A speed guidance strategy based on cooperative vehicle-infrastructure environment at signalized intersections

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Abstract. It is a problem that most traffic scholars have been studying to enable motor vehicles to pass through signalized intersections without parking or with little parking, so as to improve the traffic efficiency of urban road network and reduce congestion. In the vehicle-road collaboration environment, speed guidance strategy has become an effective solution and trend, aiming at the characteristics and shortcomings of the current trunk signal coordination control as a passive response control based on vehicle arrival drive. In this paper, the principle of speed guidance strategy at signalized intersections is systematically proposed, and the corresponding speed guidance strategy model is proposed according to the different traffic conditions when the guided vehicles arrive at the intersections. This strategy can make the guided vehicles pass through the intersections without stopping or stopping time at least, reduce the delay of vehicles and improve the traffic efficiency at the intersections.

1. Introduction

Urban intersections are usually the bottleneck of traffic problems. In particular, vehicles frequently stop, queue or speed up or slow down at signalized intersections, which not only affect the traffic efficiency of the whole road network, but also bring problems such as fuel consumption and exhaust emission. With the development of Internet of vehicles technology, it has become an effective solution and trend for urban traffic to improve traffic efficiency to guide vehicles at the intersection group without stopping or with the least stopping time by virtue of vehicle-road collaboration technology.

Many scholars at home and abroad have studied the speed guidance of intersections under cooperative vehicle-infrastructure environment. QING et al.[1] established a fleet discrimination algorithm based on time headway with real-time traffic data of vehicle-road collaboration technology, and established a signal control optimization model for coordinated control of trunk roads at multiple intersections. RAKHA et al.[2] proposed a speed guidance strategy based on vehicle-road coordination at signalized intersections to improve fuel efficiency. CHEN et al.[3] conducted speed guidance through the roadside variable information board, and proposed a signal control optimization method combining dynamic speed guidance with dynamic signal control, which was used for coordinated control of trunk roads at multiple intersections. Li et al.[4] proposed for individual vehicle speed guide mechanism and model, but the model only for single intersection is analysed, and on the basis of overall benefit in intersection best as the goal, put forward the signal intersection car speed guidance model[5]. However, the influence of signal timing and adjacent intersections was not considered in this study. An et al.[6] proposed a green driving control method for signalized intersections based on multi-stage variable speed limit. However, due to the speed limit and the choice of following model, the optimal results were not obtained. Jing et al.[7] proposed a green wave coordinated control method of
double-cycle arterial road based on acceleration and deceleration guidance, but the model did not take into account the coordination between vehicles guided by the upstream intersection and the queued fleet at the downstream intersection and the current signal phase. Long et al.\cite{8} set up the integrated speed guidance and green wave optimization model of trunk line with the maximum green wave bandwidth and the minimum vehicle delay and stopping times as the control variables. But whether there is consistency or mutual influence between multiple objective functions selected in this study requires further study. Liu et al.\cite{9} regarded the guided vehicle and the ordinary vehicle after it as a fleet, and proposed a speed guidance strategy for the signal intersection under the condition of different driving states through the intersection. However, this method does not consider the mutual influence and speed fluctuation between vehicles, and the applicable scene is limited.

Combined with the above existing research and deficiencies, this paper systematically analyses the principle of speed guidance strategy for signalized intersections under the cooperative vehicle-infrastructure environment, and proposes the vehicle guidance speed strategy model under different traffic conditions, in order to provide some references for scholars in this field.

2. Speed guidance principle

In a vehicle speed guidance system at an intersection, we need to collect traffic control information and the running state information of the guided networked vehicle. For the convenience of expression, information about each guided car can be expressed as

\[ i = \{E(i), S(i)\} \]

Where, \( i \) represents the number of vehicles in the system. \( E \) represents traffic environment information, such as current signal phase, remaining time of signal phase, recommended speed of guidance, whether there is a queue ahead. \( S \) represents the state of the guided networked vehicle, such as acceleration, deceleration, stop. The main variables and their physical significance are shown in table 1.

| Variable | Physical meaning |
|----------|------------------|
| \( i \)  | Number of guided vehicle |
| \( a \)  | Acceleration of the guided vehicle |
| \( d \)  | The distance from the guided vehicle to the downstream intersection |
| \( b \)  | Deceleration of the guided vehicle |
| \( V_{\text{max}} \) | The maximum speed on the road |
| \( V_{\text{min}} \) | The minimum speed on the road |
| \( V_0 \) | The original speed of the guided vehicle |
| \( V(i) \) | Recommended speed of guided vehicle |
| \( P(i) \) | The phase of the guided vehicle |
| \( T(i) \) | Phase remaining time |

The vehicle state \( S(i) \) can be expressed as

\[ S(i) = [V_0, d, a, b], \quad i = 1, 2, \ldots, n \]  \( (1) \)

The current traffic environment can be expressed as

\[ E(i) = [R(i), T(i), Q(i), V(i)], \quad i = 1, 2, \ldots, n \]  \( (2) \)

With

\[ R(i) = \begin{cases} 
1 & \text{During the red light} \\
0 & \text{During the green light}
\end{cases}, \quad Q(i) = \begin{cases} 
1 & \text{Queue ahead} \\
0 & \text{No queue ahead}
\end{cases} \]  \( (3) \)

The speed guidance schematic diagram is shown in figure 1. In this paper, the speed guidance strategy model is established according to the green and red traffic conditions when the network vehicles arrive at the intersection.
3. Speed leading strategy discussion
To simplify the research process, the following basic assumptions are made in this research:
• There is no interference from non-motor vehicles, pedestrians and bus stops in the guidance area;
• The vehicles have changed lanes before entering the controlled region, i.e., the vehicles will not change lanes in the controlled region;
• The guided vehicles all strictly follow the speed guidance strategy.

3.1. Speed guidance strategy during red light
Case1: There is no queue at the entrance to the intersection, \( S(i) = [R(I), T(i), Q(0), V(i)] \)

(1) Keep going with the original speed
If \( \frac{d}{V_0} > T(i) \), then the speed guidance strategy of guided car \( i \) is "keep the original speed".

(2) Slow down to \( V(i) \) and pass
If \( \frac{d}{V_0} < T(i) \), it indicates that the guided car \( i \) will drive at the original speed to the stop line and wait for the green light to start. At this time, the speed of the guided car \( i \) adopts a speed guidance strategy of "slow down to \( V(i) \) and drive", so that when the guided car \( i \) reaches the stop line at the guidance speed, the green light will turn on, and then it can pass the intersection without stopping.

(3) Slow down and stop
If the remaining time of the current red light is too long and the guided car \( i \) slows down to the minimum limit speed of the road, it means that the current phase of the guided car to the stop line is still a red light. Then the speed guidance strategy of guided car \( i \) is "slow down, stop and wait for the green light".

Case2: There is queue at the entrance of the intersection, \( S(i) = [R(I), T(i), Q(1), V(i)] \)

(1) Slow down to follow the line of the last car through
When the guided car \( i \) slows down near the end of the queue, the rear vehicle just starts. At this time, the guided car \( i \) can follow the rear vehicle. If the time for the guided car \( i \) to the stop line is longer than the remaining time for the red light, the speed guidance strategy of guided car \( i \) is "slow down and follow the line of the last car through".

(2) Slow down and stop
When the guided car \( i \) slows down to reach the end of the queue, the vehicle at the end of the queue still hasn’t started, then the guided car \( i \) can only stop and wait. At this time, the speed guidance strategy of guided car \( i \) is "slow down and stop".

3.2. Speed guidance strategy during green light
Case1: There is no queue at the entrance to the intersection, \( S(i) = [R(0), T(i), Q(0), V(i)] \)
4. Velocity guidance strategy model

4.1. Model constraints

In actual road traffic, the speed guidance value is not unlimited, and the comfort of driving should also be taken into account. Therefore, all the speed guidance models proposed in this paper are based on the following constraints:

- The range of guidance speed is \( V_{\text{min}} \leq V(i) \leq V_{\text{max}} \);
- Refer to the values of comfort acceleration and comfort deceleration proposed by Yi et al.\cite{10}, then \( a_{\text{max}} = 2.5 \, \text{m/s}^2 \), \( b_{\text{max}} = 1.0 \, \text{m/s}^2 \);
- Combined with experience and domestic and foreign literature, the constraint of the speed variation range cannot exceed 60% of the initial running speed, so the guiding speed still needs to be satisfied \( 0.4V_0 \leq V(i) \leq 1.6V_0 \).

4.2. Model building

4.2.1. During the red light

Case1: There is no queue at the entrance to the intersection

(1) Slow down to \( V(i) \) and pass

The guided car \( i \) decelerates firstly and then travels at a uniform speed. The driver's reaction time is \( t_d \), and the deceleration time is \( t_b \), according to the kinematic formula, then

\[
L(i) = V_0 t_d + \frac{V^2 - V_0^2}{2b} + V(i)(T_i - t_d - t_b)
\]

Guided car \( i \) to pass through the stop line without parking should satisfy the following optimization function:
\[
\begin{aligned}
F_1 &= \max \left( \min \left( 0, d - L(i) \right) \right) \\
F_2 &= \min \left( \max \left( 0, T_r(i) - T_{travel}(i) \right) \right)
\end{aligned}
\] (5)

Where, \( T_{travel} \) is the travel time of the guided car \( i \) from receiving deceleration information to passing through the stop line.

(2) Slow down and stop

The guided car \( i \) has slowed down to \( V_{min} \) and is still in the red light when it reaches the stop line. It can only stop and wait for the green light to start, then:

\[
T_{\text{travel}}(i) = t_d + t_b + \frac{V^2_{min} - V^2_0}{2b} < T_r(i)
\] (6)

At this point, the guided speed is \( V_{min} \).

Case 2: There is queue at the entrance to the intersection

(1) Slow down to follow the line of the last car through

When the guided car \( i \) is standing at the back of the queue near the entrance of the intersection, the rear car has just started, it should be satisfied:

\[
T_{\text{travel}}(i) = nt_d + \frac{V(i) - V_0}{b} + \frac{L_{\text{max}}}{V_b} + \frac{L_{\text{max}}}{V_d} + \frac{d}{V(i)} < T_r(i)
\] (7)

Where, \( V_b \) represents the speed of the wave in front of the queue, \( V_d \) represents the starting wave speed of queuing vehicles in front.

(2) Slow down and stop

When the guided car \( i \) queues up at the rear of the vehicle queue near the entrance of the intersection, the rear car still does not start. The guided car \( i \) needs to stop and queue up, so it should be ensured that the guided car \( i \) can stop completely before the collision with the rear car. Then the braking distance should meet equation (8).

\[
L_s = V_0 \left( t_d + \frac{t_b}{2} \right) + \frac{V^2_0}{2b_{\text{max}}} + d_s
\] (8)

Where, \( d_s \) is the safety workshop distance after parking, take 1.5m.

4.2.2. During the green light

Case 1: There is no queue at the entrance to the intersection

(1) Accelerate and pass

When the remaining green time is short and the guided car \( i \) can pass the stop line by accelerating, then:

\[
L(i) = V_0 t_d + \frac{V^2(i) - V^2_0}{2a} + V(i) \left( t_g(i) - t_d - t_a \right) \geq d
\] (9)

Where, \( t_a \) is the time of accelerating to \( V(i) \)

Case 2: There is queue at the entrance to the intersection

(1) Slow down to follow the line of the last car through

Network car \( i \) near the entrance of the intersection to queue at the end of the vehicle line, the rear car has just started, it should meet:

\[
T_{\text{travel}}(i) = nt_d + \frac{V(i) - V_0}{a} + \frac{L_{\text{max}}}{V_b} + \frac{L_{\text{max}}}{V_d} + \frac{d}{V(i)} < T_g(i)
\] (10)

(2) Slow down and stop

the braking distance should meet equation (8).
5. Solution method of velocity guidance strategy model
At present, the test methods of speed guidance are not mature, and three test methods are mainly adopted: field test, driving simulator and micro-simulation. Among them, micro-simulation software can establish scenes that are difficult to realize in the real world, and it has many advantages such as controllable, lossless, safe, reproducible, which is the most commonly used method in transportation research in recent years.

6. Conclusions and prospects
This paper systematically analysed the principle of speed-guiding strategy, according to the signal status information, the distance between a vehicle and the stop line, vehicle running status information, etc. The kinematics theory is used to construct the vehicle speed guidance model during green light and red light. The guided vehicle can pass the intersection at least without stopping or for a minimum of time under different traffic conditions. This model is the basic model to study and analyse the running state of vehicles that can efficiently pass through the intersections in the vehicle-road collaborative environment, which will provide certain reference value for scholars in this aspect in the future. The next step is to verify and evaluate the proposed model and further study the method of multi-vehicle coordinated speed guidance at signalized intersections under the cooperative vehicle-infrastructure environment.

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