The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2632-0487.htm

Intersection control strategy optimization based on exchangeable lanes modeling

Bo Liu and Jingwen Hou
Research Institute of Highway Ministry of Transport, Beijing, China
Xiaoping Ma
State Key Laboratory of Traffic Control and Safety, School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China, and
Mengtong Shi, Sibo Lu and Ruoxuan Wang
School of Traffic and Transportation, Beijing Jiaotong University, Beijing, China

Received 29 June 2022
Revised 21 September 2022
Accepted 21 September 2022

Abstract

Purpose – Due to the conflicts between left turn traffic and opposite straight-going traffic in urban traffic network, some of the traffic lanes cannot be used to discharge vehicles during its green phases and the intersection capacity can be greatly reduced. This study/paper aims to reduce the effect of conflicts and increase its capacity through the reasonable pre-signal phase time with the exchangeable lanes.

Design/methodology/approach – This paper took into consideration various influence factors to intersection capacity and formulated the capacity optimization model based on 0-1 mixed-integer programming model. This model is efficiently solved by standard branch-and-bound algorithms.

Findings – The authors took an intersection as an example and solved the optimal signal timing and entrance lane capacity via this model. Then, simulations were carried out to verify the effect of the exchangeable lanes strategy of this intersection through the simulation software VISSIM and take the traffic volume and delay as outputs, which indicated that this model has better performance.

Originality/value – The front-end control strategy can not only exploit the full potential of the intersection but also significantly improve the operational efficiency of the intersection. It plays a positive role in improving urban intersection congestion.

Keywords Sorting strategy, Pre-signal, 0-1 Mixed-integer programming model, Standard branch-and-bound algorithms

Paper type Research paper

This project was supported by the Central Public-Interest Scientific Institution Basal Research Fund (2020-9018 and 2021-9081) and National Training Program of Innovation and Entrepreneurship for Undergraduates (Contract No. 202110004113).

Smart and Resilient Transportation
Vol. 4 No. 3, 2022
pp. 209-224
Emerald Publishing Limited
e-ISSN: 2632-0495
p-ISSN: 2632-0487
DOI 10.1108/SRT-06-2022-0014

1. Introduction

With the development of the city, urban road traffic gradually increases, the mutual interference of various traffic is also increasingly serious. Especially at the location of road intersections, because of the need to take the traffic in all directions into account, the capacity of the intersection is less than the capacity of the road section and also restricts the overall capacity of urban roads (Dengguo and Fan, 2012). Improper traffic signal timing, coordination and optimization at urban intersections are the main technical causes of traffic congestion. By optimizing the intersection signal timing scheme, the safety and smoothness of urban traffic can be effectively improved (Xu and Xi, 2021).

The optimization goal of urban traffic signal timing is to improve intersection capacity by reasonable signal timing, so that it can be optimized under existing road conditions. The use of traffic management to solve the problem requires less capital and is more effective than strengthen transportation infrastructure, so it is favored by most countries (Xiao, 2017). Research on this can be divided into two categories. One is building common model of intersection signal timing. As the signal assigns unreasonable time to each intersection, it will reduce the intersection road capacity, so changing the assigned time of the road intersection signal is a proven method (Xiao, 2017). The method mainly considered factors such as intersection lane layout, signal phase and signal timing cycle (Improta and Cantarella, 1984; Improta and Cantarella, 1984). Representative methods are Webster method (Parker, 2009) and the bilevel programming model, which was proposed by Allsop (1972), and combined problems of traffic signal optimization controlling and path choice (Gallivan and Heydecker, 1988). Two-level planning is a hierarchical planning problem containing a two-level recursive structure, where the upper-level model and the lower-level model have their own objective functions and constraints, respectively. Both layers can independently build their own mathematical models and form their own decisions. At the same time, the decisions made by the decision-makers of each layer will influence the parameter values and decision methods of the other layer, and finally, both layers can obtain their own optimal objective values (Chen and Chou, 2011). Additionally, Australian scholar Akeelik (2016) introduced the “parking compensation factor” to combine the number of stops and vehicle delays to establish a signal timing scheme. The ARRB method is used to optimize the comprehensive index. Finally, the HCM method for optimal signal period is based on the US Road Capacity Manual (Peng, 2012).

The other is separating left-turn traffic from traffic in other directions during the green phase, including left-hand turn forbiddance, advanced shunting of left-turn traffic flow and the left-turn lane, which increases intersection capacity by eliminating left-turn traffic or left-turn demand (Silcock, 1997; Laval, 2011). In recent years, there has been an intersection signal control method based on exchangeable lane strategy, which reorganizes interlace traffic flow by setting up a pre-signal, so all lanes at the intersection can run traffic flow when turning left phase. Xuan *et al.* proposed the tandem exchangeable lane strategy with advance signal in 2011, which is realized by setting the space area with changing lanes between the pre-signal light and intersection signal light (Xuan *et al.*, 2011), as shown in Figure 1.

In Figure 1, no matter the traffic flow is going straight or turning left, the vehicles that enter the queuing area of the interchange lane first can use all the lanes of the entrance lane to pass by using the pre-signal, so as to quickly release the traffic flow accumulated in the flow direction. However, the queuing area of the interchange lane is too long, by which the travel time consumption caused cannot be ignored. To reduce the length of the queuing area, Xuan *et al.* suggested a phase-divided queueing strategy for exchangeable lanes in 2011. Through the control of pre-signal, only traffic flow in one direction is allowed to accumulate and queue into the queuing area of the interchange lane at a time (Xuan *et al.*, 2011). This method can effectively reduce the length of the queuing area and the consumption of passing time, as shown in Figure 2.

At the beginning of the cycle, the pre-signal light shows green light to left-turn traffic to allow left-turn traffic to enter the exchange queuing area. At this time, the intersection signal light shows red, and left-turn vehicles use all lanes of the entrance lane and stop at the intersection parking line. In Figure 2(a), the pre-signal light turns red and the intersection signal light turns green, and left-turning vehicles use all lanes to pass quickly until the exchange queuing area is cleared. In Figure 2(c) and 2(d), only the left-turn traffic flow is replaced by the straight-going traffic flow, and the operation method of the signal control system remains the same. The type and timing of vehicles in the mixed lanes are assigned through pre-signal linkage control, which can well eliminate the problem of low intersection capacity and thus make efficient use of intersection space and time resources (Luo, 2007).

The research object of this paper is exchangeable lane queuing strategy in subphase described in Figure 2. An optimization model of this strategy is established based on 0-1 mixed integer programming model to maximize traffic capacity under the implementation of this strategy.

In this study, Synchro microscopic traffic simulation software is used to simulate and evaluate each timing scheme. Because Synchro software has powerful traffic signal timing optimization functions, the study is able to use the software to compare the traffic signal

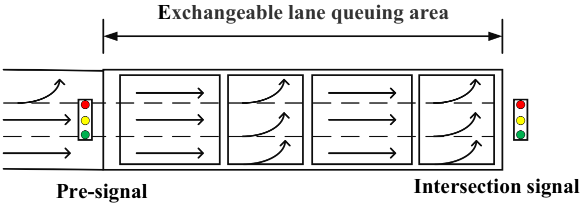

Figure 1. Tandem exchangeable lane strategy

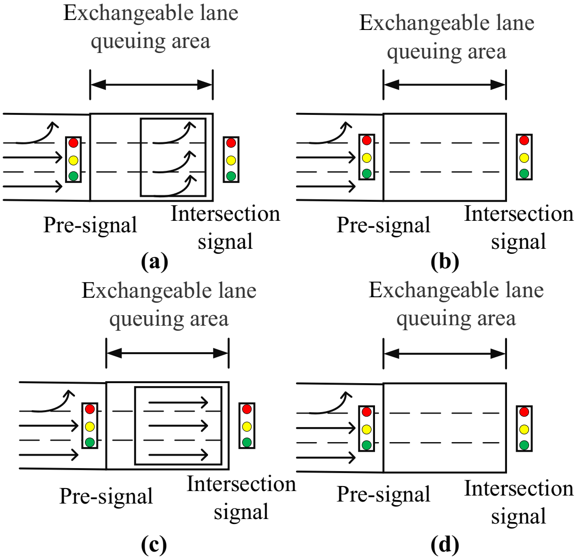

Figure 2. Exchangeable lane queuing strategy in subphase

timing schemes before and after optimization and discuss the optimization results of different timing schemes to verify the optimization effect of the model proposed in this paper (Deng, 2021).

Recently, many research on intersection traffic signal control have been studied. A traffic flow prediction model can predict future traffic state and consider the variables that affect actual traffic conditions (Kim and Jeong, 2020; You and Zhou, 2020). This model optimizes signal timing by improving the ability of acquiring information at intersections. However, it has some problems like low efficiency in large-scale problems, external disturbance and uncertainties.

Moreover, with the emerging connected vehicle (CV) technology, a new joint control model which optimized the speeds of the CVs and coordinated signals along an arterial simultaneously has been proposed (Liang *et al.*, 2019). It optimizes signal timing plans along an arterial to achieve lower signal delay and higher throughput. This method developed a dynamic platoon dispersion model to predict vehicle arrivals by using CV data. Then, a signal timing optimization model is constructed by minimization of average vehicle delay as the optimization objective and setting the green time duration of each phase as a constraint, which can also provide speed guidance to individual vehicles to minimize total number of stopping maneuvers (Yao *et al.*, 2020; Du, 2020). But the data that drives the model relies heavily on fully CV technology and infrastructure. The application of this method is usually affected by the penetrance of CVs.

Another set of methods use main signal and pre-signal to control the direction of dynamic waiting lane periodically. Based on the study of vehicle delay at intersections with dynamic waiting lanes and the constraint relationship between the main signal and the pre-signal, a coordinated control model of the main signal and the pre-signal was established to minimize the waiting lane and average delay (Chen *et al.*, 2018; Li *et al.*, 2019; Zhao *et al.*, 2020). The pre-signal system can make full use of all lane space, which can significantly improve the utilization rate of road space. However, these studies seldom consider the case of intersection oversaturation.

In this paper, we base on the exchangeable lanes strategy to reduce the effect of conflicts and increase its capacity through the reasonable pre-signal phase time. This paper took into consideration various influence factors to intersection including exchange queue area capacity limits, signal timing constraints and split-phase principle capacity and formulated the capacity optimization model based on 0-1 mixed-integer programming model. The model can directly address the key issues in the implementation of the exchangeable lane strategy and improve the application value of the model. This method belongs to pre-signal control, which is applied to congestion and noncongestion, especially congestion. The signal cycle time of the original timing scheme is not changed, which is convenient to promote the subsequent single point to surface collaborative control research, and ensures the accuracy and credibility of the evaluation results of vehicle average delay.

2. Introduction to exchangeable lane strategy

2.1 Operation of the exchangeable lane strategy

For the pre-signal, no matter the traffic flow is going straight or turning left, the vehicles that enter the queuing area of the interchange lane can use all the lanes of the entrance lane to pass, which means that the lanes are no longer reserved for traffic in one specific direction. In a word, the flow direction of traffic in the lanes is exchangeable and controlled by the pre-signal.

To introduce the operation method of the exchangeable lane queuing strategy in subphase, this paper takes an intersection where all intersections have interchangeable lane queuing area as an example, as shown in Figure 3.

Figure 3(a) is the initial state of the intersection, where both the pre-signal light and the intersection signal light are red. Figure 3(b) is the first state, where the pre-signal light at intersection 1 and intersection 3 turns green and the straight-going traffic enters the exchange queuing area. Figure 3(c) is the first phase of the signal light at the intersection. The intersection signal light turns green, allowing the straight-going traffic at intersections 1 and 3 to pass. At this time, the pre-signal light at intersections 1 and 3 turns red, whereas the pre-signal light at intersections 2 and 4 turns green, allowing the straight-going traffic enter the exchange queuing area. The subsequent phases can be operated according to this principle. Through subphase control, the traffic flows passing through the exchange queuing area can quickly leave the intersection without conflict by using all road resources. To facilitate comparison, the operation statistics of the control system are shown in Table 1.

2.2 Model design thinking based on the strategy

In the analytical investigation of exchangeable lane queuing strategies, right-turning traffic flow is generally ignored in the existing research results, such as the literatures published by Xuan (2012) and Zhou and Zhuang (2013). The goal of this paper is to build a capacity optimization model for this strategy, where right-turning traffic flow should be considered at the same time. Therefore, the influence of all possible traffic directions should be taken into account when building the model in the study. As shown in Figure 4(a), the right-turning traffic flow can also be controlled by setting the pre-signal for exchangeable lane queuing strategy. However, right-turning traffic flow does not conflict with other traffic flow, there is no need to set pre-signal control separately for right-turning traffic flow, as shown in Figure 4(b). Of course, there can also be no pre-signal for turning left or going straight, but it should be noted that the time distribution of straight-go traffic flow at the exchange queued opposite intersection is at different levels. Under this method, the left-turn traffic flow can no longer set a dedicated left-turn lane, as shown in Figure 4(c).

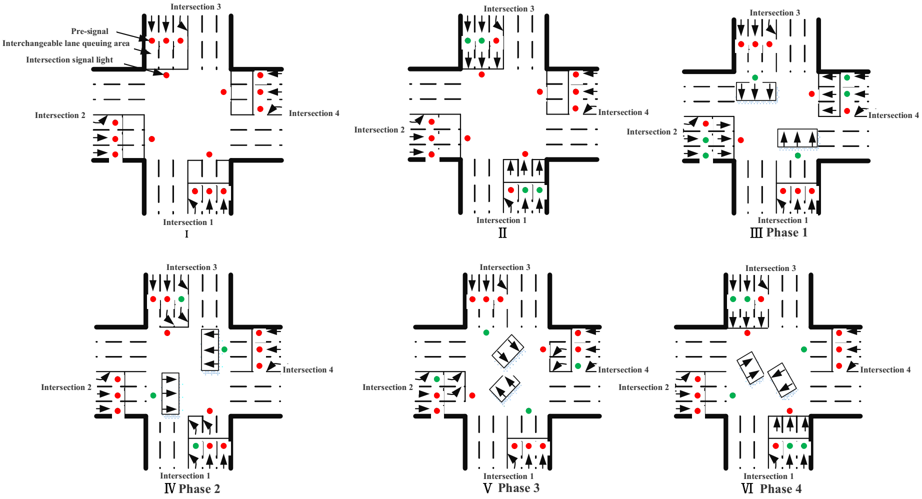

Figure 3.
Operation of exchangeable lane strategy

Table 1.
Statistical table of the signal change of exchangeable lane queuing strategy in subphase

	Intersection 1, intersection 3				Intersection 2, intersection 4			
	Pre-signal				Pre-signal			
Phase	Turn-left	Go-straight	Exchangeable lane queuing	Intersection signal	Turn-left	Go-straight	Exchangeable lane queuing	Intersection signal
1	Red light	Red light	Go-straight	Green-light	Red light	Green-light	Go-straight	Red light
2	Green-light	Red light	Turn-left	Red light	Red light	Red light	Go-straight	Green-light
3	Red light	Red light	Turn-left	Green-light	Green-light	Red light	Turn-left	Red light
4	Red light	Green-light	Go-straight	Red light	Red light	Red light	Turn-left	Green-light

In the case of going straight, it is necessary to conditionally not set the pre-signal. Going straight without the pre-signal separates left turn and right turn, indirectly making left turn and right turn unable to exchange queue in any lane other than lane of their own flow, so the strategy cannot be implemented, as shown in Figure 5(a). However, it is meaningful to set a separate pre-signal for straight traffic. If the straight traffic flow is controlled, the left-turn traffic flow will no longer conflict with traffic flow, and there is not signal lights delay can also improve the capacity of the intersection, as shown in Figure 5(b).

To sum up, under the exchangeable lane strategy, lane arrangement can be divided into two types: participating in the exchange queuing and not participating in the exchange queuing. The layout of pre-signals will change with the difference of lane layout, so lane layout needs to be determined in model construction. In addition, the exchangeable queuing area is used to exchange accumulated traffic flow, and its length is too short, which may cause some vehicles to queue upstream of the pre-signal. However, if it is too long, it will increase the passing time of vehicles participating in the exchange queue and reduce the through capacity. Therefore, the length of the exchange queuing area should be optimized during model construction. Finally, according to the flow characteristics of traffic flow at the intersection, the road marking should be left turn, straight go, right turn and other traffic flows from the road center line to the road edge line. This paper does not consider the case of special marking.

3. Construction of capacity optimization model

This paper proposes a capacity optimization model based on the exchangeable lane strategy. The input parameters of the model include intersection type (determine the total number of intersections), the number of lanes in each entrance and exit lane, the traffic demand of each traffic direction and the length of signal cycle. The output of the model includes the setting position of the pre-signal light, the length of the exchange queuing area, the lane layout of each traffic direction in the exchange queuing area, the timing scheme of the pre-signal light and the intersection signal light and the improvement degree of the intersection capacity.

3.1 Model design thinking based on the strategy

To abstract the real problems into mathematics, this paper describes the actual situation of intersections through design variables according to the characteristics of intersections. As

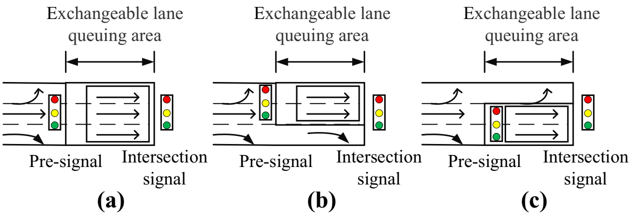

Figure 4. Layout scheme 1 of exchangeable lane strategy

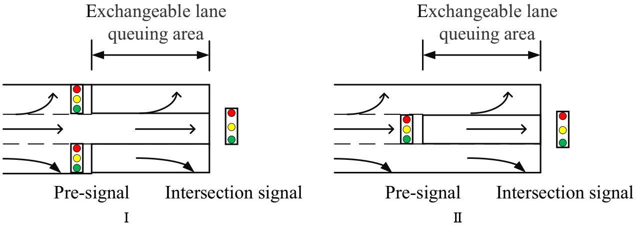

Figure 5. Layout scheme 2 of exchangeable lane strategy

shown in Figure 6, i represents the ith intersection, and the total number of intersections is N, then $i \in (1, N)$. N_i^{in}, N_i^{out}, respectively, represent the number of inlet and outlet roads at intersection i. To facilitate the recording of traffic flow direction, this paper takes intersection I, the starting point of traffic flow, as the origin and turns in clockwise direction to record, so the other intersections in turn are $1 \sim \text{N-1}$, denoted as j. Based on this, (i, j) can be defined to represent the traffic direction, as shown in Figure 6.

According to Figure 6, if you want to know which intersection the actual traffic direction is from intersection i to, the end point can be defined as intersection $\text{H}(i,j)$, if $i + j \leq \text{N}$, $\text{H}(i,j) = i + j$, otherwise $\text{H}(i,j) = i + j - \text{N}$.

Because the different influences of lane arrangement will affect the arrangement of the pre-signal, each one is a scheme. Suppose there are altogether K_i plans at intersection I and use k to represent the kth scheme, then the number of lanes that can be exchanged in the exchange queuing area is defined as $\text{N}_{i,k}^{R}$, then $N_i^{\text{in}} \geq \text{N}_{i,k}^{R}$. $N_i^{\text{in}} \geq \text{N}_{i,k}^{R}$. In addition, the model is constructed with the expectation that the front signal-controlled traffic flow can use more lane resources for queue exchange because of capacity optimization considerations, so $\text{N}_{i,k}^{R}$ must be at least one more than the number of lanes in that direction of flow upstream of the front signal. Let the number of traffic flow lanes upstream of the preceding signal be $\text{N}_{i,j}^{P}$. Then, we have $\text{N}_{i,k}^{R} \geq min\left\{\text{N}_{i,j}^{P}\right\} + 1$. Let $N_{i,j,\text{k}}^{R}$ be the total number of exchange queue lanes used in flow direction (i, j) in the KTH scenario, where the total should neither exceed the total number of lanes at the incoming intersection nor the total number of regional lanes $N_{i,k}^{R}$, so we have $N_{i,j,\text{k}}^{R} = \min\left\{N_{i,k}^{R}, N_{\text{H}(i,j)}^{out}\right\}$. As the number of lanes at each junction itself is actually not very large, there are not many feasible solutions in urban roads because of the constraints of the previous analysis, so the construction model can be considered not to filter the solutions, but to enumerate them for comparison and select the one with the best capacity.

Set a 0-1 variable$y_{i,j}$. If flow direction (i, j) participates in the exchange queue, its value is 1. Regarding the queue area length, which is actually determined by the queue length of the accumulating traffic, the model assumes that the lengths of the various types of vehicles are known and that the queue area length can be determined from the composition of the vehicle types in the traffic flow and the total number of vehicles queued in a single lane, as

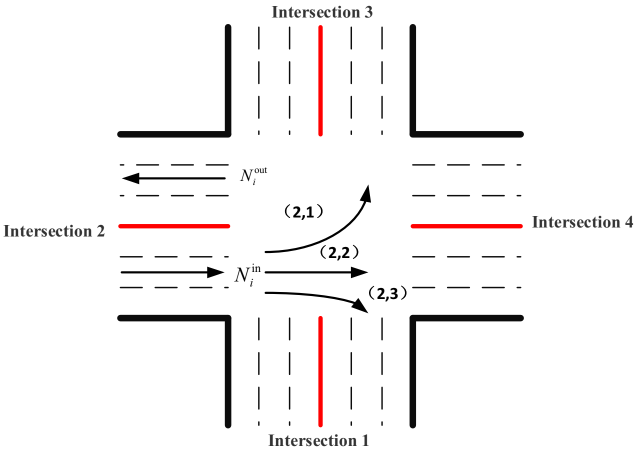

Figure 6.
Naming of traffic flow direction

well as the safe stopping interval. Let the safe stopping interval be L_i. Then, $L_i = f(N_L,\cdots,S_{\mathrm{safe}})$, where $N_L = f\left(N_L^{car}, N_L^{bus}, \cdots, r\right)$. The traffic demand of each flow direction is expressed as $q_{i,j}$, let the saturated traffic in the upstream lane of the preceding signal be s and the saturated traffic in the direct lane be s_{straight}. According to the calculation method proposed in Wong and Wong (2003), the saturated traffic flow of a lane in flow direction (i, j) can be set as $s_{(i,j)} = s_{\mathrm{straight}}/(1 + r_{i,j})$, where $r_{i,j}$ is the turning radius, which according to the literature is generally taken as 10 m for left turns, 3 m for right turns and M for straight ahead, denoting infinity.

As for the signal cycle length C, the signal cycle before the implementation of the interchangeable lane strategy can be taken, which has no special requirements for the signal cycle. Let $C \bullet \theta_{i,j}, C \bullet \phi_{i,j}$ be the onset and duration of the traffic flow phase at the intersection, $C \bullet \Psi_{i,j}$ and $C \bullet \Phi_{i,j}$ denote the onset and duration of the green light for the preceding signal traffic flow, respectively. Based on the traffic demand and the saturated traffic flow, the minimum green light time $g_{i,j}$ for the flow direction can be found. In addition, for two conflicting traffic flows (i, j) and (i', j'), a safety control time $t_{(i,j),(i',j')}$ needs to be set aside between the two phase alternations to ensure the safe operation of the intersection.

3. 2 Construction of the model

3.2.1 Determination of objectives. The algorithm of lane saturation traffic flow is analyzed, but lanes are not generally expected to operate at saturation traffic, and the ratio of the maximum number of vehicles carried by a lane to the saturation traffic can generally be set as $P_{i,j}$. A further parameter E is introduced, which represents the ratio of intersection capacity to the original intersection after the strategy has been implemented, and the feasibility of the strategy is known by the relationship between the magnitude of E and 1. The objective of the model in this paper can then be understood as an increase in capacity at each intersection, in each direction of flow, to an overall increase of $E - 1$. Assuming that the intersection lanes are symmetrical, the capacity at each intersection is E times the original, and if in practice the intersection lanes are asymmetrical, the proportion of $E - 1$ shared by each intersection can be calculated based on the number of lanes. Based on the above analysis, the objective function of the model can be set as:

$$\max Z = \sum_{i \in I, j \in J} \frac{E \cdot q_{i,j} \cdot C \cdot y_{i,j}}{N_{i,j,K}^{R}\left(\phi_{i,j} \cdot C + e\right) \cdot s_{i,j}} + \frac{E \cdot q_{i,j} \cdot C \cdot \left(1 - y_{i,j}\right)}{N_{i,j,K}^{P}\left(\phi_{i,j} \cdot C + e\right) \cdot s_{i,j}} \tag{1}$$

3.2.2 Binding conditions. Many of the constraints have already been covered in the previous variable descriptions, and further additions to the constraints are now made.

3.2.2.1 Boundaries of capacity optimization

$$\begin{aligned}
&\frac{E \cdot q_{i,j} \cdot C \cdot y_{i,j}}{N_{i,j,K}^{R}\left(\phi_{i,j} \cdot C + e\right) \cdot s_{i,j}} \le P_{i,j} + M \cdot \left(1 - y_{i,j}\right) \\
&\frac{E \cdot q_{i,j} \cdot C \cdot y_{i,j}}{N_{i,j,K}^{P}\left(\Phi_{i,j} \cdot C + e\right) \cdot s} \le P_{i,j} + M \cdot \left(1 - y_{i,j}\right) \\
&\frac{E \cdot q_{i,j} \cdot C \cdot \left(1 - y_{i,j}\right)}{N_{i,j,K}^{P}\left(\phi_{i,j} \cdot C + e\right) \cdot s_{i,j}} \le P_{i,j} + M \cdot y_{i,j} \\
&\forall i \in I, j \in J, k \in K_i
\end{aligned} \tag{2}$$

3.2.2.2 Exchange queue area capacity limits:

$$L_i \cdot N_{i,j,K}^R \geq E \cdot q_{i,j} \cdot C - M \cdot \left(1 - y_{i,j}\right) \tag{3}$$

This condition indicates that the queuing area should be long enough to avoid vehicles queuing outside the queuing area and interfering with the upstream traffic flow of the preceding signal.

3.2.2.3 Subphase principle restrictions. Because of the split-phase principle, different traffic flows from the same junction cannot use the intersection running traffic at the same time. Assuming there are two flows (1,*m*) and (1,*n*), let $\pi_{l,m,l,n}$denote the sequence of the two from the same junction, if $\theta_{l,m} \leq \theta_{l,n}$, then $\pi_{l,m,l,n} = 0$, otherwise its value is 1, which means that $\pi_{l,m,l,n}$ is a 0-1 variable. Then, the constraints on the split phase are as follows:

$$\pi_{l,m,l,n} + \pi_{l,n,l,m} = 1 \tag{4}$$

$$\theta_{l,m} + \phi_{l,m} \leq \Psi_{l,n} + \pi_{l,m,l,n} + M \cdot \left(2 - y_{l,m} - y_{l,n}\right) \tag{5}$$

For the two conflicting traffic flows (i,j) and $\left(i^{'},j^{'}\right)$, there must also be a sequential order of passage. Let $\boldsymbol{\Omega}_{i,j,i^{'},j^{'}}$ denote this order, if $\theta_{i,j} \leq \theta_{i^{'},j^{'}}$, then $\boldsymbol{\Omega}_{i,j,i^{'},j^{'}} = 0$, otherwise its value is 1, which means that $\boldsymbol{\Omega}_{i,j,i^{'},j^{'}}$ is a 0-1 variable. Then, there is the constraint that:

$$\boldsymbol{\Omega}_{i,j,i^{'},j^{'}} + \boldsymbol{\Omega}_{i^{'},j^{'},i,j} = 1 \tag{6}$$

$$\theta_{i,j} + \phi_{i,j} + t_{(i,j),\left(i^{'},j^{'}\right)}/C \leq \theta_{i^{'},j^{'}} + \boldsymbol{\Omega}_{i,j,i^{'},j^{'}} \tag{7}$$

3.2.2.4 Signal timing constraints. For front signals:

$$\Psi_{i,j} \leq \theta_{i,j} + M \cdot \left(1 - y_{i,j}\right) \tag{8}$$

$$g_{i,j}/C - M \cdot \left(1 - y_{i,j}\right) \leq \Phi_{i,j} \leq 1 + M \cdot \left(1 - y_{i,j}\right) \tag{9}$$

For intersection signals:

$$g_{i,j}/C \leq \phi_{i,j} \leq 1 \tag{10}$$

When the preceding signal changes to red, the intersection signal cannot immediately change to green because of the time needed to clear the traffic in the exchange queue area; this time difference is set to $T_{i,j}$. The description can then be expressed as:

$$\Psi_{i,j} + \Phi_{i,j} + T_{i,j}/C \leq \theta_{i,j} + \phi_{i,j} + M \cdot \left(1 - y_{i,j}\right) \tag{11}$$

In fact, with regard to $T_{i,j}$, to be on the safe side, its value should be greater than the clearing time for any case, that is:

$$T_{i,j} \geq T_{\max} = L_i / s_{i,j} \tag{12}$$

4. Example analysis

In this paper, an intersection of two six-lane roads with the width of 3.5 m in both directions is chosen as an example to validate the model, with a certain amount of input traffic at each intersection, as shown in Table 2 for the actual demand. It is worth mentioning that the "Actual needs" is the actual flow set during VISSIM simulation and the "Calculation of capacity" is the calculation result of the model. The vehicle model parameters in VISSIM are shown in Table 3. For comparison purposes, two signal control schemes are used, the usual scheme with signal control at the inlet only and the forward control strategy proposed in this paper. In the forward control scheme, both lanes in the queue area are available for either straight or left-turning traffic. The model is then solved using software such as LINGO and the results of traffic capacity at each intersection and green time at each intersection are obtained in Table 2. The signal control scheme is shown in Figure 7. The signal timing scheme of the pre-signal control strategy is formulated on the basis of the signal timing scheme under the general control strategy, and the signal periods of the two schemes are equal, both being 120 s. Taking the traffic flow starting from intersection, as an example, the right-turn traffic flow is not controlled by a separate pre-signal, and it is green throughout the whole process. Set up pre-signal control for right- and left-turn traffic. In this study, based on the straight traffic flow (1,3), according to the cyclic sequence from the front signal (1,3), to the intersection signal (1,3) to the front signal (1,2) to the intersection signal (1,2) to complete the timing of each phase. During this process, pay attention to the clearing time and the yellow light time of the front signal and the intersection signal. According to the above steps, the pre-signal timing scheme for one intersection is completed and the same for other intersections. As for whether different signal timing will influence the position of the end signals, it is indeed worth analyzing in the next research, but it is not within the scope of this manuscript.

The conventional signal timing scheme generated by Synchro software is shown in Figure 8. The signal cycle of both schemes is 120 s. The regular signal control strategy we set up for the benchmark intersection is a typical four-phase timing scheme. At the beginning of the signal cycle, straight and left-turn traffic at Entrance 1 will pass, with a green light time of 35 s. Then, there are straight vehicles on the 2nd and 4th entrances, and the green light time is 35 s. Then, there are three entrances going straight and left-turn traffic passing, the green light time is 35 s. Finally, the left-turn traffic at Entrance 2 and Entry 4 will pass, and the green light time is 15 s. The signal timing scheme is shown in Table 4.

Based on the intersection information provided earlier, a simulation model of the intersection is constructed in VISSIM software, and the signal timing scheme solved by the model is used to control the intersection. The simulation period is 240 s, that is, two signal cycle times, and the final results of the flow and delay evaluation indexes can be output as shown in Table 4. By comparing the differences, the reduction in "Average Delay" of the simulation results means the reduction in delay time and the increase in "Total simulated flow" of the simulation results means the increase in intersection capacity.

According to Table 4, it can be found that in both signal cycles, the through flow at each intersection under the front control strategy is greater than under the conventional control condition and the delays are less, and ultimately, in terms of overall total flow for the two cycles of the simulation, the total flow at the intersection under the front control strategy is 11 pcu greater than under the conventional control and the overall average delay is 1.25 s less. The simulated hourly flow rates obtained from the recursive calculation of the simulated flow rates at each intersection are very close to the calculated hourly flow rates, with an average absolute error of 4.87% and a maximum error of 11.48%, indicating that the accuracy of the model proposed in this paper is high; moreover, the overall simulation results (Table 5 and Figure 9) show that the intersection operation under the front-end control strategy is more orderly and makes full use of the

Table 2.
Result of capacity and green time in each intersection entrance

From the junction	To the junction	Actual needs (pcu/h)	Calculation of capacity (pcu/h)	Green light time (s)
1	2	400	403	25
1	3	600	616	39
1	4	500	506	–
2	1	500	505	–
2	3	300	307	16
2	4	500	511	37
3	1	600	614	39
3	2	400	416	–
3	4	500	506	25
4	1	300	304	16
4	2	500	504	37
4	3	400	415	–

Table 3.
Vehicle model parameters in VISSIM

Vehicle model parameter	
Car-following model type	Wiedemann 74
Length (m)	3.75
Width (m)	1.85
Maximum acceleration (m/s^2)	3.50
Expected acceleration (m/s^2)	3.00
Maximum deceleration (m/s^2)	−7.50
Expected deceleration (m/s^2)	−2.75

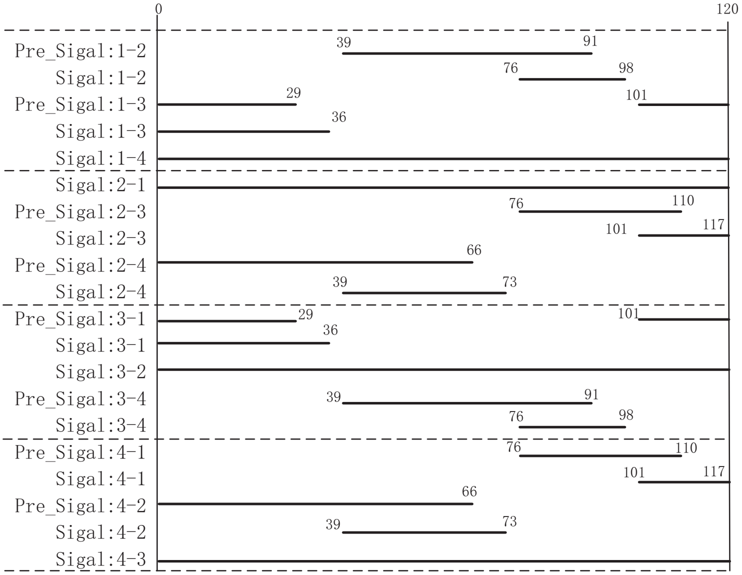

Figure 7.
Signal timing diagram of pre-control strategy

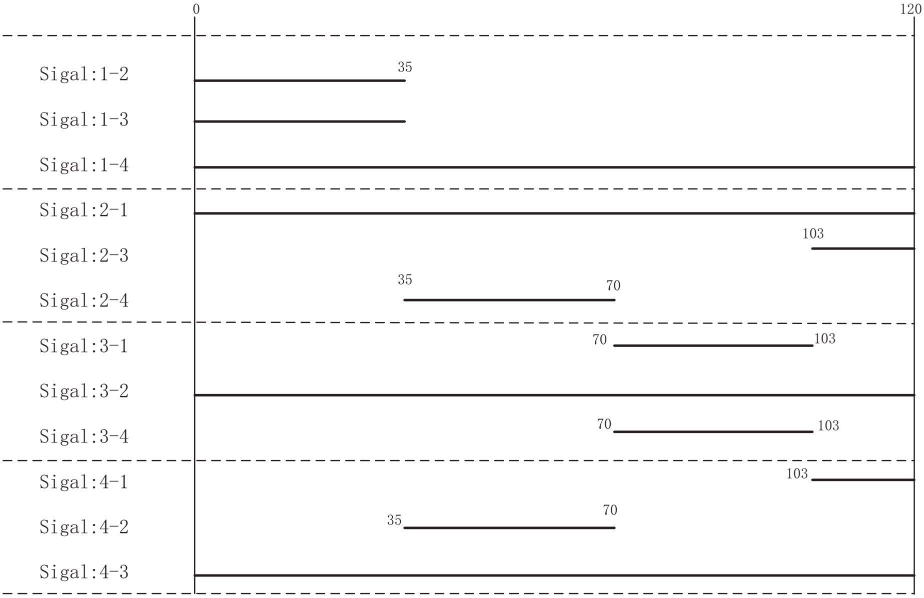

Figure 8. Signal timing diagram of regular control strategy

Phase no.	Traffic flow	Green light time (s)
1	(1,2) (1,3)	35
2	(2,4) (4,2)	35
3	(3,1) (3,4)	35
4	(2,3) (4,1)	15

Table 4. Regular signal timing scheme

space resources of the intersection. Therefore, the front-end control strategy can not only exploit the full potential of the intersection but also significantly improve the operational efficiency of the intersection.

5. Conclusion

In this study, a comparative simulation experiment was carried out on the traffic capacity and delay of the intersection under the control of the pre-signal control strategy and the regular signal control strategy without changing the length of the signal period. Simulation results show that the total simulated flow increased 165 pcu/h and the average delay was reduced by 1.25 s, which means a 3.14% improvement in the capacity and a 4.11% reduction in time delay. Considering that this study only changed the form of traffic control at the intersection without taking other measures, it is believed that the improvement effect of pre-signal is relatively obvious.

Based on the idea of intersection front signal control with exchangeable lane strategy, a capacity optimization model is constructed in this paper. The model considers the capacity optimization problem at following multiple levels– exchange queue area capacity limits: this condition is to avoid the exchange queuing area being too short, which will lead to the

Table 5.
Simulation results of VISSIM under these two control strategies

Control mode	Junction	Simulation flow (pcu)	Total simulated flow (pcu)	Simulated hourly flow (pcu)	Calculating hourly flow rates (pcu)	Delay for four intersection entrances (s)	Average delay (s)
General control	1	90	350	1,350	1,525	31.42	30.38
	2	84		1,260	1,323	29.18	
	3	94		1,410	1,536	31.43	
	4	82		1,230	1,223	28.86	
Front control	1	94	361	1,410	1,525	30.46	29.13
	2	86		1,290	1,323	27.39	
	3	99		1,485	1,536	30.69	
	4	82		1,230	1,223	27.56	

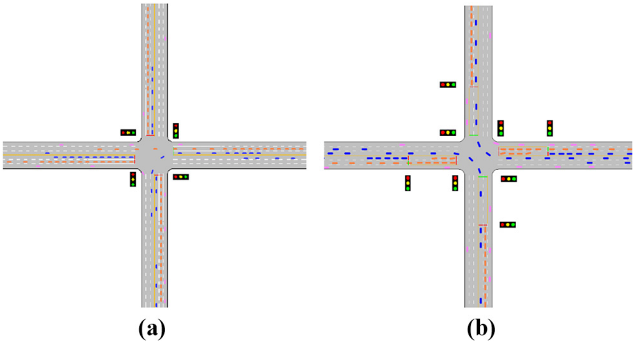

Figure 9.
Simulation effect of VISSIM under these two control strategies. (a) Conventional control solutions. (b) Front-end control strategy

interference between the queuing vehicles at the intersection and the upstream vehicles; signal timing constraints: this condition adjusts the phase of the front signal light and the intersection signal light to control the variable to ensure that the signal cycle under the front signal control strategy is equal to the signal cycle of the general control, so that the comparison results are credible; and split-phase principle: this condition is to determine the sequence of traffic flows in different directions from the same intersection, which is also based on the signal timing scheme under the general control strategy. It involves a comprehensive range of capacity influencing factors, directly addressing the key issues in the implementation of the exchangeable lane strategy and improving the application value of the model. The model is analyzed through an intersection example and solved using LINGO software programming to compare the degree of change in capacity before and after the implementation of the strategy, fully verifying the feasibility of the model.

References

Akcelik, R. (2016), "Traffic signals: capacity and timing analysis", research report.

Allsop, R.E. (1972), "Delay at a fixed time traffic signal—I: theoretical analysis[J]", *Transportation Science*, Vol. 6 No. 3, pp. 260-285.

Chen, H.K. and Chou, H.W. (2011), "Real-time vehicle routing for repairing damaged infrastructures due to natural disasters", *Mathematical Problems in Engineering*, Vol. 2011 No. 6, pp. 1253-1284.

Chen, Z., Chang, Y. and Peng, Z. (2018), "Coordinated control model of main-signal and pre-signal for intersections with dynamic waiting lanes", *Sustainability*, Vol. 10, p. 2849.

Deng, C. (2021), "Multi-objective optimization of intersection signal timing for urban traffic congestion sections", Northeastern Agricultural University.

Dengguo, W. and Fan, D. (2012), "Optimization of existing intersection capacity", *Urban Roads and Bridges and Flood Control*, Vol. 5, doi: 10.3969/j.issn.1009-7716.2012.05.083.

Du, R. (2020), "A review of research on intersection control based on connected vehicles and data-driven intelligent approaches", *Electronics*, Vol. 9 No. 6, p. 885.

Gallivan, S. and Heydecker, B. (1988), "Optimising the control performance of traffic signals at a single junction", *Transportation Research Part B*, Vol. 22 No. 5, pp. 357-370.

Improta, G. and Cantarella, G. (1984), "Control system design for an individual signalized junction", *Transportation Research Part B*, Vol. 18 No. 2, pp. 147-167.

Kim, D. and Jeong, O. (2020), "Cooperative traffic signal control with traffic flow prediction in multi-intersection", *Sensors (Basel, Switzerland)*, Vol. 20 No. 1.

Laval, J.A. (2011), "Hysteresis in traffic flow revisited: an improved measurement method", *Transportation Research Part B: Methodological*, Vol. 45 No. 2, pp. 385-391.

Li, Y., Nan, S., Gong, X. and Ma, R. (2019), "A geometric design method for intersections with pre-signal systems using a phase swap sorting strategy", *Plos One*, Vol. 14 No. 5, p. e0217741.

Liang, X.J., Guler, S.I. and Gayah, V.V. (2019), "Joint optimization of signal phasing and timing and vehicle speed guidance in a connected and autonomous vehicle environment", *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2673 No. 4.

Luo, J. (2007), "Multi-phase fuzzy control of single intersection based on pre-signal", *Traffic Standardization*, Vol. 2007 No. 7, doi: 10.3869/j.issn.1002-4786.

Parker, P.M. (2009), *Pierre Bourdieu: Webster's Timeline History, 1958-2007[J]*.

Peng, F. (2012), "Optimization and simulation research of signal timing at urban road level intersections", Beijing Jiaotong University.

Silcock, J. (1997), "Designing signal-controlled junctions for group-based operation", *Transportation Research Part A*, Vol. 31 No. 2, pp. 157-173.

Wong, C.K. and Wong, S.C. (2003), "Lane-based optimization of signal timings for isolated junctions", *Transportation Research Part B*, Vol. 37 No. 1, pp. 63-84.

Xiao, W. (2017), "Urban road traffic signal timing optimization based on VISSIM", *Journal of Lanzhou Institute of Technology*, Vol. 24 No. 6, pp. 76-81.

Xu, J. and Xi, J. (2021), "Q-reinforcement learning based signal timing model for arterial intersections", *Journal of Guangxi University (Natural Science Edition)*, Vol. 46 No. 4, pp. 1036-1044, doi: 10.13624/j.cnki.issn.1001-7445.2021.1036.

Xuan, Y., Cassidy, M. and Daganzo, C. (2012), "Using a pre-signal to increase bus-and car-carrying capacity at intersections: theory and experiment", *Transportation Research Board 91st Annual Meeting*, 12-1133.

Xuan, Y., Daganzo, C.F. and Cassidy, M.J. (2011), "Increasing the capacity of signalized intersections with separate left turn phases", *Transportation Research Part B: Methodological*, Vol. 45 No. 5, pp. 769-781.

Xuan, Y. (2011), "Increasing the flow capacity of signalized intersections with pre-signals: theory and case study", Ph.D. thesis, University of California, Berkeley.

Yao, Z., Jiang, Y., Zhao, B., Luo, X. and Peng, B. (2020), "A dynamic optimization method for adaptive signal control in a connected vehicle environment", *Journal of Intelligent Transportation Systems*, Vol. 24 No. 2.

You, S. and Zhou, Y. (2020), "Optimization driven cellular automata for traffic flow prediction at signalized intersections", *Journal of Intelligent and Fuzzy Systems*, Vol. 40 No. 1, pp. 1547-1566.

Zhao, J., Kigen, K.K. and Xia, X. (2020), "An alternative design for traffic intersections with work zones by using pre-signals", *Journal of Intelligent Transportation Systems*, Vol. 26 No. 2, pp. 1-15.

Zhou, Y. and Zhuang, H. (2013), "The optimization of lane assignment and signal timing at the tandem intersection with pre-signal", *Journal of Advanced Transportation*, Vol. 48 No. 4, pp. 362-376.

Corresponding author
Xiaoping Ma can be contacted at: xpma@bjtu.edu.cn