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Control method for intersections downstream of urban expressway off-ramp using pre-signals

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Abstract: To improve the traffic efficiency of the urban expressway off-ramp and connected downstream intersection, a pre-signal control method for intersections downstream of the urban expressway off-ramp was proposed. Based on the analysis of the flow distribution characteristics of an off-ramp ground point section, a vehicle lane change delay model in an off-ramp junction area is constructed. Using the traffic shockwave theory, a pre-signal upstream queue length model and sorting area length model are established. Considering the constraints of the main signal timings and queue length constraints, pre-signal timing parameters and pre-signal setting position are optimized. The results of a case study show that the pre-signal method can significantly improve the capacity of the intersection with an off-ramp and significantly reduce the average vehicle delay. The effects of the left-turn traffic proportion, traffic volume, and ramp junction length on the model are studied through numerical analysis. The results demonstrate the effectiveness and advantage of the pre-signal method.

Key words: traffic engineering; off-ramp; pre-signal; connected intersection; traffic shockwave theory

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With the increasing traffic demand, many cities throughout the world are choosing to construct urban expressways to improve mobility[1]. These expressways have to connect with local surface streets via on-and off-ramps. However, in China, due to the limitation of urban land use, the distance between the off-ramp ground point and the downstream intersection is usually very short[2-3]. The off-ramp, downstream signalized intersection, and their connecting segments often constitute a potential bottleneck in urban road networks[4-6].

Due to the limited space between the off-ramp and downstream intersection, queues at the downstream intersection during the red phase may easily prevent the off-ramp exiting traffic from merging into their target approach lanes. The queue on the off-ramp then generates a spillover onto the mainstream of urban expressways[7]. Conversely, the poor utilization of the downstream intersection capacity may occur because strong lane-changing demand between expressways and surface street traffic induces extra delays and prevents vehicles from reaching the downstream stop line during the green phase[8].

To solve the above problems, transportation researchers have been investigating various methods. In the existing literature, these methods mainly fall into two categories: time optimization methods and space optimization methods.

Time optimization methods improve the performance of intersections with off-ramps by adjusting the intersection signal timings. Yang et al.[9] developed an integrated control system. Once the off-ramp queue emerges onto the freeway, the ramp priority strategy will be adopted. However, the optimization objective should not be to only focus on improving the operational performance of the expressway traffic flow. Accordingly, Messer[10] proposed a scheme to solve the traffic congestion of off-ramps using the equity offset. Similarly, Lim et al.[11] proposed a model that minimizes the total delay time using a cycle length and signal time on an intersection of an arterial downstream. However, the traffic congestion problem still persists during the peak period because these methods fail to solve the serious traffic weaving problem among different directions of traffic flows.

Spatial optimization methods mainly refer to the optimization of lane assignment at the downstream intersection. Chen et al.[12] investigated the safety impacts of dual right-turn lanes. Zhao et al.[13] proposed an integrated design model for non-traditional lane assignment and signal optimization at an off-ramp. The use of spatial optimization methods can significantly eliminate the problem of traffic weaving, which could be used to improve traffic efficiency. However, these methods have strict requirements for the space of a connected section. When the distance of the ramp connected section is short, the queue of special lanes (e.g., the left-turn lane in the middle) is

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too long, which will prevent vehicles from changing lanes, resulting in inefficient utilization of some lanes.

In this study, a complete method with pre-signals is proposed to eliminate traffic weaving and to improve the section's overall operational efficiency. This method mainly consists of three parts: lane assignment scheme, signal timing scheme, and layout scheme.

1 Design Concept

When using a pre-signal in an intersection with an upstream off-ramp, the pre-signal could be set near the off-ramp ground point, as shown in Fig. 1. A pre-signal is used to organize left-turn movements and through the movement upstream of the intersection in advance. All lanes in the area between the pre-signal and main signal, which is called the "sorting area", could be made to completely discharge the left-turn movement and through movement alternatively during both subphases[14].

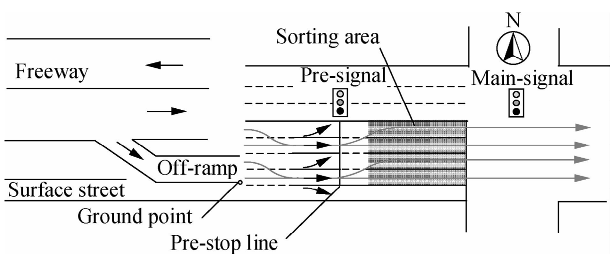

Fig. 1 Idea of using a pre-signal in an intersection with an upstream off-ramp

Despite the promising effect of pre-signals in reorganizing traffic and mitigating weaving movements, the following critical issues remain to be addressed:

1) Lane assignment. The upstream traffic flow distribution of the intersection with an off-ramp is special. At this time, if the traditional lane assignment scheme is adopted, traffic weaving becomes serious. Therefore, a new lane assignment method should be set up according to the section's traffic and geometric characteristics.

2) Position of the pre-signal. When the upstream of an intersection is connected by an off-ramp, the setting of the pre-signal is limited. On the one hand, if the position of the pre-signal is too close to the main signal, it will lead to the queue overflow of the sorting area, resulting in the waste of the pre-signal green time. On the other hand, if the pre-signal location is too far from the main signal, it will lead to the waste of space resources.

2 Method

2.1 Lane assignment

In the conventional lane assignment of urban intersections, the principle that the allocation of the left-turn, though, and right-turn lanes should be ordered from left to right is often followed. However, when the intersection is connected to an off-ramp due to the special flow distribution characteristics, the traditional lane assignment plan has serious traffic weaving.

According to different decision-making processes and their impacts on surrounding traffic, lane-changing maneuvers are usually classified as mandatory lane-changing (MLC) and discretionary lane-changing (DLC). In this paper, we assume that the vehicle lane-changing process is as follows: Firstly, vehicles take MLC to their target lanes due to the need for strategic route choices. Secondly, after MLC, the queue lengths of different lanes become different. Drivers take DLC to seek better driving conditions. Finally, the queue lengths of lanes with the same function are the same.

Based on the above assumptions, the frequency of MLC and DLC could be calculated. To facilitate the calculation of the model, this paper assumes that the delay caused by DLC and MLC is a constant. Thus, the lane-changing delay can be calculated as

$$D = \alpha \sum_{k=1}^{n} (q_{kxw}^{1} \mid k - x \mid (1 - x_{kx})) + \beta \sum_{k=1}^{n} (q_{kxw}^{2} \mid k - x \mid x_{kx}) \tag{1}$$

where D is the lane-changing delay; α and β denote the delay factors of MLC and DLC, respectively; q_{kxw}^{1} indicates the lane-changing volume from lane k to the x lane during stage one; q_{kxw}^{2} indicates the lane-changing volume from lane k to lane x during stage two; and n is the number of lanes.

We define q_L, q_T, and q_R as the left-turn movement, through movement, and right-turn movement volume during the peak period, respectively. The number of the lanes with different functions should be calculated based on the volume ratio as

$$N_L = \text{Round}\left(n \frac{q_L}{q_L + q_T + q_R}\right) \tag{2}$$

$$N_T = \text{Round}\left(n \frac{q_T}{q_L + q_T + q_R}\right) \tag{3}$$

$$N_R = n - N_L - N_T \tag{4}$$

where N_L, N_T, and N_R denote the numbers of the left-turn lane, through lane, and right-turn lane, respectively.

To save the green time of the intersection, the right-turn movement is not controlled. The right-turn lane is set at the outermost of the intersection approach. The locations of the through and left-turn lanes could be adjusted according to the traffic demand. The total number of intersection lane assignment plans η could be calculated as

$$\eta = \frac{(N_L + N_T)!}{N_L! N_T!} \tag{5}$$

As the lane-changing delay is negatively correlated with the intersection efficiency, the corresponding lane assignment scheme with the smallest lane-changing delay should be selected.

$$D^{*} = \min[D(1), D(2), \cdots, D(\eta)] \tag{6}$$

where D^{*} indicates the lane-changing delay of the selected lane assignment scheme; $D(x)$ represents the lane-changing delay corresponding to the lane assignment scheme x.

To prevent undesirable traffic merging activities, the total number of lanes assigned to permit such a movement is limited by the number of lanes at the corresponding receiving leg. The sorting area can effectively reduce the queue length and improve the efficiency of space utilization[15]. Thus, high-saturation lanes should be controlled when the number of lanes at the corresponding receiving leg is limited.

In addition, to ensure the traffic safety and efficiency of the sorting area, the lanes controlled by the pre-signal should be adjacent to one another. Moreover, the pre-signal lanes controlled by the pre-signal should contain left-turn and through lanes.

2.2 Signal timing

In terms of signal control, the following aspects should be noted[15]: Firstly, due to the special-lane assignment design, the conflict between the through movement and left-turn movement should be avoided. Secondly, to ensure a safe operation, vehicles driving into the sorting area should be discharged during the corresponding phase of the main signal.

Fig. 2 depicts the signal phase for the pre-signal design at a four-leg signalized intersection. In stage one, the through movements on the south and north legs starts to be discharged by the main signal (movements 4 and 7 in Fig. 2). At the same time, the through movement on the west starts to be discharged by the pre-signal (movement 10 in Fig. 2). In stage two, the through movement on the west and east legs starts to be discharged by the main signal (movements 2 and 6 in Fig. 2), and the through movement on the west continues to be discharged by the pre-signal. After a while, the pre-signal on the west leg turns red. Meanwhile, the main signal continues to display a green light until the sorting area is cleared. The following stages are similar to the first two stages mentioned above.

To ensure the coordinated operation of the pre-signal and main signal, a common cycle length should be set.

$$C = g_1^{m} + g_2^{m} + g_3^{m} + g_4^{m} + 4I \tag{7}$$

$$C = g_1^{p} + g_2^{p} + \Delta t_1 + \Delta t_2 + 2t_c + 2I \tag{8}$$

$$t_c = \frac{L_s + L_c}{v_s} \tag{9}$$

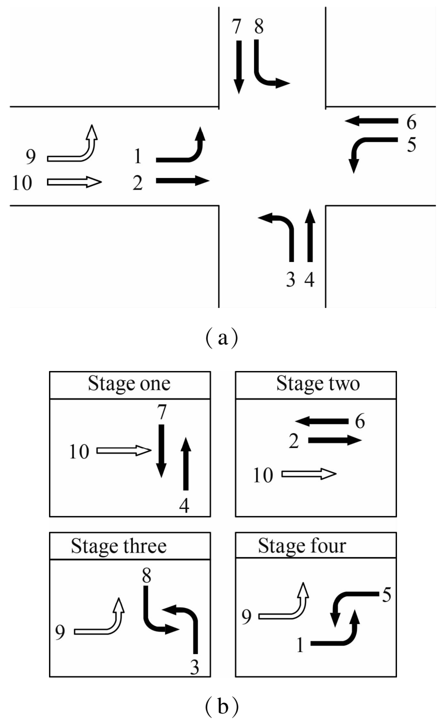

Fig. 2 Signal control plan for the main and pre-signals at the signalized intersection with an upstream off-ramp. (a) Traffic flows; (b) Signal phase

where g_1^{m}, g_2^{m}, g_3^{m}, and g_4^{m} are the durations of the main signal phase one, phase two, phase three, and phase four in a cycle, respectively; C indicates the signal cycle length of the intersection; I is the clearance time for a pair of conflicting traffic movements, which includes the amber period and all-red period; g_1^{p} and g_2^{p} represent the durations of the pre-signal phase one and phase two in a cycle, respectively; g_2^{p} indicates the duration of the pre-signal phase two in a cycle; t_c is the duration of the clearance time of the sorting area; Δt_1 is the duration of the offset time between the main signal phase one and pre-signal phase one; Δt_2 is the duration of the offset time between the main signal phase three and pre-signal phase two; v_s denotes the mean speed of vehicles; L_s is the length of the sorting area; and L_c represents the length of the lane-changing area.

The duration of the pre-signal green time is constrained by the main signal timing.

$$g_1^{p} \leqslant g_1 + g_2 + I - t_c \tag{10}$$

$$g_2^{p} \leqslant g_3^{m} + g_4^{m} + I - t_c \tag{11}$$

The capacity of a tandem intersection is determined by the pre-signal capacity and main signal capacity. Considering traffic safety and efficiency, the pre-signal capacity should be set to less than and close to the main signal capacity. The pre-signal green time is the maximum value when the pre-signal capacity is equal to the main signal capacity.

$$g_{1\max}^{\mathrm{p}} = \frac{S_{\mathrm{T}}^{\mathrm{m}} g_2^{\mathrm{m}} n_{\mathrm{s}}}{S_{\mathrm{T}}^{\mathrm{p}} n_{\mathrm{T}}^{\mathrm{p}}} \tag{12}$$

$$g_{2\max}^{\mathrm{p}} = \frac{S_{\mathrm{L}}^{\mathrm{m}} g_4^{\mathrm{m}} n_{\mathrm{s}}}{S_{\mathrm{L}}^{\mathrm{p}} n_{\mathrm{L}}^{\mathrm{p}}} \tag{13}$$

where $g_{1\max}^{\mathrm{p}}$ and $g_{2\max}^{\mathrm{p}}$ are the maximum green durations of the through and left-turn phases of the pre-signal, respectively; $S_{\mathrm{T}}^{\mathrm{m}}$ and $S_{\mathrm{L}}^{\mathrm{m}}$ represent the saturation flow rates of the through and left-turn lane at the pre-signal, respectively; n_{s} denotes the lane number of the sorting area; $n_{\mathrm{T}}^{\mathrm{p}}$ and $n_{\mathrm{L}}^{\mathrm{p}}$ are the numbers of through and left-turn lanes at the pre-signal, respectively.

When the main signal is certain, the longer the pre-signal green time, the greater the capacity of the whole intersection. Accordingly, the preliminary calculation of the pre-signal green time $g_{1\mathrm{initial}}^{\mathrm{p}}$ and $g_{2\mathrm{initial}}^{\mathrm{p}}$ is as follows:

$$g_{1\mathrm{initial}}^{\mathrm{p}} = \min\{g_1 + g_2 + I - t_{\mathrm{c}}, g_{1\max}^{\mathrm{p}}\} \tag{14}$$

$$g_{2\mathrm{initial}}^{\mathrm{p}} = \min\{g_3 + g_4 + I - t_{\mathrm{c}}, g_{2\max}^{\mathrm{p}}\} \tag{15}$$

2.3 Position of the pre-signal

2.3.1 Pre-signal upstream queue length constraint

The upstream road segment should be longer than the sum of the lengths of the queue generated by the pre-signal. The average queue length during the green phase stage can be analyzed using the traffic shockwave theory. To simplify the discussion, we assume that the arrival of vehicles within one cycle is uniform. Based on this assumption, how queues form and discharge at a signalized intersection can be approximated, as shown in Fig. 3.

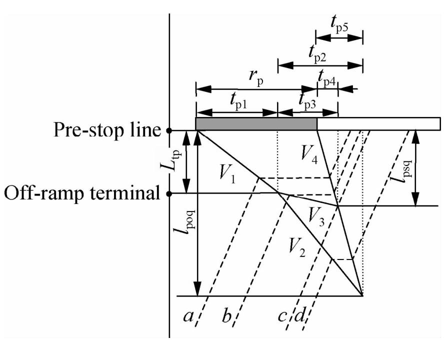

Fig. 3 Shockwave propagation at the pre-stop line

In Fig. 3, L_{tp} indicates the distance between the off-ramp terminal and pre-stop line, and l_{poq} and l_{psq} denote the maximum queue lengths at the surface street and off-ramp, respectively. In addition, V_1 is the queue-forming wave before the queue reaches the off-ramp terminal; V_2 is the queue-forming wave of the surface street after the queue reaches the off-ramp terminal; V_3 is the queue-forming wave of the off-ramp after the queue reaches the off-ramp terminal; V_4 is the queue-discharging wave, and t_{px} is the time parameter required for the model calculation.

In the early stage of the pre-signal red phase, vehicles from the surface street and off-ramp could change lanes before reaching the pre-stop line, and the queue-forming wave is V_1. When the queue reaches the ramp terminal, due to the barrier caused by the queue, the surface street traffic and off-ramp traffic form an independent queuing system. When the pre-signal green light turns on, the queue starts to dissipate, and the dissipating wave speed is V_4. When the dissipating wave reaches the end of the queue, the ground road and off-ramp queue up to the farthest upstream position. Based on the traffic shockwave theory, the speeds of the four waves can be calculated as

$$V_1 = \left| \frac{0 - q_{\mathrm{a}}}{k_{\mathrm{j}} - k_{\mathrm{a}}} \right| = \frac{q_{\mathrm{a}}}{k_{\mathrm{j}} - k_{\mathrm{a}}} \tag{16}$$

$$V_2 = \left| \frac{0 - q_{\mathrm{o}}}{k_{\mathrm{j}} - k_{\mathrm{o}}} \right| = \frac{q_{\mathrm{o}}}{k_{\mathrm{j}} - k_{\mathrm{o}}} \tag{17}$$

$$V_3 = \left| \frac{0 - q_{\mathrm{s}}}{k_{\mathrm{j}} - k_{\mathrm{s}}} \right| = \frac{q_{\mathrm{s}}}{k_{\mathrm{j}} - k_{\mathrm{s}}} \tag{18}$$

$$V_4 = \left| \frac{q_{\mathrm{m}} - 0}{k_{\mathrm{m}} - k_{\mathrm{j}}} \right| = \frac{q_{\mathrm{m}}}{k_{\mathrm{j}} - k_{\mathrm{m}}} \tag{19}$$

where q_{a} and k_{a} are the average volume and density of the arrival flow from the moment the red phase starts to the moment the queue reaches the off-ramp terminal, respectively; q_{o} and k_{o} denote the average volume and density of the off-ramp arrival flow from the moment the queue reaches the off-ramp terminal to the moment the green phase starts; q_{s} and k_{s} indicate the average volume and density of the surface street arrival flow from the moment the queue reaches the off-ramp terminal to the moment the green phase starts, respectively; k_{j} is the jam density; v_{f} is the free flow speed; q_{m} is the maximum volume; k_{m} is the critical density.

Based on the traffic shockwave theory, the maximum queue length at the off-ramp and surface street can be calculated as

$$V_1 t_{\mathrm{p1}} = L_{\mathrm{tp}} \tag{20}$$

$$L_{\mathrm{tp}} + V_3 t_{\mathrm{p3}} = l_{\mathrm{psq}} \tag{21}$$

$$V_4 t_{\mathrm{p4}} = l_{\mathrm{psq}} \tag{22}$$

$$t_{\mathrm{p1}} + t_{\mathrm{p3}} = r_{\mathrm{p}} + t_{\mathrm{p4}} \tag{23}$$

$$l_{\mathrm{psq}} = L_{\mathrm{tp}} + V_3 \left(\frac{V_4 L_{\mathrm{tp}} - V_1 V_4 r_{\mathrm{p}} - V_1 L_{\mathrm{tp}}}{V_1 V_3 - V_1 V_4} \right) \tag{24}$$

$$L_{\mathrm{tp}} + V_2 t_{\mathrm{p2}} = l_{\mathrm{poq}} \tag{25}$$

$$V_4 t_{\mathrm{p5}} = l_{\mathrm{poq}} \tag{26}$$

$$t_{\mathrm{p1}} + t_{\mathrm{p2}} = r_{\mathrm{p}} + t_{\mathrm{p5}} \tag{27}$$

$$l_{\mathrm{poq}} = L_{\mathrm{tp}} + V_2 \left(\frac{V_4 L_{\mathrm{tp}} - V_1 V_4 r_{\mathrm{p}} - V_1 L_{\mathrm{tp}}}{V_1 V_2 - V_1 V_4} \right) \tag{28}$$

where r_p denotes the duration of the pre-signal green phase in a cycle.

Constraint 1 To ensure traffic operation safety at the upstream intersection and the mainline of the expressway, the available queue space after setting the pre-signal should be larger than the maximum queue length. The available queue space can be calculated based on the number of off-ramp lanes. If the number of off-ramp lanes is greater than two, vehicles can be allowed to queue on the off-ramp; otherwise, vehicles are prohibited from queueing.

$$L_a = \begin{cases} L_f + L_{tp} & n_o \geqslant 2 \\ L_{tp} & n_o = 1 \end{cases} \tag{29}$$

$$L_a \geqslant l_{psd} \tag{30}$$

$$L_{ui} \geqslant l_{psq} \tag{31}$$

where L_a denotes the available queue space for vehicle queuing; L_{ui} indicates the distance from the upstream intersection to the pre-signal stop line; and L_f denotes the length of the off-ramp.

2.3.2 Sorting area length constraint

The process of queue formation and discharge in the sorting area can be approximated, as shown in Fig. 4. W_1, W_2, and W_3 denote the queue-forming waves at different stages; W_4 indicates the queue-discharging wave; l_{sq} is the maximum queue length in the sorting area; L_s denotes the length of the sorting area; L_c indicates the length of the lane-changing area; and t_{mx} is the time parameter required for the model calculation.

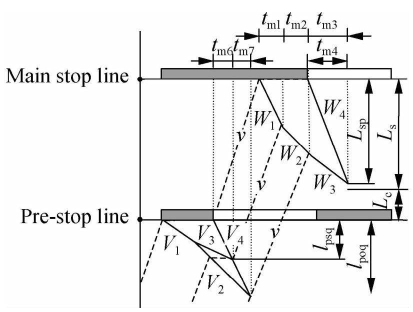

Fig. 4 Shockwave propagation in the sorting area

The service rate at the beginning of the green phase stage is the saturation flow rate S_p, and the queue-forming wave is W_1. When the surface street queue is cleared, the vehicle arrival flow rate decreases, and the queue-forming wave is W_2. When the off-ramp queue is cleared, the vehicle arrival flow rate decreases again, and the queue-forming a wave is W_3. After the main signal turns green, the queue starts to discharge and forms a queue-discharging wave W_4. When the queue-discharging wave reaches the forming wave, the queue reaches the farthest upstream position.

Based on the traffic shockwave theory and geometry knowledge, the maximum queue length in the sorting area can be calculated as

$$W_1 t_{m1} + W_2 t_{m2} + W_3 t_{m3} = W_4 t_{m4} \tag{32}$$

$$t_1 + t_2 + t_3 + t_5 = t_4 + \Delta g_p \tag{33}$$

$$v t_{m5} = L_s + L_c \tag{34}$$

$$v t_{m8} + W_1 t_{m1} = L_s + L_c + l_{psq} \tag{35}$$

$$v t_{m9} + W_1 t_{m1} + W_2 t_{m2} = L_s + L_c + l_{poq} \tag{36}$$

$$t_{m5} + t_{m1} = t_{m6} + t_{m8} \tag{37}$$

$$t_{m6} + t_{m7} + t_{m9} = t_{m5} + t_{m1} + t_{m2} \tag{38}$$

$$t_{m6} = t_{p4} \tag{39}$$

$$t_{m7} = t_{p5} \tag{40}$$

$$t_{m5} = \frac{L_s + L_c}{v} \tag{41}$$

$$t_{m6} = \frac{L_{tp}}{V_4} + \frac{V_3}{V_4}\left(\frac{V_4 L_{tp} - V_1 V_4 g_{pr} - V_1 L_{tp}}{V_1 V_3 - V_1 V_4}\right) \tag{42}$$

$$t_{m7} = \frac{L_{tp}}{V_4} + \frac{V_2}{V_4}\left(\frac{V_4 L_{tp} - V_1 V_4 g_{pr} - V_1 L_{tp}}{V_1 V_2 - V_1 V_4}\right) \tag{43}$$

$$t_{m1} = \frac{L_s + L_c + l_{psq} - v[(L_s + L_c)/v - l_{psq}/V_4]}{v + W_1} \tag{44}$$

$$t_{m2} = \frac{L_s + L_c + l_{poq} - W_1 t_{m1} - v(t_{m5} + t_{m1} - t_{m6} - t_{m7})}{v + W_2} \tag{45}$$

$$t_{m3} = \frac{W_4(t_{m1} + t_{m2} + t_{m5} - g_{pw}) - W_1 t_{m1} - W_2 t_{m2}}{W_3 - W_4} \tag{46}$$

$$l_{sq} = W_1 t_{m1} + W_2 t_{m2} + W_3 t_{m3} \tag{47}$$

Constraint 2 To ensure the operational efficiency of the intersection, the length of the sorting area should be greater than the length of the maximum queue in the sorting area. Taking into account the volatility of the traffic volume, the safety distance is set. Based on the known length of the sorting zone, the location of the pre-signal setting can be determined, expressed as the distance from the downstream main signal stop line.

$$L_s \geqslant l_{sq} + L_a \tag{48}$$

$$L = L_s + L_c \tag{49}$$

where L indicates the location of the pre-signal.

In summary, considering the geometric constraints of the section and the efficiency of the intersection and the main line of the expressway, the following steps are designed to select the location of the pre-signal setting:

Determine the initial pre-signal setting position L according to Constraint 2.

Check whether the upstream queuing length of the pre-signal meets Constraint 1 when the sorting area is L.

If yes, determine L as the pre-signal setting position; if not, adjust the pre-signal green light lighting time and return to the first step.

Determine the pre-signal green light start time Δg_p and pre-signal green time g_p.

3 Case Study

A case study was applied to validate the effectiveness of the control method. The intersection of Ziyou Road-Xiantai Road in Changchun, China, was selected. The geometric layout of the intersection is shown in Fig. 5(a). Limited by land use, the distance between the off-ramp terminal and the downstream intersection is only 128 m. The traffic demand during peak hours was surveyed in October 2019, as shown in Tab. 1. In this study, the saturation flow rate for every lane is 1 800 veh/h, and the designed speed is 30 km/h.

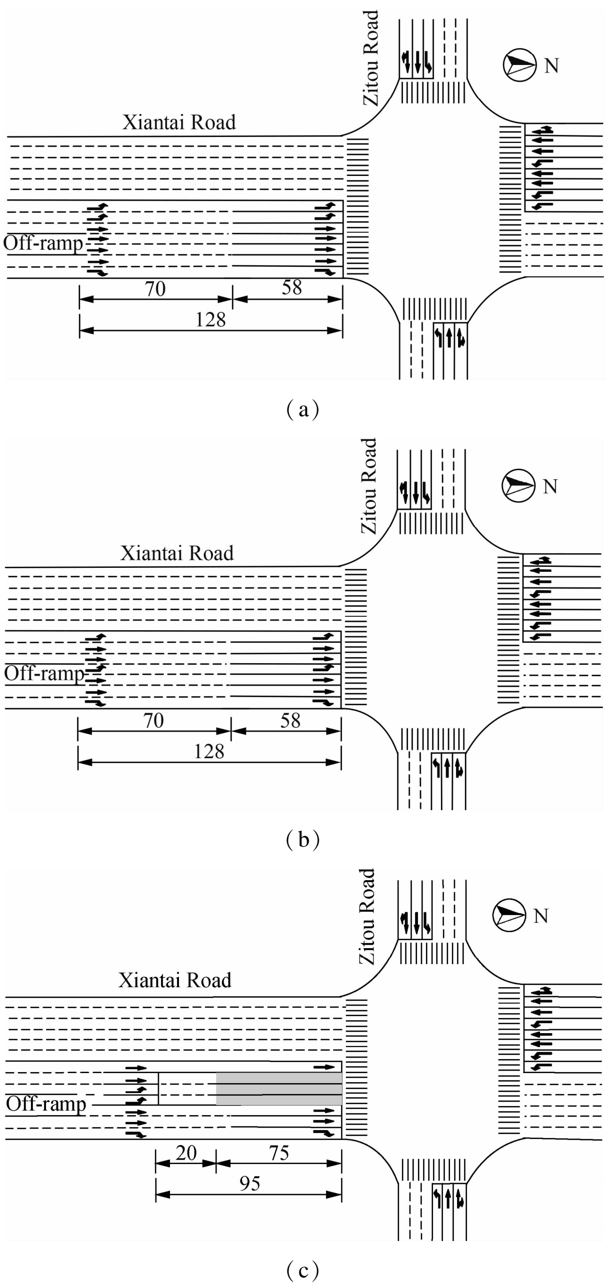

Fig. 5 Layout design(unit: m). (a) Original layout; (b) Separate left-turn design layout; (c) Proposed layout

Tab. 1 Traffic demand

Leg	Volume/(veh · h^{-1})		
	Left	Through	Right
South (surface street)	369	1 103	124
South (off-ramp)	641	807	142
North	985	1 804	269
East	146	445	89
West	177	356	147

The optimized layout for the intersection is illustrated in Fig. 5(c). The sorting area length was set to 75 m, and the lane-changing area length was set to 20 m. Fig. 6 is the signal timing. The signal timing under the original layout scheme was calculated by Webster. In addition, the separate left-turn design was set for comparison. The idea of the separated left-turn design is to add several left-turn lanes at the downstream entrance of the off-ramp.

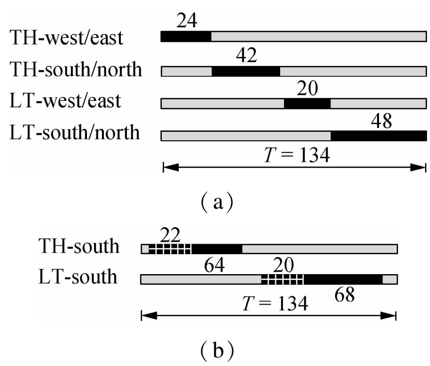

Fig. 6 Signal timing(unit: s). (a) Main signal; (b) Pre-signal

The VISSIM simulation package evaluated the performance of the intersection. The average vehicle delay and total throughput are the performance indicators used for the evaluation. The comparison results, which are the average results of 10 simulation runs, are shown in Tabs. 2 and 3.

Tab. 2 Performance comparison of delay s

Road	Movement	Conventional method	Separate left-turn method	Proposed method
Off-ramp	L	48.1	32.1	20.2
	T	74.9	91.9	48.5
	R	31.7	38.9	36.6
Surface street	L	50.2	30.4	27.3
	T	85.9	65.1	31.3
Average		54.9	57.7	33.1

Tab. 3 Performance comparison of throughput veh/h

Road	Movement	Conventional method	Separate left-turn method	Proposed method
South leg	L	838	884	904
	T	1 818	1 699	1 944
	R	246	244	249
Overall		2 902	2 827	3 097

As shown in Tabs. 2 and 3, the proposed method with the pre-signal reduced the average delay. The average delay of the left-turn flow coming from the off-ramp was decreased by 37.07% to 47.68%. On average, the proposed method can relatively obtain a 39.71% to 42.63% reduction in the average delay. Under the proposed method, the overall throughput was improved by 6.72% to 9.55%. The separate left-turn method can reduce the delay of left-turn vehicles, but at the cost of increasing the delay of through vehicles.

4 Numerical Analysis

A comprehensive numerical analysis was conducted to identify the best utilization of the proposed method. A four-leg intersection comprising 11 traffic lanes on each leg (six approach lanes and five exit lanes) was used for the analyses. The number of off-ramp lanes is two. The desired speed is 30 km/h. The off-ramp length is 200 m. The traffic volume of the west leg is 2 000 veh/h. The section length is 140 m. The left-turn proportion in the off-ramp flow is 0.3.

4.1 Traffic volume imparts

The traffic volume ranges from 50% to 150% of the initial volume, as shown in Fig. 7(a). The proportion of the left-turn traffic and the length of the connecting section were set to 0.3 and 140 m, respectively. As shown in Fig. 7(a), the advantage of the proposed pre-signal method in deducing delay will be reflected more significantly with an escalation in the traffic volume. The percentage of the decrement in the average delay obtained could be divided into two stages depending on the increase in the traffic volume. Firstly, if the traffic volume is low (less than 2 000 veh/h), the conventional method and separate left-turn method keep the average delay at a low value. The benefit of the proposed method in reducing average delay is not significant. Secondly, when the traffic volume is high (more than 2 000 veh/h), the delay under the conventional method rapidly increases with the traffic volume increase. Hence, the separate left-turn method is better than the conventional method. The decrement in the average delay obtained by the proposed method rapidly grows with the increase in the traffic volume.

4.2 Traffic distribution imparts

The left-turn proportion in the off-ramp flow was set from 0.1 to 0.7. The traffic volume and the length of the connecting section were set to 100% and 140 m, respectively. As shown in Fig. 7(b), for the conventional method, as the proportion of the left-turn traffic increases, the delay of the intersection significantly increases. Different from the conventional method, the separated left-turn method is more suitable for the high left-turn

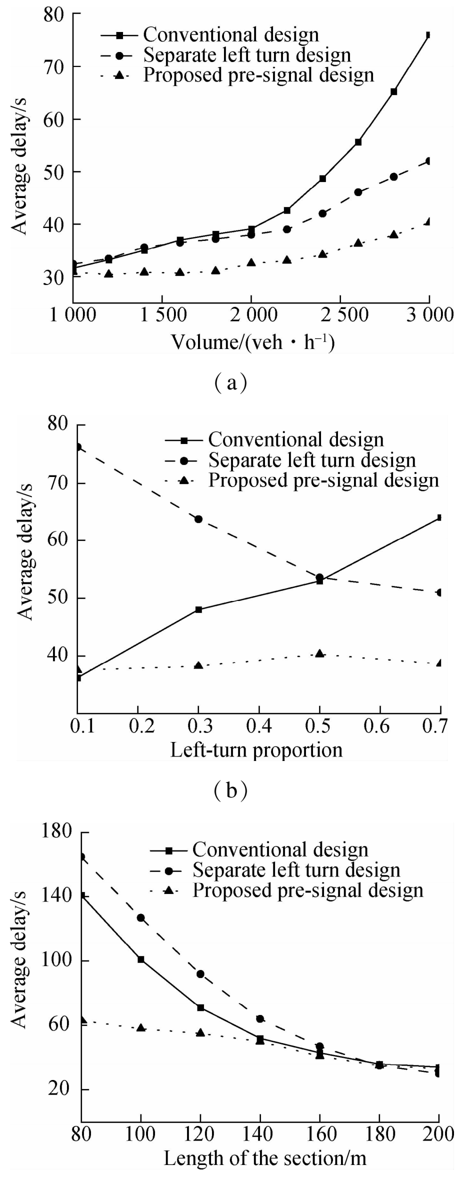

Fig. 7 Operational efficiency with different scenarios. (a) Traffic volume imparts; (b) Traffic distribution imparts; (c) Length of the section imparts

traffic flow. When the left-turn traffic flow is 0.7, the separated left-turn method can effectively reduce the vehicle delay as compared with the conventional method. However, the separated left-turn method will cause a large delay when the left-turn proportion is small. Compared with the above two methods, the delay of the pre-signal method proposed in this paper is not significant as the proportion of the left-turn flow increases, which indicates that the pre-signal method is relatively stable.

4.3 Connected section length imparts

To assess the section length imparts, the length of the connecting section was set to 100 to 200 m. The traffic volume and the left-turn ratio were set to 100% and 0.3, respectively. The results are shown in Fig. 7(c). For the conventional scheme, the length of the section has a great effect. When the section is short (less than 140 m), due to the limited interleaving distance, the vehicle delays are significant. Compared with the conventional method and separated left-turn method, the pre-signal method proposed in this paper can effectively alleviate the problem of vehicle efficiency reduction caused by insufficient weaving length.

5 Conclusions

1) A control method with a pre-signal is proposed to solve the weaving problem at the intersection downstream of an expressway off-ramp. The lane-changing delay model and queue models are established to support the method.

2) The case study shows that the pre-signal method can significantly improve the section's overall operating efficiency. The overall throughput is improved by 6.72% to 9.55%, respectively. The average delay is reduced by 39.71% to 42.63%. The numerical analysis results demonstrate the effectiveness and advantage of the pre-signal method.

3) In practice, the traffic flow is pre-organized by the pre-signal when the pre-signal is set, which results in changes in the traffic flow release characteristics. Thus, the conventional signal optimization model is not applicable, and the main signal timing parameters need to be further optimized.

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基于预信号的城市快速路出口匝道衔接交叉口控制方法

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摘要:为了提高城市快速路出口匝道与下游衔接交叉口的通行效率,提出了一种基于预信号的出口匝道衔接交叉口控制方法.分析流量流向分布特征,构建衔接区域换道延误计算模型;利用交通波理论,建立预信号上游排队长度和排序区长度模型;考虑主信号配时参数约束和排队长度约束优化,得到预信号配时参数以及预信号设置位置.案例分析结果表明,预信号方法可以显著提高衔接交叉口的通行能力,降低车均延误.通过数值仿真研究了左转交通比例、交通流及匝道衔接段长度对模型的影响,证实了所提模型的有效性和优越性.

关键词:交通工程;出口匝道;预信号;排序区;交通波理论

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