

Modeling and simulation of intersection quasi-moving block speed guidance based on connected vehicles

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Abstract

Purpose – This study aims to propose a speed guidance model of the CV environment to alleviate traffic congestion at intersections and improve traffic efficiency. By introducing the theory of moving block section for high-speed train control, a speed guidance model based on the quasi-moving block speed guidance (QMBSG) is proposed to direct platoon including human-driven vehicles and connected vehicles (CV) through the intersection coordinately.

Design/methodology/approach – In this model, the green time of the intersection is divided into multiple block intervals according to the minimal safety headway. Connected vehicles can pass through the intersection by following the block interval using the QMBSG model. The block interval is assigned dynamically according to the traveling relation of HV and CV, when entering the communication range of the intersection. To validate the comprehensive guidance effect of the proposed model, a general evaluation function (GEF) is established. Compared to CVs without speed guidance, the simulation results show that the GEF of QMBSG model has an obvious improvement.

Findings – Compared to CVs without speed guidance, the simulation results show that the GEF of QMBSG model has an obvious improvement. Also, compared to the single intersection speed guidance model, the GEF value of the QMBSG model improves over 17.1%. To further explore the guidance effect, the impact of sensitivity factors of the CVs' environment, such as intersection environment, communication range and penetration rate (PR) is analyzed. When the PR reaches 75.0%, the GEF value will change suddenly and the model guidance effect will be significantly improved. This paper also analyzes the impact of the length of block interval under different PR and traffic demands. It is found that the proposed model has a better guidance effect when the length of the block section is 2 s, which facilitates traffic congestion alleviation of the intersection in practice.

Originality/value – Based on the aforementioned discussion, the contributions of this paper are three-fold. Based on the traveling information of HV/CV and the signal phase and timing plans, the QMBSG model is proposed to direct platoon consisting of HV and CV through the intersection coordinately, by following the block interval assigned dynamically. Considering comprehensively the indexes of mobility, safety and environment, a GEF is provided to evaluate the guidance effect of vehicles through the intersection. Sensitivity analysis is carried out on the QMBSG model. The key communication and traffic parameters of the CV environment are analyzed, such as path attenuation, PR, etc. Finally, the effect of the length of block interval is explored.

Keywords Simulation analysis, Block interval, Connected vehicle, Quasi-moving block, Speed guidance

Paper type Research paper

1. Introduction

Intersection is an influx and distribution node of traffic flow in urban road networks. The mismatch between the signal phase and timing (SPaT) plans and the approaching flow is one of the most important factors that cause urban traffic congestion. Congestion alleviation at intersections is crucial to the

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improvement of mobility, safety and environment of urban road networks. To alleviate the congestion at the intersections, many studies have been carried out by scholars. The main solutions for congestion alleviation at intersections are off-line fixed signal timing and the actuated or adaptive signals timing method (Wong *et al.*, 2010; Xuan *et al.*, 2011; Papageorgiou *et al.*, 2004). The major disadvantage of the solutions abovementioned is the assumption of vehicles passing through the intersection on a constant speed. In actual situations, the algorithm often causes the low traveling efficiency at intersections because of the dynamic speed variability of the vehicles approaching the intersection.

With the development of the connected vehicles (CV) technology, it has become a novel method to alleviate the congestion at intersections. The CV technology provides a coordinated mechanism to realize information sharing between vehicles and road-side units (RSU) in complex intersection environment (Barth *et al.*, 2011; Yu *et al.*, 2019; Stevanovic *et al.*, 2015). Using the information of the SPaT plans, an advisory speed is presented to direct the vehicles approaching the intersection through the intersection, which can alleviate the congestion at intersections. Scholars at home and abroad have conducted extensive research on the application of the CV technology in traffic congestion alleviation at intersections.

One of applications of the CV technology in intersection congestion alleviation is to guide the approaching vehicles to pass through the intersection by the speed guidance model. However, most of the speed guidance models under the condition of CV focus on the traveling efficiency of the vehicles passing through the intersection and failed to consider comprehensively the balance between mobility and safety. Based on the high-speed train operation state, the moving block section theory can consider comprehensively the brake distance and the track density of high-speed train to ensure the safety and mobility of the whole operation. Therefore, this paper proposes a quasi-moving block speed guidance (QMBSG) model by introducing the block section theory.

The remainder of this paper is organized as follows: in Section 2, a literature review of the current research on speed guidance at intersections is carried out. Sections 3 and 4 introduce the QMBSG model and the general evaluation function (GEF), respectively. To verify the actual effect of the model, Section 5 describes a case study that has been performed using the proposed model. The data of the simulation results are analyzed, and the impact of the intersection environment, communication range, penetration rate (*PR*), initial space headway and the block interval on the guidance effect is explored. Section 6 presents the conclusions and scopes for future research.

2. Related work

For urban complex traffic, congestion alleviation at intersections can significantly improve the operation efficiency of the road network. By sharing the SPaT plans and the vehicle's traveling state, the mobility and safety of vehicles passing through an intersection can be significantly improved. Therefore, a considerable amount of research has been conducted on the congestion alleviation at intersections. The current research has three aspects:

- 1 macroscopic dynamic speed control under the traditional environment (T-MDSC);
- 2 microcosmic dynamic speed control under the environment of CV (CV-MDSC); and
- 3 microcosmic dynamic speed guidance under the environment of CV (CV-MDSG).

The earliest application of the T-MDSC is based on the off-line fixed signal timing based on the historical data. Subsequently, the T-MDSC studies based on the actuated or adaptive signals timing method are conducted (Wong *et al.*, 2010; Xuan *et al.*, 2011; Papageorgiou *et al.*, 2004). These methods are used to determine the SPaT plans using the real-time traffic data measured by various traffic detectors. The traditional dynamic speed control is mostly based on the assumption of a constant speed of vehicles entering the intersection. In practical situations, these models often lead to low traffic efficiency and even fail to control the SPaT plans because of the dynamic fluctuation in speed.

In recent years, CV technology has enabled the integration of real-time traveling information of vehicles into intersection control and realized the CV-MDSC. According to the real-time traffic data, Abu-Lebdeh *et al.* optimize the signal control parameters periodically, which could effectively improve the traffic flow. The control center sets an optimal speed for the road section in the control period and updates the optimal speed at the end of control period (Abu-Lebdeh, 2002). Later, Abu-Lebdeh and Chen, (2010) take the speed as a control variable and optimize the dynamic network by establishing a dynamic speed control system to realize the optimization target at different speeds. Wang *et al.* (2011) and Yang *et al.* (2010) establish the variable speed control model, respectively, based on the traveling information of vehicles obtained in the CV environment. The simulation shows that the models can effectively improve the traffic situation. Based on the real-time speed and dynamic information of the SPaT plans, Chen *et al.* (2011) propose a trunk-signal-coordinated control model and dynamically limit the speed of vehicles traveling on road sections. The experiment shows that both the vehicle's delay and parking time are improved effectively. These abovementioned studies have significantly improved the efficiency at intersections. However, the studies have realized the low-level coordination of CV system and intersection control system and the characteristics of real-time information cannot be fully excavated.

Scholars have also used the vehicle traveling data and the SPaT plans at intersection to design the speed guidance strategy and realize the high-level coordination of the CV system and the intersection control system, which is called the CV-MDSG. Li *et al.* (2012) establish a speed guidance model for a single vehicle to minimize the stop time in a CV environment. The simulation result shows that the proposed model can effectively improve the delay and stop time. Li *et al.* (2013) design a multi-vehicle collaborative speed guidance model based on the single-vehicle speed guidance. The simulation results show that the multi-vehicle collaborative guidance model has better adaptability than the single-vehicle model and the improvement of stop times and parking time is better. He (2010) proposes a mixed-integer linear program for optimizing the SPaT plans and designs a unified platoon-based mathematical function suitable for various traffic

modes to minimize speed delay based on real-time platform data and current traffic control status. Yang *et al.* (2010) propose bidirectional communication speed guidance strategy based on the vehicle's space-time trajectory and parameters of the SPaT plans. This strategy could effectively reduce the number of stops and delay times at intersection. Cai *et al.* (2014) puts forward a coordinated optimization control method based on speed guidance and information interaction at uncontrolled intersection, which can reduce the average delay, stop times and queue length of the intersection. Lily and Ranka (2017) establish a headway minimization model and the CV could maintain a more stable headway with the vehicle ahead. The aforementioned studies alleviate the traffic congestion at intersection by the integration the traveling information of vehicles and the information of SPaT plans. However, these studies emphasize more on the efficiency of the intersections and do not consider comprehensively the impact of the passing vehicles. To contribute to this field, some scholars analyze the performance of speed guidance model from a more comprehensive perspective using the numerical simulations of MATLAB/VISSIM (Lee, 2008; Chen *et al.*, 2014; Zhang *et al.*, 2015). Zhou *et al.* (2015) put forward a parsimonious shooting heuristic algorithm through controlling trajectories of a platoon of vehicles. The proposed algorithm can find a feasible solution to the original complex multi-trajectory control problem under certain mild conditions, but this algorithm cannot fully explore the guidance impact of path attenuation, signal masking and other parameters of the CV environment. Zhou *et al.* (2020) propose a reinforcement-learning-based car following model for connected and automated vehicles to obtain an appropriate driving behavior to improve travel efficiency, fuel consumption and safety at signalized intersections in real time. This study reveals a great potential of emerging reinforcement learning technologies in transport research and applications.

Although the speed guidance model of the CV environment significantly alleviates traffic congestion at intersections and improves traffic efficiency, the research still contains the following three deficiencies:

- 1 The study focuses on the efficiency of vehicles passing through an intersection and does not fully take into account the comprehensive guidance effect such as mobility, safety and environment.
- 2 The research on the coordinated control of multi-vehicle cooperative guidance strategy and signal timing system at intersections is relatively inadequate and the research on multi-vehicle coordinated control under the constraint of the SPaT plans is not comprehensive.
- 3 Although some scholars have used VISSIM and other software to simulate the speed guidance strategy of a CV environment and introduced the impact factor of PR, these test methods cannot consider the path attenuation, signal masking and other key parameters on the speed of the guidance effect.

In view of limitation, this paper proposes the QMBSG model to direct multi-vehicle platoon through the intersection coordinately by following the block interval assigned dynamically. Meanwhile, the paper designs the GEF to conduct a comprehensive evaluation of the model and studies

the influence factors such as the intersection environment, communication range, equipment PR and the block interval.

3. Algorithm description

The algorithm description consists of three aspects: the principle of the quasi-moving block (QMB) theory is introduced in *A* and the speed guidance model based on the QMB theory is also derived. Then, the guidance strategies of the QMBSG model are described in *B*. At last, a calculation method for determining the suggested speed value is presented in *C*.

3.1 Principle of quasi-moving block theory

The traditional fixed block theory divides a station section into several block sections L_{block} . Each block section only allows one train to run at a given time. The leading train and the following train are separated by a certain number of block sections, such that multiple trains in the same direction can be tracked at a distance of L_{FBS} at the same station section, as shown in Figure 1.

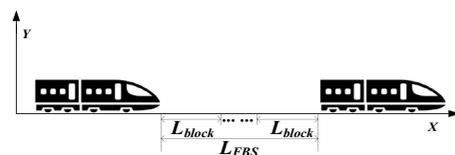
Using the real-time position of the train, the QMB theory is proposed based on the fixed-block theory. The track process and operation principle of the QMB theory are shown in Figure 2. The minimum track section L_{QMB} is composed of the driver response distance L_{action} , the braking distance L_{brake} and the safety distance L_{safe} . Two trains run at the minimum tracking interval L_{QMB} .

The key problem of the QMB theory is the determination of block section. The block section varies in real time according to the position and speed of the leading train and the following train. The QMB theory obtains the minimum block section L_{QMB} between two trains based on the real-time running information of the trains, which ensures the safety and mobility of the trains. In the CV environment, the RSU can obtain the real-time position and speed of the CV in guidance range. Therefore, the QMB theory can be applied to the intersection speed guidance

As shown in Figure 2, the minimum block section L_{QMB} can be converted to the minimum space headway L_{AB} of vehicles. Because of the difference of speed guidance at intersection, three issues need to be considered:

- 1 Vehicles passing through the intersection are not only affected by the leading vehicle but also influenced by the SPaT plans.
- 2 A large-scale computing workload will affect the update interval of the suggested speed considering the real-time variation of headway L_{AB} for entering the intersection, especially for a large traffic flow.
- 3 The space headway L_{AB} will dynamically spread to the downstream owing to the speed fluctuation in the upstream vehicles, which affects the updating interval of the suggested speed of all subsequent vehicles.

Figure 1 Fixed-block theory



The frequent update of the suggested speed is adverse to the safety and efficiency of flow. Therefore, the minimum block section L_{QMB} is replaced by the corresponding time. Herein, the minimum space headway L_{AB} is translated to the minimum safety time headway T_{AB} , which is the block interval. Subsequently, the green-light time is divided into n block intervals with the length of T_{AB} and the vehicle can reach the intersection at assigned block interval through the proposed model. Thus, a QMBSG model for intersection based on block interval is proposed by the reference of QMB theory.

3.2 Description of guidance strategy

The QMBSG model follows three assumptions:

- The QMBSG model is applied to a single intersection.
- The signal light at intersection is the fix-timing control.
- The pedestrians and non-motorized vehicles are not considered.
- The yellow light time is short and vehicle usually decelerates and stops when the driver encounters the yellow light. Therefore, the yellow light time and the red light time are combined.

The guidance strategy consists of two steps: the acquisition of the vehicle traveling state and the implementation of the QMBSG model.

1 Acquisition of the state parameters

The step provides the data for the calculation of the suggested speed. The QMBSG model requires two kinds of traffic state parameters, including static and dynamic parameters, as shown in Table 1.

2 Implementation of the QMBSG model

After obtaining the state parameters, the vehicular on-board unit (OBU) adopts the speed guidance strategy to direct vehicle passing through the intersection according to the vehicle's traveling states. Based on the obtained vehicle's traveling state, the diagram of QMBSG model is shown in Figure 3.

3 The implementation process of the QMBSG model is:

- When vehicle entering the guidance range of the intersection determined by communication distance, the RSU judges whether the vehicle approaching the intersection is a CV. For a CV, whether receiving the

speed guidance is determined to avoid the receiving of guidance information repeatedly.

- At the same time, the OBU receives the information of the SPaT plans, the block interval, the traveling state of the leading vehicle and the distance to the stop line.
- The QMBSG model judges whether the first vehicle can arrival the stop line at speed limit during the green-light time. If yes, the time t_t^1 of the first vehicle arriving the stop line is the starting point T_0 of the block interval; otherwise, the first vehicle is guided to arrival the stop line at the beginning of the green light of the next cycle and the time t_t^1 is taken as the starting point T_0 .
- The QMBSG model takes the time T_0 as the starting point and the green-light time in subsequent signal cycle is divided into n block intervals by the length of minimum safety time headway T_{AB} . The end time for block interval j ($j = 1, 2, \dots, n$) is:

$$T_j = T_0 + j \times t_{AB} \quad (1)$$

- For vehicle i , $[T_j, T_j + t_{AB}]$ is the block interval for passing through the intersection. The QMBSG model determines whether the vehicle can pass through the intersection at the speed range $[V_{min}, V_{max}]$. If the speed interval satisfies the requirements, the process goes to Step (7). Otherwise, the next block interval is selected as the alternative to continue the judgment of the suggested speed.
- For vehicle i , if all the subsequent block intervals in this signal cycle cannot meet the requirements, the block interval assigned to vehicle i is set as the first block section in the next signal cycle and the process returns to Step (5) to continue the judgment.
- If the vehicle i in block section $[T_j, T_j + t_{AB}]$ satisfies the speed range, the block interval of vehicle i is checked with the block interval of vehicle $i + 1$. If they are the same, the block interval of vehicle $i + 1$ is shifted backward to $[T_j + t_{AB}, T_j + 2t_{AB}]$, which avoids multiple vehicles to be assigned to the same block interval.

3.3 Calculation of suggested speed

The calculation of the advisory speed considers three driving stages:

- 1 When the driver receives the advisory speed information, a reaction time t_d occurs, then the vehicle continues to travel at the initial speed.
- 2 Vehicle i accelerates or decelerates from the initial speed v_0^i to the advisory speed v_{sug}^i .
- 3 the vehicle passes through the intersection at the advisory speed v_{sug}^i .

- The distance S_1 shows that the vehicle travels at the initial speed:

$$S_1 = v_0^i \cdot t_d \quad (2)$$

- The distance S_2 shows that the vehicle accelerates or decelerates to the advisory speed during the Stage 2:

Figure 2 Track process of QMB theory in speed guidance model

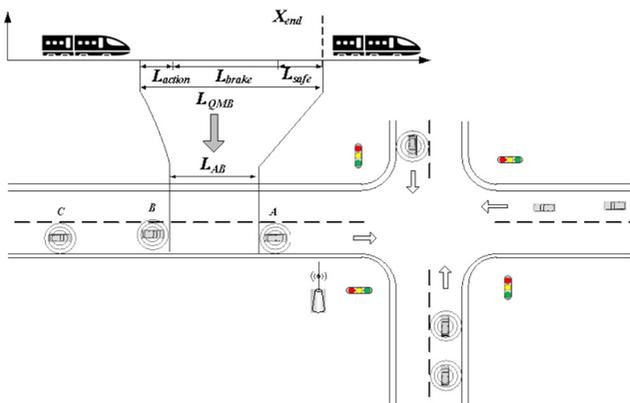
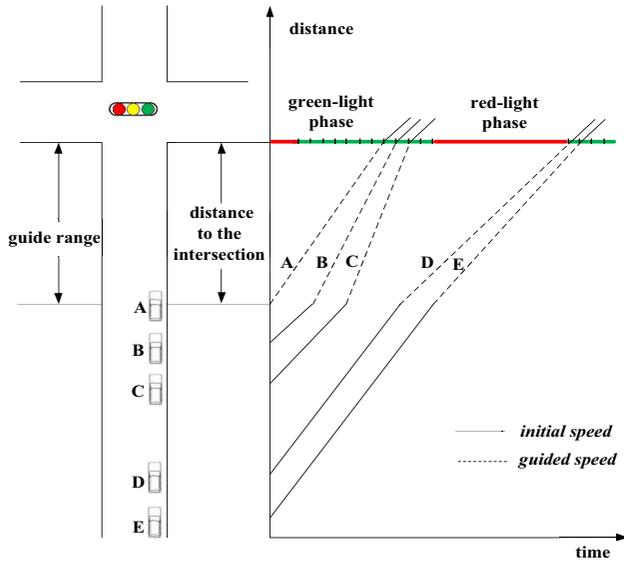


Table 1 Static and dynamic traffic state parameters

Types	Symbols	Description
Static traffic state parameters	t_d	The driver's reaction time to guide decisions
	g	The length of green time
	r	The total length of red and yellow times
	T_{AB}	The minimum safety time headway
	v_{\max}	Maximum speed limit
Dynamic traffic state parameters	v_{\min}	Minimum speed limit
	t_0^i	The moment when vehicle i enters the guidance range
	t_t^i	The moment when vehicle i reaches the stop line
	v_0^i	The speed when vehicle i enters the guidance range
	v_{sug}^i	The suggested speed calculated by the QMBSG model
	d^i	Distance between vehicle i and stop line
	c^i	The guidance number of vehicle i
	a	Vehicle acceleration (including acceleration and deceleration)
	$[T_0, T_1]$	Block section assigned to vehicle 1
	T_0	Starting point of the first block section
	$[T_j, T_j + t_{AB}]$	Block section assigned to vehicle i

Figure 3 Diagram of guidance strategy of the QMBSG model



$$S_2 = \frac{v_{sug}^i{}^2 - v_0^i{}^2}{2a} \quad (3)$$

The elapsed time t_2 is calculated in Stage 2:

$$v_{sug}^i = v_0^i + at_2 \quad (4)$$

- The elapsed time t_3 is calculated in Stage 3:

$$d^i - S_1 - S_2 = v_{sug}^i \cdot t_3 \quad (5)$$

- The moment t_t^i shows that the vehicle reaches the stop line:

$$t_t^i = t_0^i + t_d + \left| \frac{v_{sug}^i - v_0^i}{a} \right| + \frac{d^i - v_0^i t_d - \left| \frac{v_{sug}^i{}^2 - v_0^i{}^2}{2a} \right|}{v_{sug}^i} \quad (6)$$

According to equation (6), the advisory speed under the acceleration strategy is:

$$v_{sug}^i = \left[v_0^i + a(t_e^i - t_d) \right] - \sqrt{a^2(t_e^i - t_d)^2 + 2av_0^i(t_e^i - t_d) - 2a(d^i - v_0^i t_d)} \quad (7)$$

The advisory speed under the deceleration strategy is:

$$v_{sug}^i = \left[v_0^i - a(t_e^i - t_d) \right] + \sqrt{a^2(t_e^i - t_d)^2 - 2av_0^i(t_e^i - t_d) + 2a(d^i - v_0^i t_d)} \quad (8)$$

where $t_e^i = t_t^i - t_0^i$, t_0^i is the time to arrive the guidance range for vehicle i .

The overall logical flow chart of the QMBSG model is shown in Figure 4.

4. Model evaluation

4.1 Framework of the general evaluation function

To assess the impact of the QMBSG model on mobility, safety and environmental benefits, the GEF for speed guidance models is established by combining six evaluation indexes. The architecture of the GEF is shown in Figure 5.

1 Environmental evaluation function (EEF)

The EEF is evaluated by analyzing the total emissions of HC, CO and NO_x at intersection. The CO, HC and NO_x emissions model proposed by Zhang *et al.* (2015) is used and the relationship between the three pollutants and the speed is shown in Table 2.

According to the abovementioned model, the pollutant emissions of the vehicles can be calculated every 0.1 s and the total pollutant emissions can be obtained. The EEF is as follows:

Figure 4 Overall logical flow chart of the QMBSG model

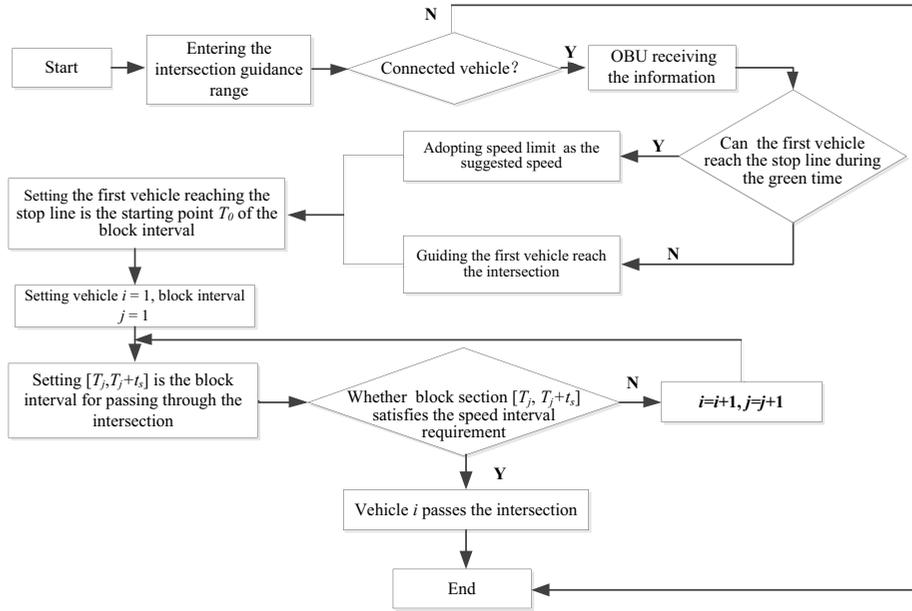
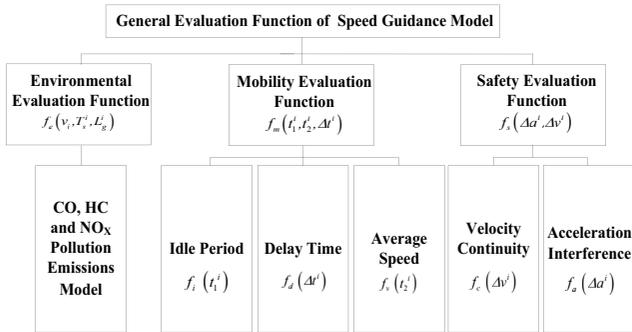


Figure 5 Architecture of the general evaluation function



$$f_e(v^i, T_s^i, L_g^i) = \frac{1}{3600} \sum_{k=1}^m T_s^i \times E_{Ik} + \frac{1}{1000} \sum_{t=0}^T \sum_{k=1}^m L_g^i \times E_k \quad (9)$$

where T_s^i denotes the total idle time of vehicle i passing through the intersection, E_{Ik} denotes the idle emission factor of the pollutant k , L_g^i denotes the traveling distance of vehicle i within the recorded time, E_k denotes the driving emission factor of the pollutant k , T denotes the travel time crossing the intersection excluding idle time and k denotes the type of pollutant.

2 Mobility evaluation function (MEF):

- Idle period (IP) $f_i(t_1^i)$

The IP refers to the sum of the time that the speed is zero because of congestion and signal control, when the vehicle runs at the intersection:

$$f_i(t) = \sum t_1^i \quad (10)$$

where t_1^i denotes the time of parking vehicle i in the intersection range.

3 Average speed (AS) $f_v(t_2^i)$:

$$f_v(t_2^i) = \frac{L}{t_2^i} \quad (11)$$

where L denotes the length of the intersection range and t_2^i denotes the time that vehicle i passes through the intersection range.

4 Delay time (DT) $f_d(\Delta t^i)$

The DT refers to the range of the DT within 100 m upstream and downstream of the intersection in the CV environment:

$$f_d(\Delta t^i) = \Delta t^i - t_f = (t_B^i - t_A^i) - t_f \quad (12)$$

where t_f denotes the travel time of vehicle passing through the intersection range in the free flow state; t_B^i denotes the moment when vehicle i leaves Point B, which is 100 m downstream of the intersection; t_A^i denotes the moment when vehicle i leaves Point A, which is 100 m upstream of the intersection.

Therefore, the MEF expression is as follows:

$$f_m(t_1^i, t_2^i, \Delta v^i) = \omega_{f_i^*}(t_1^i) - \omega_{f_v^*}(t_2^i) + \omega_{f_d^*}(\Delta t^i) \quad (13)$$

where $f_i^*(t_1^i)$, $f_v^*(t_2^i)$ and $f_d^*(\Delta t^i)$ denote the normalized results of the IP, AS and DT, respectively; and ω_b , ω_v and ω_d denote the corresponding weights, respectively.

5 Safety evaluation function (SEF)

- Acceleration interference (AI) $f_a(\Delta a^i)$

The purpose of AI is to evaluate the frequency of acceleration and deceleration during vehicle running, which reflects the traffic safety. According to the works by Zhou et al. (2008), the AI expression is:

$$f_a(\Delta a^i) = \sqrt{\frac{1}{T} \int_0^T (\Delta a^i)^2 dt} = \sqrt{\frac{1}{T} \int_0^T (a_t^i - \bar{a})^2 dt}$$

$$= \sqrt{\frac{1}{T} \sum_{t=0}^T (a_t^i - \bar{a})^2} \quad (14)$$

where, T denotes the total travel time of the vehicle in the intersection range, t denotes the unit recording time, a_t^i denotes the vehicle acceleration at time t and \bar{a} denotes the average acceleration.

- Velocity continuity (VC) $f_c(\Delta v^i)$

The VC refers to the difference in the running speed of the vehicle passing through the intersection. According to the works by Lin (2016), the VC expression is:

$$f_c(\Delta v^i) = |\Delta v^i| = |v_n^i - v_{n-1}^i| \quad (15)$$

where, v_n^i denotes the vehicle speed at the n road section and v_{n-1}^i denotes the vehicle speed at the $n-1$ road section.

Therefore, the SEF expression is:

$$f_s(\Delta a^i, \Delta v^i) = \omega_c f_c^*(\Delta v^i) + \omega_a f_a^*(\Delta a^i) \quad (16)$$

where, $f_c^*(\Delta v^i)$ and $f_a^*(\Delta a^i)$ denote the normalized results of the VC and AI, respectively, and ω_c and ω_a denote the corresponding weights, respectively.

4.2 Formulation of the general evaluation function

By combining three evaluation functions, the GEF is shown by the following equation:

$$f_{syn} = \alpha f_e(v^i, T_s^i, L_g^i) + \beta f_m(t_1^i, t_2^i, \Delta t^i) + \gamma f_s(\Delta a^i, \Delta v^i) \quad (17)$$

where $f_e(v^i, T_s^i, L_g^i)$, $f_m(t_1^i, t_2^i, \Delta t^i)$ and $f_s(\Delta a^i, \Delta v^i)$ denote the EEF, MEF and SEF, respectively. α , β and γ denote the weights assigned to each evaluation function, respectively.

The GEF should meet the following constraints:

- The time interval between vehicles must be longer than the minimum headway.

$$T_i \geq T_{i-1} + t_s \quad (18)$$

- The suggested speed must be within the speed limit.

$$v_{min} \leq v_{sug}^i \leq v_{max} \quad (19)$$

- The acceleration must be within a reasonable acceleration range.

$$a_{min} \leq a^i \leq a_{max} \quad (20)$$

5. Case study

The proposed model is validated using the ESTINET simulation software. In this paper, the intersection of the Dongsu West–Dongsu North Street in Beijing is chosen to establish the simulation environment of road network, which is a fixed-timing control intersection. The overall road network topology is as shown in Figure 6.

In simulation, the basic traffic elements include a signal light, connected vehicles and an RSU, as shown in Figure 6. When the simulation begins, 100 vehicles including HA and CV travel according to the speed distribution curve assigned in the Estinet software. The simulation parameters and scenarios are shown in Table 3. The flow diagram is shown in Figure 7. In the simulation, the vehicles' information of position and speed is collected at intervals of 0.1 s.

5.1 Result analysis

The simulation uses the two-way ground path-loss model and the Rayleigh signal attenuation model to establish the urban environment to validate the QMBSG model. The simulation parameters, such as fading factor, path loss factor, building spacing and building height, in ESTINET software are set according to the works by Xiong (2016). For the scenarios PR of 100% and PR of 0%, the GEF of 100 CV is shown in Figure 8.

Figure 8 shows that the QMBSG model can effectively improve the overall performance of the vehicles passing through the intersection. Compared to the scenario PR of 0%, the GEF of the QMBSG model obviously improved and the variation of GEF is more stable than that of the scenario PR of 100%. The reason is that the proposed QMBSG model takes into account the collaboration guidance among HA and CV. To achieve the overall optimization, speed guidance is applied to these vehicles, resulting in a slightly higher GEF value.

This paper also uses the free-space path-loss model and the Ricean signal-attenuation model to simulate the rural intersection environment. The GEF of the connected vehicles in rural environment is shown in Figure 9. The results show that the QMBSG model also has good effects in rural intersection.

The quantitative difference of the guidance effect of the QMBSG model between two intersections is shown in Table 4. Table 4 shows that the GEF value of the QMBSG model in the urban intersection environment is greater improvement and the fluctuation is more stable. This is because those vehicles in the urban intersection tend to drive at lower speeds and can therefore adjust to the suggested speed in less time and with lesser range.

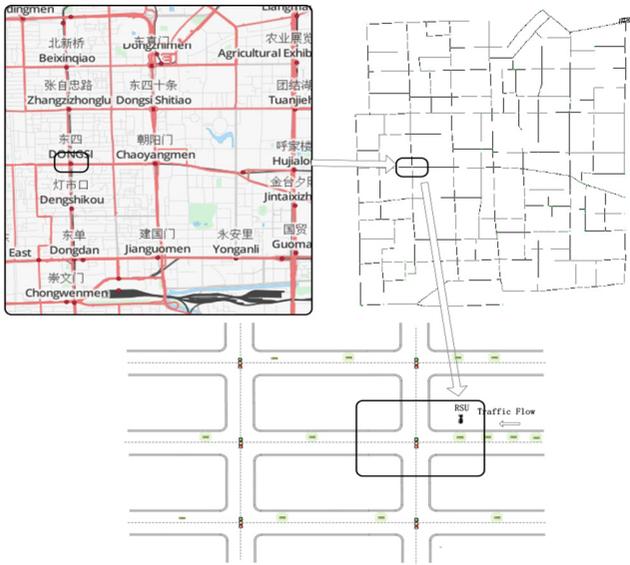
5.2 Performance comparison

To further evaluate the advantages of the QMBSG model in speed guidance, the single-intersection speed-guidance (SISG)

Table 2 Pollutants–speed relationship

Pollutants	Idle emission factor(g/[veh-h])	Relationship between driving emission factor E_i and vehicle speed V (g/[veh-km])
HC	18.83	$E_1 = 0.0011V^2 - 0.14V + 5.84$
CO	105.03	$E_2 = 0.0064V^2 - 0.63V + 29.72$
NO _x	9.57	$E_3 = 0.0006V^2 - 0.06V + 2.84$

Figure 6 Road network topology of simulated case



model under the CV environment proposed by Lv (2017) is selected as a comparative study using the same road network topology and simulation parameters.

In CV environment, the communication range between the RSU and the OBU is determined by the transmission power of the RSU, which affects the guidance effect of the model to a great extent. Therefore, for the urban intersection PR of 100%, simulation experiments are carried out according to five types of transmission power. The comparison result of two speed-guidance models is as shown in Figure 10. The *GEF*, *SEF*, *MEF* and *EEF* are used to obtain the mean of the corresponding function values for all connected vehicles.

Figure 10 shows that two speed-guidance models can significantly reduce the mean of the *GEF* and the *GEF* values of two models also show a downward trend as the increase of transmission power. Furthermore, the effect of speed guidance in intersection has a better improvement for a higher transmission power. This is because the larger transmission power can obtain a larger communication range, so the vehicle can receive speed guidance earlier. Also, when the transmission power is 12 dbm corresponding to the communication distance of approximately 218 m, the *GEF* will produce a mutation and the guidance effect of two models will be significantly improved.

To explore the specific reasons on the decline of the *GEF*, the quantitative comparison of the two models for the transmission power of 13 is shown in Table 5.

Figure 7 Simulation flow diagram

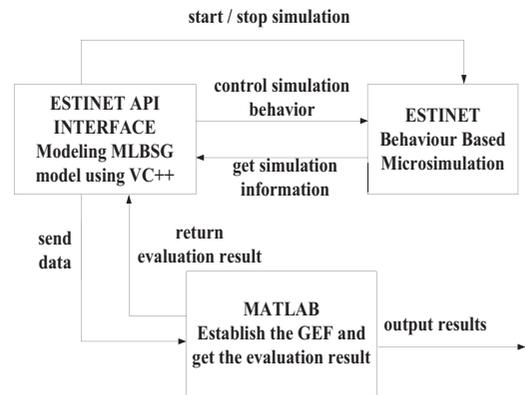


Figure 8 *GEF* of connected vehicles in the urban intersection

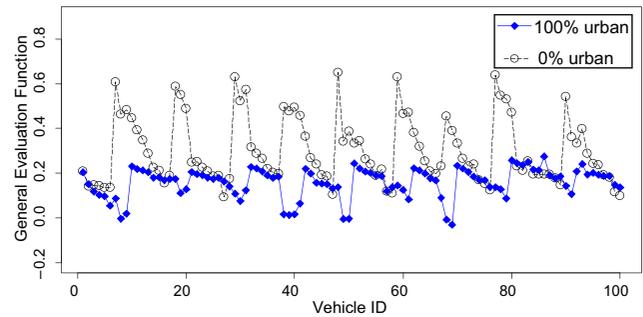


Figure 9 *GEF* of connected vehicles in rural intersection

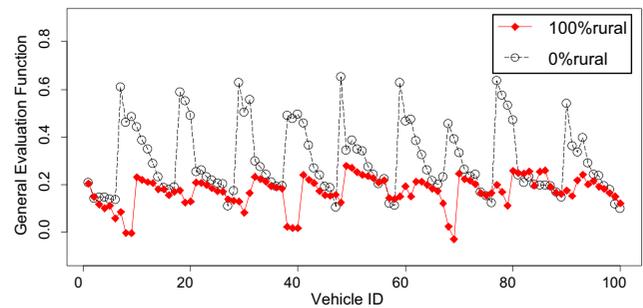


Table 3 Simulation experiment parameters and simulation scenarios

Simulation time (s)	1,000/1,200	Green-light time (s)	27
Number of vehicles	100	red-light time green time (s)	33
Maximum/minimum speed (m/s)	18/0	road network size (m)	3,000 × 2,000
Maximum acceleration (m/s ²)	2.5	number of lanes	2
Maximum deceleration (m/s ²)	4	initial space headway (m)	100/150
Minimum safety headway (s)	2	intersection environment	urban/rural
Driver's reaction time (s)	1	RSU transmitted power (db)	9, 10, 11, 12, 13
$\omega_{ii}, \omega_{vi}, \omega_{di}, \omega_{ci}, \omega_{ai}, \alpha, \beta, \gamma$	1/3, (-1/3), 1/3, 1/2, 1/2, 1/3, 1/3, 1/3,	penetration rate (PR)	0%, 25%, 50%, 75%, 100%

Table 4 Quantitative difference of the GEF between two intersection environments

Environment	Urban			Rural			
	PR	0%	100%	Rate of change (%)	0%	100%	Rate of change (%)
Mean		0.302	0.158	47.6	0.307	0.172	43.1
Variance		0.022	0.005	79.2	0.022	0.004	81.3

Figure 10 GEF of two speed guidance models for different transmission power

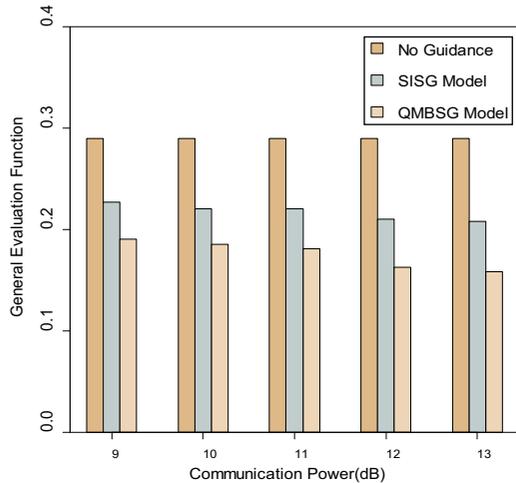


Table 5 shows that both the speed-guidance models improve the mobility and environment of the vehicles. For the mobility index, all indicators of the QMBSG model improve more than 50%, while the SISG model only improves the AS and DT. For the environment index, the EEF value of the two models is improved by 34.7% and 24.9%, respectively. For the safety index, the AI value of QMBSG model increases by 14.7% compared to the SISG model, meanwhile the QMBSG model improves the vehicle performance on the VC.

Table 5 Quantitative comparison of the six indexes of the two models

	Index	No speed guide	SISG model	QMBSG model
Mobility	AS	5.504	9.085	8.958
	Savings	-	65.1%↑	62.9%↑
	IP	6.984	10.740	0.096
	Savings	-	53.9%↑	98.6%↓
	DT	27.566	12.360	11.849
	Savings	-	55.2%↓	57.0%↓
Environment safety	E	10.634	7.986	6.946
	Savings	-	24.9%↓	34.7%↓
	VC	7.221	7.641	6.266
	Savings	-	5.8%↑	-13.2%↓
	AI	0.510	0.513	0.588
	Savings	-	0.7%↑	15.4%↑

5.3 Analysis of penetration rate

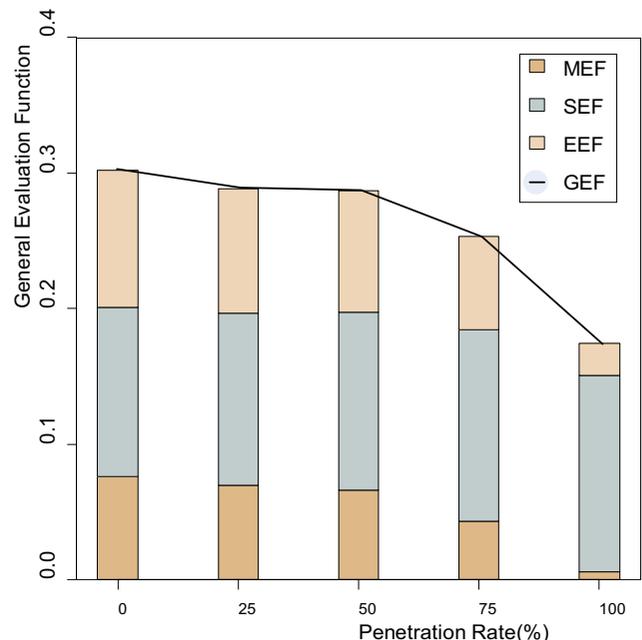
The PR is one of the most important factors to affect the speed guidance. Under the different PR, the variation of GEF, MEF, SEF and EEF of the QMBSG model are shown in Figure 11.

It can be seen from Figure 11 that the mean value of the GEF of all vehicles tends to decrease with the increase of PR. The performance of speed guidance in intersection has a better improvement for a higher PR value. This is because more vehicles are directed through the intersection. Furthermore, when the PR increases to 75%, the mean value of the GEF improves significantly. For the indexes of mobility and environment, the mean values of the MEF and EEF of all vehicles are continuously improved with the increase of PR and when the PR is above 75%, the MEF and the EEF decrease significantly. For the safety index, the mean value of the SEF tends to deteriorate with the increase of PR. The improvement of safety performance has a relatively small value comparing to the mobility and environment.

5.4 Analysis of the length of block section

In addition to the intersection environment, communication range and PR, the length of block section in the QMBSG model also has a significant impact on the guidance effect. The longer the block section, the longer is the time interval between vehicles passing through the intersection, which indicates that the speed guidance has a greater emphasis on safety. When the

Figure 11 Changes in GEF, MEF, SEF and EEF under different PRs



PR is 100%, the *GEF* values of the model according to the block sections of 2 s, 3 s and 4 s are as shown in Figure 12.

The results in Figure 12 show that the probability of the single vehicle receiving the speed guidance would increase with the increase of the length of the block section. Meanwhile, the traveling time of single vehicle passing through the intersection tends to increase, which causes a bigger delay. This is because the longer block section means the bigger interval between the guided vehicles passing the intersection. This phenomenon will spread to the downstream vehicles and the more downstream vehicles would expend the longer time delay. For all vehicles in simulation, the *GEF* of the QMBSG model with 2 s block section length is significantly better than that of the 3 s and 4 s.

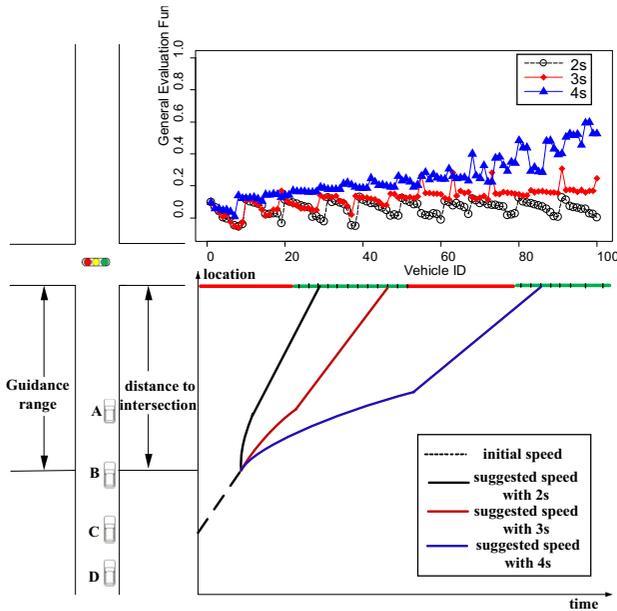
The guidance effect of different block sections is significantly affected by the PR. The *GEF* values of the QMBSG model with the block section of 2 s, 3 s and 4 s for different PRs are shown in Figure 13. The concentration areas of 2 s, 3 s and 4 s are

marked with different colors. The *GEF* of all the vehicles under the different block sections begins to decrease with the increase of PR. It is noteworthy that when the PR is 25%, the difference in *GEF* is less between the block section of 2 s and 3 s. For a high PR (PR = 100%), the improvement of the block section of 2 s is obviously better than that of 3 s and 4 s. The QMBSG model with block section of 2 s has the best improvement.

The guidance effect of different block sections is also significantly affected by traffic demand, and the initial space headway (ISH) in simulation can reflect the traffic demand. Therefore, under the simulation scenarios with different PR and ISH, the *GEF* values of different block sections are as shown in Table 6. As shown from Table 6, when the ISH sets 150 m, it indicates that the approaching flow passing through the intersection becomes less. For the lower approaching flow case, the QMBSG model with block section of 2 s still has good guidance effect. This is because the QMBSG model can automatically vacate the block sections until the calculated suggested speed meets the speed limit requirement and assigns this block section to the corresponding vehicle. The *GEF* under 3 s and 4 s decreases significantly, which shows that with the decrease in the approaching flow, the interval at which the adjacent vehicles arrive at the stop line becomes longer and the phenomenon of mismatch between the arrival interval and the distribution block section is relieved.

Therefore, under the six simulation scenarios with different PR and ISH, the quantitative comparison of the *GEF* for the model with block section of 2 s, 3 s and 4 s section lengths are shown in Table 6. In the six simulation scenarios, the model with block section of 2 s has the lowest *GEF* value.

Figure 12 *GEF* value of model with 2 s, 3 s and 4 s section lengths under 100% PR



6. Conclusion

In this paper, a QMBSG model for the CV environment is proposed by introducing the QMB theory to direct vehicle passing through the intersection. To comprehensively evaluate the guidance effect of the proposed model, the *GEF* is proposed to measure the mobility, safety and environment.

Compared with the speed guidance unavailable, the simulation results show that the QMBSG model has a 45.4% reduction in the *GEF* value. To further verify the guidance effect of the model, the QMBSG model is compared with the intersection speed guidance model in CV environment using

Figure 13 Diagram of *GEF* value with block interval of 2 s, 3 s and 4 s corresponding to different PRs

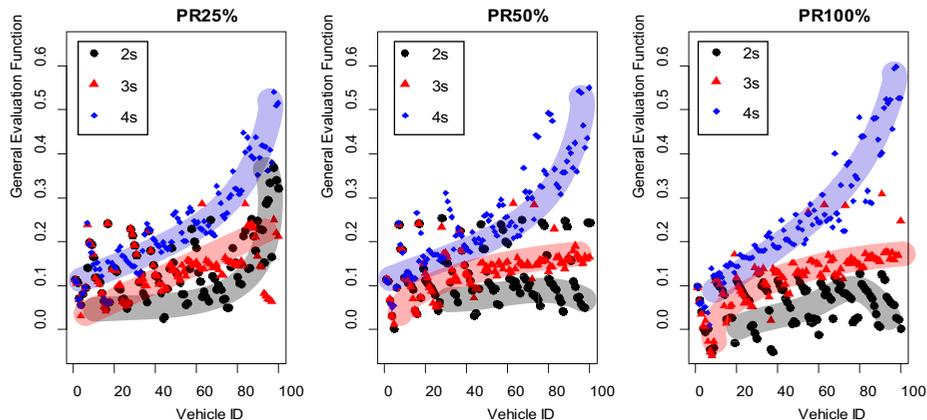


Table 6 GEF values with block interval of 2 s, 3 s and 4 s corresponding to different PRs and ISHs

Block interval	PR25%			PR50%			PR100%		
	ISH100	ISH150	Savings	ISH100	ISH150	Savings	ISH100	ISH150	Savings
2 s	0.1388	0.1122	↓0.1916	0.1205	0.0968	↓0.1967	0.0587	0.0415	↓0.2930
3 s	0.1401	0.1133	↓0.1913	0.1383	0.0981	↓0.2907	0.1225	0.0474	↓0.6131
4 s	0.2603	0.1131	↓0.5655	0.2598	0.0919	↓0.6463	0.2533	0.0479	↓0.8109
Block interval of minimum GEF	2s	2s	—	2s	2s	—	2s	2s	—

the same road network topology and simulation parameters and the GEF value decreases over 17.1%. To explore the guidance effect, this paper analyzes the influence factors of the CV environment, such as the intersection environment, PR and communication range. Among them, when the PR is above 75%, the GEF value will have a mutation and the guidance effect will increase significantly. This is a very good reference for congestion alleviation in the actual intersection. This paper also explores the scenarios of the different length of block section under different traffic demands and PR. The results show that when the block section is 2 s, the GEF value is the lowest and the improvement effect is the best.

At present, the authors are studying the application of QMBSG model in collaboration control of multiple intersections. According to the limitation that the model is only applied on single-lane roads in the same direction, the next step is to study how the QMBSG model can be applied to multiple lanes to model a more realistic scenario.

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Further reading

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