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The Modeling and Simulation of the Tandem Intersection Considering the Vehicle Operation Law

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ABSTRACT. *In order to alleviate the problem of utilization of lane resources at the intersection, allow more vehicles pass through the intersection quickly before the end of green light at each phase and reduce waiting time of vehicles on the basis of making full use of existing resources. Based on the vehicle operation law and behavior, we established the calculation model of the length of the array area and the diversion area, and the coordination control model of the main-signal and pre-signal of the tandem intersections by analyzing the design principle of the phase sequence and timing. Finally, a practical case is used for simulation, and the implementation effect of the model in this paper is tested by the three indexes of maximum queue length, stopping times and vehicle delay.The results show that the proposed model can help to determine the length of the array area and the diversion area at the tandem intersections and reasonably set the pre-signal control according to the actual flow, which can significantly improve the road capacity and reduce the waste of road resources, parking time and delay when the intersection flow is large.*

KEYWORDS: *Tandem intersections, The vehicle operation law, Pre-signal, Simulation*

1. Introduction

With the development of social economy and increased car ownership, intersection congestion phenomenon is increasingly serious. It is an important means to improve the capacity of intersections by optimizing the design and control of intersections, making full use of existing road resources, and making each phase

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green time through more vehicles, to ensure the efficient operation of the intersection.

In order to improve the traffic capacity of the intersection, the traffic resources of the intersection can be fully utilized during the peak period by pre-organizing the upstream vehicles of the intersections. In 1991, British Transport Authority first proposed the idea of pre-signal control to solve the problem of priority control of public transport at intersections [1]. Xuan Y [2] and Jiang Jinsheng [4] systematically analyzed the influence of setting pre-signals and reasonable waiting area length on the capacity of intersections. Ma et al. [3] and Ma Wanjing [5] all studied the tandem intersections by building the tandem signal control optimization model and coordinating control method. Zhao Jing et al. [6] optimized the tandem signal control by constructing the delay and optimal cycle model under three phase sequences of the formation intersection.

Tandem intersections of existing studies, most concentrate on optimizing the signal control design and setting the waiting area, when selecting the position of the main-stop and pre-stop lines, actual vehicle operation law and intersection saturation flow not give enough attention, and lack of quantitative analysis based on the actual survey data of research, and the method to determine the phase offset between main-signal and pre-signal is also less studied. By analyzing the control methods of tandem intersections , a calculation model for the array area length and the diversion area length was established, which is based on actual traffic intersection and vehicle operation law , and on this basis, the coordination control model of the main-signal and pre-signal of the tandem intersections was established .Finally, a simulation study was carried out at the intersection of Yiyang Avenue and Longzhou Road in Yiyang city to verify the accuracy of the model.

2. Control method of the tandem intersections

Principles of traffic control methods for "tandem" is: double stop line method is adopted, that is to draw a second stop line (pre-stop line) in front of the existing stop line, and the area between two stop lines are divided into "array area" and "diversion" area, the lane in the area is no longer divided into straight, left and right turns. All vehicles that need to enter the intersection first queue up outside the pre-stop line and guide the traffic flow in the same direction into the "tandem area" in accordance with the traffic signal guidance facilities (road traffic signs and markings). When reached the main-stop line, they need to wait again until the green light up, all vehicles in "tandem area" quickly through the intersection. Schematic diagram of tandem intersection structure as shown in Figure 1.

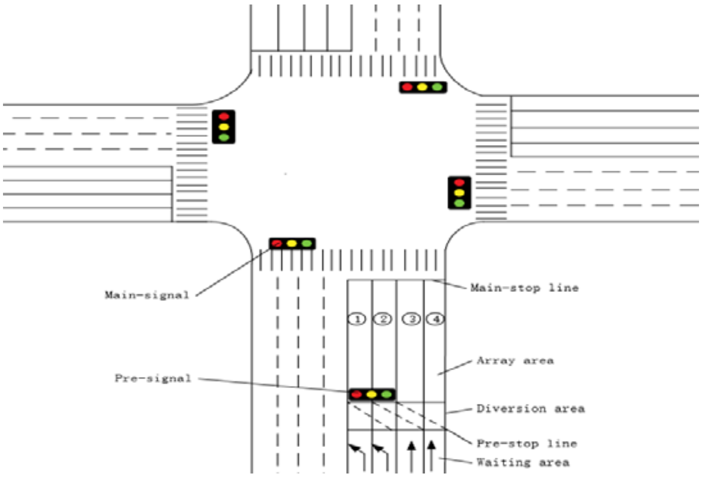

Figure. 1 Schematic diagram of a single tandem intersection structure

3. Model construction

3.1 Assumptions

(1) Since right turn vehicles does not affect the overall control strategy, for simplification, only left-turn and straight-going vehicles are considered in the model, and right turn and u-turn are not considered;

(2) The driver passes according to the control scheme, and lines up automatically after entering the array area, so that each lane in the array area can be used to the maximum extent possible;

(3) All vehicles entering the array area will be able to pass through the intersection within the corresponding phase green time;

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(4) There will be no vehicle parking in the diversion area and no disturbance to subsequent vehicles.

3.2 Vehicle operation law

Since the vehicle running condition at the pre-stop line is similar to the stop line of the conventional signalized intersection, the vehicle arrival characteristics are not studied in depth.The process of vehicles arriving at and passing through the intersection is simplified as follows: firstly, wait the pre-stop line; secondly , select the lane according to the pre-signal to enter the diversion area; thirdly, follow the process to enter the array area to arrive at the main-stop line for waiting. During the process of vehicle starting, lane changing, following and stopping, the curve of speed change is shown in Figure 2:

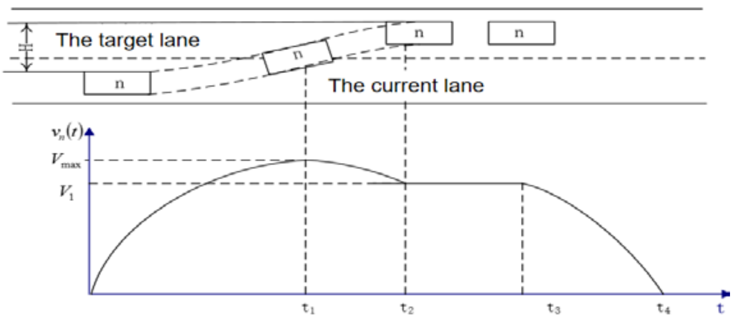

Figure. 2 Dynamics diagram of vehicle lane change process

(1) Process of lane change (0-t_2)

It is assumed that the vehicle trajectory during lane change is closely connected by two continuous inverted circular curves, and the driver of lane change vehicle n operates smoothly during lane change; The lateral displacement generated by the target vehicle changing lane to the target lane is H, then the vehicle reaches H/2, the vehicle speed reaches the maximum value V_{max} at the time of t_1;Then the vehicle slowly slowed down to run smoothly at a speed V_1, and t_2 was considered as the end of lane change.

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(2) Process of following (t_2-t_4)

After entering the array area, the vehicle follows at the optimal speed and gradually slows down to the main-stop line to stop and wait.At this point, it is assumed that the vehicle state is the same as the following behavior of ordinary road vehicles during driving. In this paper, the Full Velocity Difference (FVD) model [7] is adopted to describe the following behavior:

$$a_n(t)=\frac{dv_n}{dt}=\alpha\left[\min\left(V_{\min}+\beta,V\left(\Delta x_n(t)\right)-V_n(t)\right)\right]+\lambda\Delta V_n(t) \tag{1}$$

$$\Delta v_n(t)=v_n(t)-v_{n-1}(t) \tag{2}$$

$$V\left(\Delta x_n(t)\right)=V_{\max}\left[\tanh\left(\Delta x_n(t)-l_c\right)+\tanh(l_c)\right] \tag{3}$$

Where $V_n(t)$ is the speed of the vehicle n at time t; $a_n(t_i)$ is the acceleration of the vehicle n at time t; $\Delta x_n(t)$ is the distance between the following car and the leading car; α corresponds to sensitive coefficient; β corresponds to boot speed margin, $V_{\min}+\beta$ is to describe the minimum following speed acceptable to a driver who is about to queue for a stop; λ corresponds to feedback coefficient, if the following car is the leading car, $\lambda = 0$; $\Delta v_n(t)$ is the speed difference between the leading vehicle (n-1) and the following vehicle; $V\left(\Delta x_n(t)\right)$ corresponds to optimized velocity function; $V_{\max}$ is the maximum driving speed; l_c is vehicle safety spacing.

3.3 The array area length model

The distance between the main-stop and pre-stop lines (L) includes the length of the array area (L_1) and the length of the diversion area (L_2). The main factors affecting the distance between the two stop lines are the traffic flow, the number of lanes, whether there is a bus stop and its specific location, etc. [8]. The traffic flow

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and saturated flow in the intersection is an important factor to decide the location of the second stop line, in order to study the effect of "tandem" design accurately, original intersection signal timing remain unchanged, to exploring the changes of the intersection traffic capacity after setting pre-stop line. The location selection mainly consider the main light release of saturated flow of imports.

$$L_1 = \frac{S_i}{N}\overline{h_d} \tag{4}$$

In this equation, i represents the four inlet directions of the intersection; S_i is the saturation flow of inlet lane i; N is the number of lanes at entrance i; $\overline{h_d}$ Is the average headway distance.

3.4 The diversion area length model

The safe lane change area (diversion area) is marked with yellow warning line (yellow grid), similar to the form and function of the existing no-parking area at intersections.Based on the above assumptions, the vehicle lane change velocity in this paper conforms to the sine wave model, and the acceleration conforms to the cosine model and the driving distance model:

$$v_n(t_i) = V_{\max}\sin\frac{\pi t}{2t_1} \tag{5}$$

$$a_n(t_i) = \frac{dv(t)}{dt} = \frac{\pi V_{\max}}{2t_1}\cos\frac{\pi t}{2t_1} \tag{6}$$

$$S_n(t) = \int_0^{t_2} v_n(t)dt = -\frac{2t_1}{\pi}\left(\cos\frac{\pi t_2}{2t_1} - 1\right) \tag{7}$$

$$L_2 = \left[S_n(t_2)^2 - H^2\right]^{\frac{1}{2}} \tag{8}$$

$$L = L_1 + L_2 \tag{9}$$

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Where $S_n(t)$ is the track distance of vehicle lane change at time t; H is the lateral offset of the vehicle transition to the farthest lane.

4. Phase sequence control of tandem intersection

Phase sequence control of “tandem” refers to the design of phase sequence of main-signal and pre-signal.Compared with ordinary intersection, tandem intersection adopts the phase sequence with intersecting straight and left phases for the main signal lamp, and adjusts the pre-signal to control the vehicles with different phases entering the array area, make each direction of the vehicle (go straight or turn left) in the corresponding phase during the green light to be able to efficiently use all the lanes in the area.

Take five lanes (1 and 2 are left turning lanes and 3, 4 and 5 are straight going lanes) as an example, and the control scheme is shown in Figure 3:

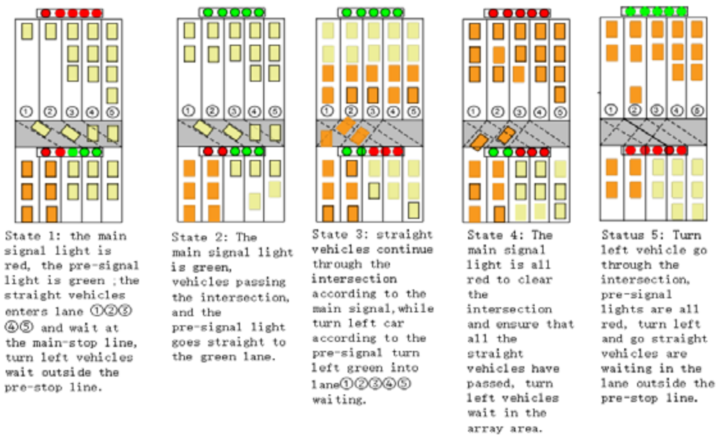

Figure. 3 Schematic diagram of vehicle running state at a tandem intersection

4.1 Timing of intersection signals

The setting of signal timing at a tandem intersection requires the coordinated control of the main-signal and pre-signal lights for the vehicles going straight and

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turning left to enter the tandem area at different time periods. In order to fully reflect the ”tandem” function, in this paper, the phase timing of the main-signal lamp is unchanged during simulation, and the pre-signal lamp timing is adjusted.In addition, the signal timing of one direction is analyzed, so as to compare with the situation without tandem area.The timing diagram of the tandem signal is shown in Figure 4:

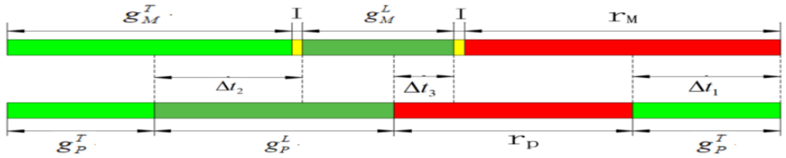

Figure. 4 Timing diagram of main-signal and pre-signal

Constraints:

(1) The duration of main-signal and pre-signal cycles is equal:

$$g_M^T + g_M^L + r_M = g_P^T + g_P^L + r_P \tag{10}$$

(2) The number of vehicles entering the tandem area shall not exceed the phase saturation flow, and make full use of lane resources:

$$\max g_P^k = \frac{S_M^k g_M^k}{S_P^k} \tag{11}$$

(3) Ensure that before the main-signal green light starts, the straight-ahead vehicles have reached the main stop line and queued up:

$$\Delta t_1 \geq \frac{L}{h_d} \overline{h_t} \tag{12}$$

(4) Ensure that vehicles entering the tandem area are cleared and pass as many vehicles as possible:

$$\Delta t_2 \leq \frac{L}{v_n(t)} \tag{13}$$

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(5) The left-turn vehicle follows the straight vehicles to the main-stop line and passes the main-stop line without stopping:

$$\Delta t_2 \geq \frac{L - \frac{S_M^T}{N}}{\overline{h_d}} \overline{h_t} \tag{14}$$

Where g_M^k is the green time of going straight or turning left at the main signal, k=T,L represents going straight and turning left respectively; g_P^k is the green time for the pre-signal to go straight or turn left; I is green interval; r_M is red light of the main-signal; r_P is red light of the pre-signal; S_M^k correspond to the saturation flow rate at the main signal; S_P^k correspond to the saturation flow rate at the pre-signal; $\overline{h_t}$ is the average time headway; $\overline{v_n(t)}$ is the average following speed ; Δt_i is the time difference between main-signal and pre-signal.

5. Simulation analysis of the tandem intersection

5.1 Analysis of current situation of target intersection

Take the intersection of Yiyang Avenue and Longzhou Road in Yiyang City, Hunan Province as the target intersection.The Traffic organization channelization blueprints for the intersection are shown in Figure 5.

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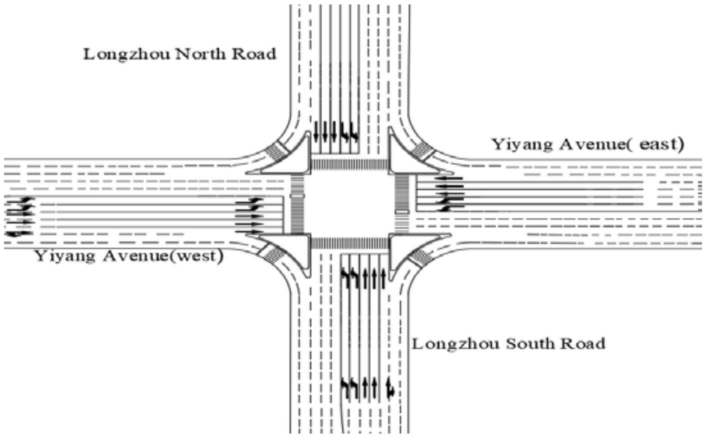

Figure. 5 Traffic organization channelization blueprints for the intersection

5.2 Current situation of intersection signal control

Four-phase signal control is adopted at the intersection. The cycle time C is 172s, and the yellow time of each phase is 3s. In brackets are the corresponding green time of each phase, the signal phase is shown in Figure 6.

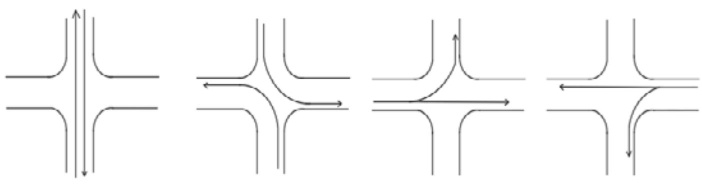

Figure. 6 Signal phase diagram of the target intersection

5.3 Simulation in Vissim

(1) Data collection

With the help of the camera of the traffic department in Pengli Square at the intersection of Yiyang Avenue and Longzhou Road, data collection was conducted

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on working days with good weather and high visibility. The specific time was 17:45-18:45 on November 4, 2019 and November 6, 8 and 11 respectively, and a total of about 5 hours of video data were acquired. This study selects the evening peak traffic volume to evaluate and analyze the current situation. The flow diagram at the target intersection as shown in Figure 7.

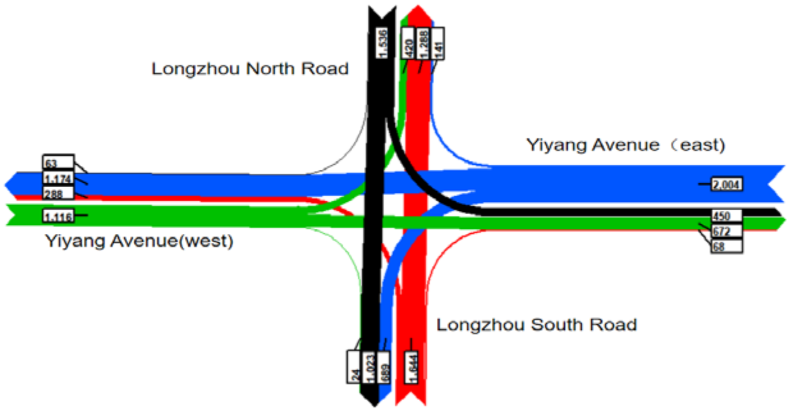

Figure. 7 Flow diagram at the target intersection

(2) Intersection problem and solutions

According to the analysis of the current situation, the main problem at the intersection is that there is a large amount of direct traffic from the north to the south intersection entrance lanes, but the two left-turn lanes of the south have less traffic flow. And the north entrance road direction left traffic flow is large, forming a serious traffic jam.

Aiming at the main problem of this intersection, it is proposed that only the south entrance and the north entrance should be reformed into the tandem traffic control system.In combination with the current traffic flow and by applying the model in this paper, the optimal length of the array area and diversion area at the intersection is calculated, as shown in Table 1. The signal timing scheme at the peak tandem intersection is shown in Figure 8.

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Table 1 Optimal length of intersection array area and diversion area

		the north entrance	the south entrance
Number of lanes in tandem area		5	5
North - South straight traffic maximum saturation flow/pcu		67	
North - South turn-left traffic maximum saturation flow/pcu		23	
Average headway $\overline{h_d}$		7m	
Average time headway $\overline{h_t}$		1.9s	
Length of array area/m		100m	100m
V_{max} /m/s	Straight	11.7	11.7
	Turn-left	8.3	8.3
Length of diversion area/m		30	30

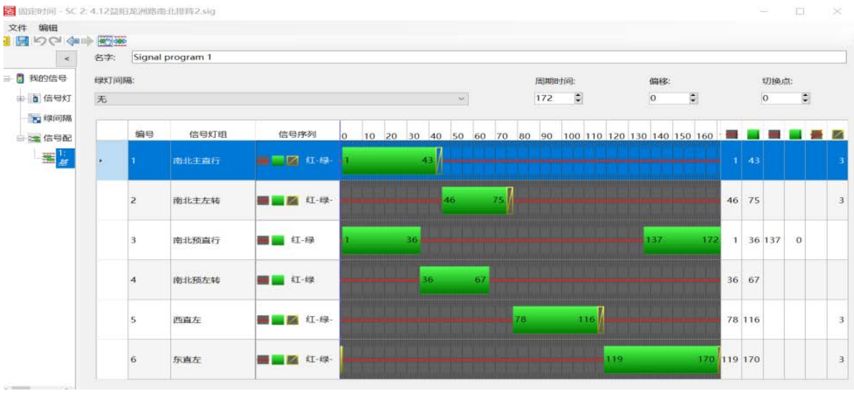

Figure. 8 Signal timing diagram during the peak

5.4 Comparison of results

Simulation software VISSIM is used to run five times and take the average value for comparative analysis. It can be seen that the model in this paper is used to design the tandem intersection , and the evaluation index of the entrance of the intersection is greatly improved; The maximum queuing length of the north-south entrance straight lane and the vehicle delay both decreased, while the maximum queuing length of the north-south entrance straight line decreased significantly,as shown in

Figure 9 and Figure 10; A reasonable setting can effectively reduce the number of second stop of the tandem, which shows that using the model in this paper to set up the tandem intersection can greatly improve the operation efficiency of the intersection.

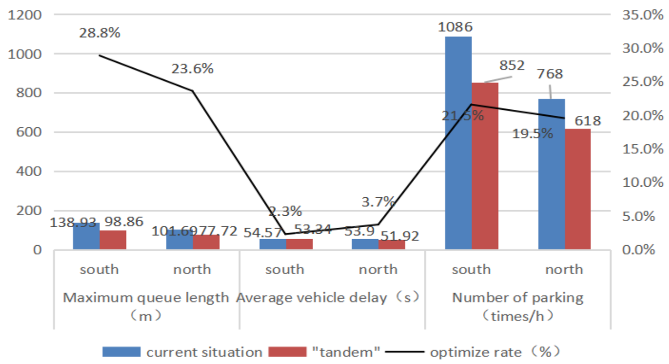

Figure. 9 Straight lane optimization comparison of north and South entrance

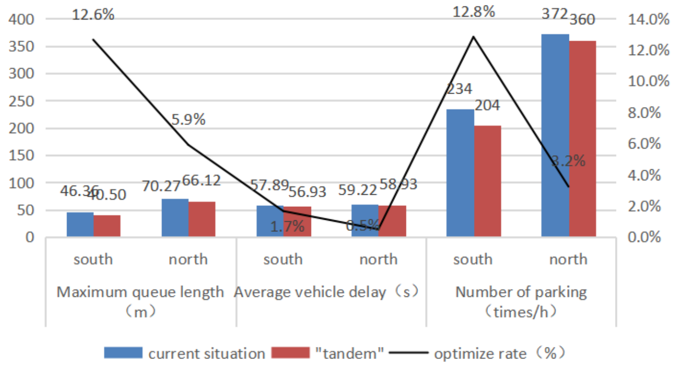

Figure. 10 Left-turn optimization comparison of South and South entrance

6. Conclusion

Adopting the control scheme of tandem intersection in the peak period can effectively improve the utilization of the lane at the intersection, so as to make full use of road resources and improve the traffic capacity.In this paper, through the analysis of vehicle operation rule and saturated flow according to the intersection to set up the model of the length of array area and lane change area, and on this basis to adjust the phase sequence of pre-signal lights set up primary and signal timing model, finally analyzes the instance using Vissim to simulate and analyze the current traffic situation intuitively, then reshape the intersection into a tandem intersection to get rid of the rush-hour congestion.The simulation results show that by this specific adjustment model of the intersection, the intersection traffic capacity increased, delay reduced, reasonable to set of green light and the time difference Δt_i , stops will reduce, can effectively reduce the secondary parking delay, improve the benefit of the operation of the intersection.

Due to the small amount of intersection data collected in this paper, the situation of mixed traffic flow is not taken into account. In addition, in terms of signal control, it is necessary to adjust the cycle time in the theoretical model establishment to make the traffic capacity better.Therefore, there is still some error between the research results and the actual situation.In practical application, the influence of lane change and following process on the location of pre-stop line and other factors need to be further studied.

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