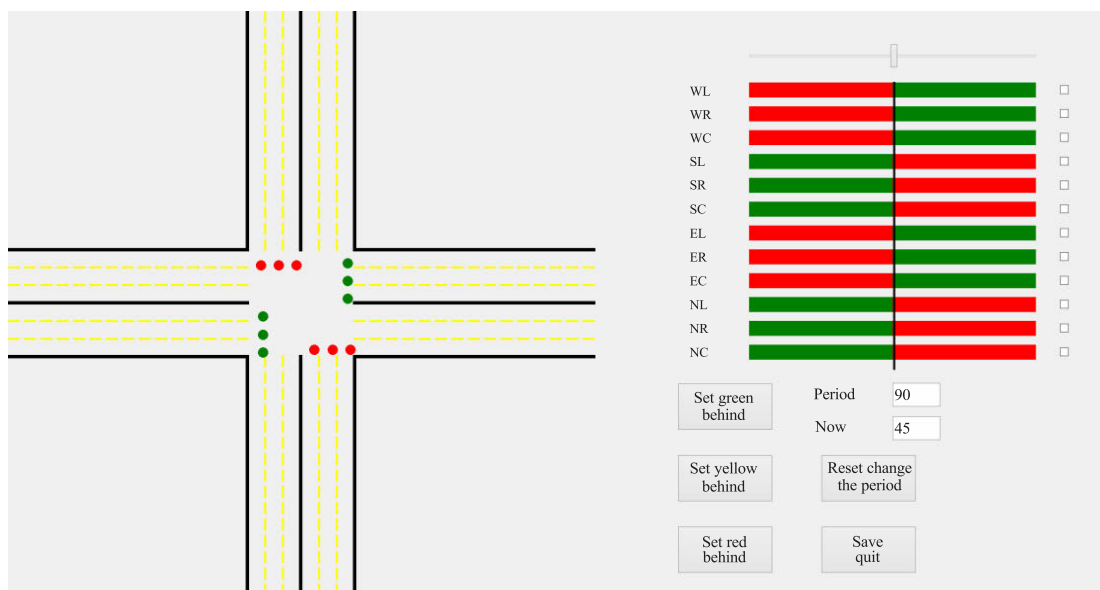


Fig. 2 Signal preset interface of the intersection traffic control simulation system in the connected vehicle environment.

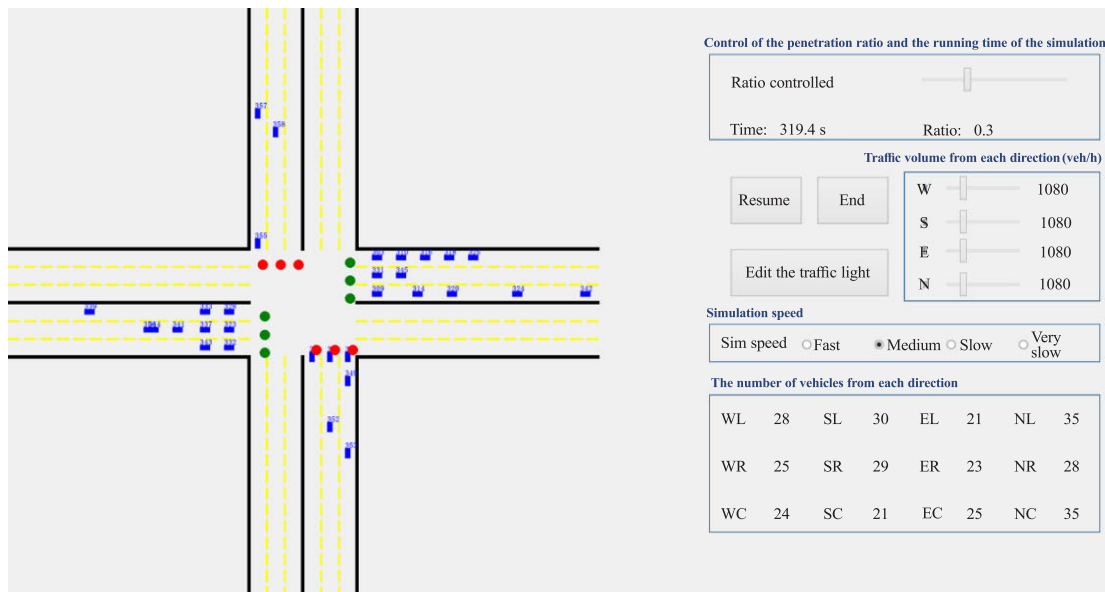


Fig. 3 Operation interface of the intersection traffic control simulation system in the connected vehicle environment.

processed data such as vehicle delay and number of stops are directly exported into Excel files.

The simulation speed is the running speed of the simulation system, i.e., the ratio between the time in the simulation system and the time in real life. Our simulation system involves four simulation speeds: fast, medium, slow, and very slow. When the simulation speed is “fast”, the simulation system’s run speed is 100 times that in the real world. When the system runs for 1 s, a vehicle in the simulation system has already run for 100 s, thus greatly accelerating the speed of the simulation experiment. When the simulation speed is “medium”, the simulation system’s run speed is 10 times that in the real world, which is suitable for a rough observation of the system operation status. “Slow” means that the simulation system has the same running speed as that in the real world, which can truly reflect the vehicles’ running states. “Very slow” means that the running speed in the simulation system is 1/10 of that in the real world, which is helpful for detailed observations of a certain vehicle’s running status. Therefore, the different simulation speeds can meet the needs of varying studies. In addition, the simulation speeds can be interchanged freely in continuous operation, which is convenient.

The simulation system has good expandability. It can increase modules by compile instructions, and provide batch compiles.

3.2 Software interfaces and operation examples

A two-way six-lane intersection is built in this research, whose signal cycle and phase can be adjusted as needed. The setting in Fig. 2 represents a signal phase setting of a 90 s cycle, with each phase having 45 s of green time (green ratio = 50%). In the interface, we use E, W, N, and S to represent east, west, north, and south, respectively, and use L, R, and C to represent the three lanes of left, right, and center, respectively (e.g., WL represents the left-turn lane from west to east).

Before simulation, the traffic volume from each direction and the penetration rate (i.e., the ratio of vehicles that install the speed guidance equipment) can be preset. The simulation speed can be chosen from the interface: fast, medium, slow, and very slow. In addition, the running time and number of vehicles through each direction can be monitored.

Figure 3 shows that the traffic volume from each direction is 1080 vehicles/h, the penetration ratio is 0.3, the simulation speed is “medium”, and the simulation has run for 319.4 s.

4 Experimental Results

A simulation-based case study is conducted using the simulation system introduced above. The results of the simulation experiments are presented in this section. Furthermore, we discuss the differences between the two speed guidance strategies.

4.1 Effect of speed guidance algorithm on traffic efficiency under different traffic volumes

We choose three common measures as indexes of traffic efficiency, namely, average delay of vehicles, average number of stops, and average stop time. To test the effectiveness of the algorithm, the signal cycle is preset to 90 s, with a green ratio of 50% (i.e., each direction has a green time for 45 s), and the traffic volume from each direction is preset to be the same, which ranges from 300 vehicles/h to 2700 vehicles/h (for 300 vehicles/h intervals) so that the traffic saturation states of low, medium, and high can all be covered.

The data measured at an intersection reveal that the queue clearance speed is about 2.5 s per vehicle (i.e., 0.4 vehicles/s) when the light turns green. Therefore, the saturation traffic volume of three lanes is calculated as follows: $3600 \text{ s/h} \div 2 \div 2.5 \text{ s/vehicle} \times 3 = 2160 \text{ vehicles/h}$.

Notably, when the traffic volume is higher than the saturation volume, vehicles would gradually accumulate in line. As a result, the collapse of the system is inevitable. The run time of the simulation experiment is set to 3600 s. The aim is to ensure sufficient time for the system to operate stably and to avoid the collapse of the system. Therefore, in the following experiment results, when the traffic flow is lower than 2160 vehicles/h, the test results will converge to a corresponding numerical test result, whereas the test results will be divergent when the traffic flow is higher than 2160 vehicles/h. We only record the run results within 3600 s.

4.1.1 Analysis of average delay

As stated above, the purpose of speed guidance is to reduce the time to pass the stop line. Therefore, the average delay of vehicles is chosen as the main index to measure the effectiveness of the algorithms. The delay of a vehicle is defined as the actual time it used to pass the stop line minus the virtual time it needs, which is calculated as the distance divided by the initial velocity.

As shown in Table 2, in the case of no speed guidance, the average delay increases slowly with the increase in traffic volume when unsaturated; however, when oversaturated (e.g., traffic volume is 2400 vehicles/h), the average delay increases sharply as most vehicles have to wait for at least one signal cycle before they can pass the stop line (refer to Fig. 4). In the case of single-vehicle speed guidance, when the traffic volume is lower than 2100 vehicles/h, the average

Table 2 Average delay of three speed guidance strategies under different traffic volumes.

Traffic volume (vehicles/h)	Average delay of vehicles (s)		
	Without speed guidance	Single-vehicle speed guidance	Multi-vehicle cooperative speed guidance
300	18.13	14.56	12.60
600	20.08	16.39	14.55
900	21.73	18.07	16.05
1200	24.12	19.85	17.38
1500	25.81	21.21	18.78
1800	28.56	23.60	20.23
2100	34.36	28.13	21.87
2400	106.01	40.17	23.48
2700	210.84	109.58	25.18

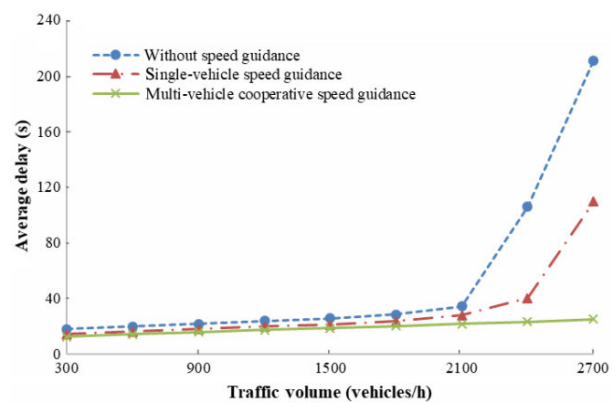


Fig. 4 Comparison of the average delay of three speed guidance strategies under different traffic volumes.

delay is about 80% of that without speed guidance; when the traffic volume is larger than 2400 vehicles/h, the average delay is about 60% or even lower than that without speed guidance; when the traffic volume reaches 2700 vehicles/h, most vehicles also have to wait for at least one signal cycle. In the case of multi-vehicle cooperative speed guidance, the average delay increases steadily, without oversaturation. When the traffic volume is lower than 2100 vehicles/h, the average delay is about 70% of that without speed guidance; when the traffic volume exceeds 2400 vehicles/h, the average delay is only about 20% or even lower than that without speed guidance. Therefore, speed guidance in the connected vehicle environment can significantly reduce the average delay of vehicles. Moreover, multi-vehicle cooperative speed guidance is more effective than single-vehicle speed guidance.

4.1.2 Analysis of average number of stops

The number of stops can directly affect the average delay of vehicles. It can also reflect the traffic efficiency.

Based on the analysis results, we find that the variation pattern of average number of stops under different traffic volumes (as shown in Table 3 and Fig. 5) is similar to the variation pattern of average delay. In the case of no speed guidance, the average number of stops rises with the increase in traffic volume and remains smaller than 1 when the traffic volume is unsaturated; however, when traffic volume reaches 2400 vehicles/h, the average number of stops rises sharply and becomes larger than 1; therefore, saturation occurs. In the case of single-vehicle speed guidance, when the traffic volume is lower than 2100 vehicles/h, the average number of stops is about 70% of that without speed guidance; when the traffic volume is larger than 2400 vehicles/h, the average number of stops is only about 40% or even lower than that without speed guidance. In the case of multi-vehicle cooperative speed guidance, the average number of stops is always 0.2, and it is only about 30% or lower than that without speed guidance.

4.1.3 Analysis of average stop time

The average stop time of vehicles is also a common

measure of traffic efficiency at intersections. As shown in Table 4 and Fig. 6, through speed guidance, the average stop time of vehicles decreases. When the traffic volume is lower than the saturation volume, the optimization effects of single-vehicle speed guidance and multi-vehicle cooperative speed guidance are about 20% and 50%, respectively. When the traffic volume is higher than the saturation volume (e.g., 2400 vehicles/h), the optimization effects of single-vehicle speed guidance and multi-vehicle cooperative speed guidance are about 50% and 90%, respectively.

4.2 Effect of penetration rate on traffic efficiency under different traffic volumes

To understand the value of using information from connected vehicles, simulation tests are conducted by varying the assumed penetration rate between 0 and 100% with 10% intervals. For these tests, the signal cycle is set to 90 s, with a green ratio of 0.5, and the traffic volume from each direction is 2160 vehicles/h. Simulation tests are run to assess the average delay of the two speed guidance strategies under different

Table 3 Average number of stops of three speed guidance strategies under different traffic volumes.

Traffic volume (vehicles/h)	Average number of stops		
	Without speed guidance	Single-vehicle speed guidance	Multi-vehicle cooperative speed guidance
300	0.54	0.35	0.18
600	0.55	0.36	0.19
900	0.56	0.37	0.21
1200	0.58	0.38	0.21
1500	0.57	0.39	0.19
1800	0.58	0.39	0.19
2100	0.63	0.44	0.19
2400	1.49	0.55	0.20
2700	3.00	1.39	0.19

Table 4 Average stop time of three speed guidance strategies under different traffic volumes.

Traffic volume (vehicles/h)	Average stop time (s)		
	Without speed guidance	Single-vehicle speed guidance	Multi-vehicle cooperative speed guidance
300	10.45	8.21	5.80
600	11.17	8.63	5.88
900	11.69	9.12	5.99
1200	12.09	9.75	6.07
1500	12.35	10.17	6.05
1800	13.10	11.02	6.07
2100	15.66	13.14	6.20
2400	54.61	20.49	6.74
2700	122.35	71.22	6.90

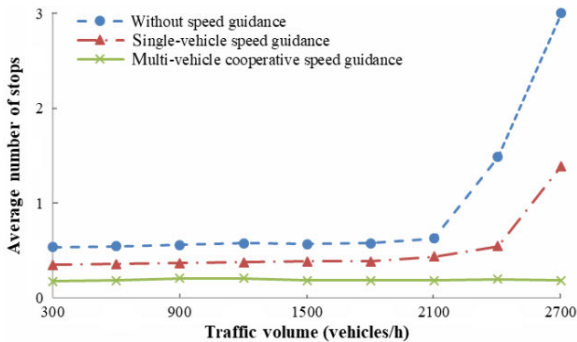


Fig. 5 Comparison of average number of stops of three speed guidance strategies under different traffic volumes.

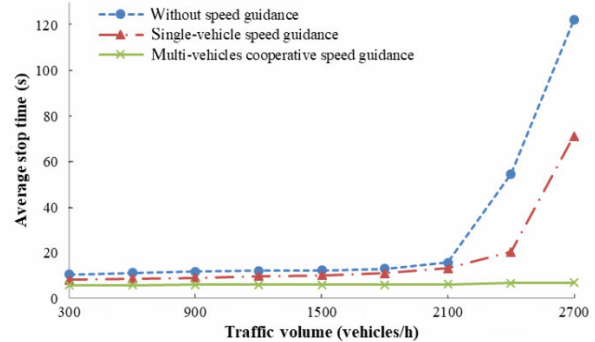


Fig. 6 Comparison of the average stop time of three speed guidance strategies under different traffic volumes.

penetration rates, and the results are shown in Table 5.

The average delay of vehicles resulting from different penetration rates is shown in Fig. 7. For the single-vehicle speed guidance and multi-vehicle cooperative speed guidance algorithms, the average delay of vehicles significantly decreases as the penetration rate increases. However, the marginal benefit obtained from more vehicles using this technology becomes relatively small after a penetration rate of 40% (for both speed guidance strategies). When the technology is in the early stage of development (i.e., when the penetration rate is low), even a few more equipped vehicles can significantly reduce the delays of all the vehicles at an intersection. At these low penetration rates, the information obtained from each vehicle is valuable. However, at high penetration rates, the additional information becomes less valuable. Guler et al.^[21] found similar effects of penetration rate.

4.3 Comparison of two speed guidance strategies

Through the above comparison, we can conclude

Table 5 Average delay of two speed guidance strategies under different penetration rates.

Penetration rate (%)	Average delay of vehicles (s)	
	Single-vehicle speed guidance	Multi-vehicle cooperative speed guidance
0	42.50	42.64
10	39.87	39.83
20	36.01	34.94
30	34.69	31.40
40	32.16	26.39
50	31.46	25.87
60	31.31	24.72
70	31.32	24.39
80	30.28	23.83
90	29.69	23.08
100	28.19	22.60

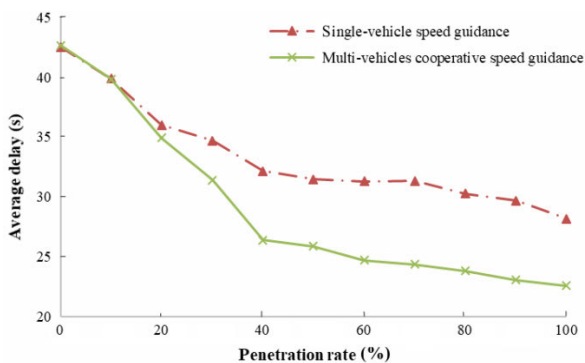


Fig. 7 Effect of penetration rates on average delay (a volume of 2160 vehicles/h per direction).

that speed guidance under the connected vehicle environment can significantly improve the intersection efficiency, and multi-vehicle cooperative speed guidance is more effective than single-vehicle speed guidance.

Further analysis implies that the two speed guidance strategies both reduce the average delay of most vehicles (Fig. 8). As the traffic volume grows, the multi-vehicle cooperative speed guidance can significantly move the overall distribution of vehicle delay to the left (i.e., significantly reduce the delay of most vehicles), thereby significantly lowering the average delay of vehicles at the intersection.

Such a difference is mainly due to the states of other vehicles around being unknown when single-vehicle speed guidance is applied; therefore, the objective of speed guidance might not be realized. For example, if the single-vehicle speed guidance algorithm guides a certain vehicle to run at the speed of 60 km/h to arrive at the intersection before the green light turns to red. However, the car before it runs at a speed lower than 60 km/h, so the speed-guided vehicle has to low down to avoid a collision. This decision might result in the speed-guided vehicle failing to arrive at the intersection before the green light turns to red and having to stop and wait. As for the multi-vehicle cooperative speed guidance algorithm, it optimizes all vehicles' time to pass the stop line, thereby calculating each vehicle's guided speed, and improving both the green time efficiency and traffic efficiency.

5 Conclusion

In this study, we have built an intersection traffic control simulation platform in the connected vehicle

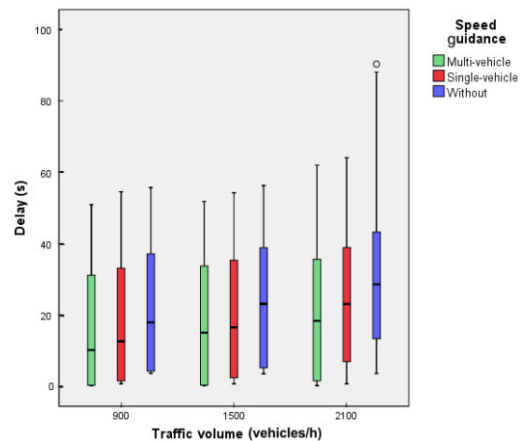


Fig. 8 Box plot of the average delay of three speed guidance strategies.

environment. We propose two speed guidance algorithms by optimizing the travel time of individual and multiple vehicles. The goal of optimization is to minimize the travel time, and common indicators such as average delay of vehicles, average number of stops, and average stop time are chosen as indexes of traffic efficiency in simulation experiments.

Compared with the case of no speed guidance, when the traffic flow is unsaturated (lower than 2160 vehicles/h), the single-vehicle speed guidance algorithm can decrease the average delay by 20%, the number of stops by 30%, and the average stop time by 20%. By contrast, the multi-vehicle speed guidance algorithm can decrease the average delay by 30%, the number of stops by 70%, and the average stop time by 50%. When the traffic flow is saturated (higher than 2160 vehicles/h), the speed guidance algorithms perform outstandingly. Compared with the case of no speed guidance, the single-vehicle speed guidance algorithm can decrease the average delay by 40%, the number of stops by 60%, and the average stop time by 50%; by contrast, the multi-vehicle speed guidance algorithm can decrease the average delay by 80%, the number of stops by 70%, and the average stop time by 90%. The effect of speed guidance gradually enhances with increasing penetration rate, and the most obvious gains are obtained when the penetration rate increases from 10% to 40%. However, when the penetration rate is higher than 60%, a further increase in the penetration rate has minimal benefits on the effect of speed guidance algorithms.

The experimental results indicate that speed guidance in the connected vehicle environment can significantly improve the traffic efficiency of intersections. Moreover, the multi-vehicle speed guidance strategy is more effective than the single-vehicle speed guidance strategy.

In the future, we will introduce vehicle-to-vehicle communication into the simulation system, and realize cooperative driving. In addition, we will optimize the speed guidance algorithms accordingly for improved results.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China (Nos. 61673233 and 71671100).

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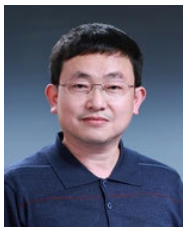
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