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An alternative design for traffic intersections with work zones by using pre-signals

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Abstract: The lane closures caused by the work zone at the approaches create a negative impact on the operational effectiveness of the signalized intersections. This paper presents an innovative design for intersections with work zones to improve the intersection's practical capacity. In this design, the lanes in the leg with work zone can be used dynamically as approach and exit lanes during different periods of a signal cycle by using the pre-signal. An optimization model for an optimal geometric layout and signal timing design is built to capture real-world operational constraints, including the lane assignment, the signal timing of the main signal and pre-signal, the distance of the mixed-usage area and the transition area, and the degree of saturation restriction. A case study and extensive numerical analysis demonstrate the effectiveness of the prospective design as compared with conventional designs under different geometric layout and traffic demand situations. Overall, the proposed design can lead to an increment in the practical capacity of the intersection with a work zone (by up to 30%) and reduce the average vehicular delay accordingly (by 50%) without necessitating an expansion of the intersection. The results show that the promising application of the proposed design when the length of the work zone is less than 160 m.

Keywords: Intersections, dynamic control, work zone, pre-signal, capacity

1. Introduction

The signalized intersections are the bottleneck of urban streets. Due to road pavement reconstruction, pipeline installation, underground engineering construction, the work zones sometimes should be set at the intersections, which results in a decrease in lane number (Li, Mori, & Work, 2018; Liu, Khattak, & Zhang, 2016). The capacity of the intersection reduces accordingly, which may even affect the adjacent road network if it the critical intersection in the region (Al-Deek and Emam, 2006; Lukose, Levin, & Boyles, 2019; Rayaprolu, Ishak, Qi, & Wolshon, 2013; Xu et al., 2020).

Three strategies can be used to reduce of adverse efficacy of the work zone on the running efficiency of the streets: optimizing diversion routes, optimizing work-zone schedules, and optimizing intersection design.

For the management of road networks, the impact of the work zone on the traffic flow was studied, and the diversion routes can be optimized to relieve the negative impact. Hou, Edara, & Sun (2015) proposed models to estimate planned work zone activities on traffic flow. Du, Chien, Lee, Spasovic, & Mouskos (2016) developed a hybrid machine-learning model to predict spatiotemporal deferral brought about by the work zone. Lethanh, Adey, & Burkhalter (2018) developed a GIS-based program to establish an optimal intervention in networks of large infrastructure with the objective of maximizing the benefits incurred by stakeholders. These various types of route guidance information can be provided by variable message signs (Z. He, Zheng, Guan, & Mao, 2016).

From the networks level, the work zone schedules and regional traffic organization strategies were optimized to improve the performance of the streets with the work zone. Zheng, Nava, & Chiu (2014) proposed a mathematical decision model to organize and set work zones in the planning process. L. Zhao, Chien, & Du (2019) developed a model to optimize work-zone schedules and associated characteristics to reduce the total cost by implementing effective traffic management strategies. The regional traffic organization method can equilibrate the traffic demands of the road network, and reduce the impacts of direct adversity on the work zone in the intersections.

Comparing with the network level strategies, the optimization design of the layout and signal control of the intersection is a more direct method of dealing with the congestion problem. The saturation flow rate should be analyzed. Hajbabaie et al. (2017) set up statistical models that gauge saturation headways as a function of the presence and arrangement of the work zone on signalized arterial avenues. Yang, Zhu, Ma, & Sun (2016) analyzed the flow rate of the signal intersection with the straddling work zone utilizing the multiplicative and linear regression models recommended by the Highway Capacity Manual. Once the saturation flow rate is determined, the function of approaches lanes should be reassigned under the requirement of the regional traffic organization schemes, such as turning prohibition (Tang and Friedrich, 2018) and one-way traffic (J. Zhao, Liu, & Li, 2016). For the signal timing, it should be adjusted accordingly with the change of the traffic demand and layout design of the intersection. Zhu, Li, Ash, Wang, & Hua (2017) developed a model to optimize the control scheme for the two-lane highway lane-closure work zone to minimize vehicular delay. Zlatkovic and Zhou (2015) proposed an integrated framework combining the signal timing and dynamic traffic assignment in feedback loops. Abdulsattar, Mostafizi, Siam, & Wang (2019) found that connected vehicle technologies can improve travel time and its reliability in the highway work zone scenario. Moreover, the traffic signs, markings, and light conditions should be set appropriately at the construction impact area to ensure traffic safety (Harb, Radwan, Abdel-Aty, & Su, 2011).

In the existing designs of the intersections with work zone, the reduction of lanes caused by lane closures was considered, but the length of the work zone was neglected. In many cases, the length of the work zone is limited, which only causes the lane closures of the approach, while the number of lanes on the road segment is unchanged.

This paper aims to improve the capacity of intersections with work zone by using pre-signals. The pre-signal was first used for transit signal priority (Wu and Hounsell, 1998). The pre-signals are installed to help buses transition out of the dedicated bus lane with minimal interruption to other vehicles (S. I. Guler and Menendez, 2014a, 2014b). H. He, Guler, & Menendez (2015) expanded the pre-signal design to be an adaptive control by formulating an online control algorithm. Jing Zhao and Zhou (2019) proposed a dynamic exclusive bus lane design. S Ilgin Guler, Gayah, & Menendez (2016) explored a novel method, in which the bus can jump a portion of the car queue using the traffic lane in the opposite direction under the control of pre-signals. Besides the transit signal priority, some unconventional intersection designs were proposed based on the concept of pre-signal, including continuous flow intersections (Jagannathan and Bared, 2004), tandem intersections (Xuan, Daganzo, & Cassidy, 2011), and exit-lanes for left-turn intersections (Jing Zhao, Ma, Zhang, & Yang, 2013).

In this study, the pre-signal will be utilized to increase the capacity of the intersection with the work zone (either on the approach or exit). The specific geometric condition of the intersection with work zone lies in that the number of lanes in the leg is limited due to the lane closures while the number of lanes on the road segment is sufficient. The proposed design makes almost all the lanes in the leg dynamically used for all movements, as shown in Fig. 1.

The rest of this paper is organized as follows. The concept of the design using pre-signal is introduced in Section 2. the optimization model is established in Section 3. A case study and extensive sensitivity analyses are conducted in Sections 4 and 5, respectively. Conclusions and recommendations are given at the end of the paper.

2. Design concept

The concept of this design is using the lanes in a leg with a work zone dynamically as approach lanes and exit lanes during different periods of a signal cycle by using the pre-signal.

In terms of geometric design, as shown in Fig. 1, a mixed-usage area is set at the leg with work zone. During various times of a period cycle, the lanes in the mixed-usage region can be used methodologically as approach and exit lanes. Besides the mixed-usage area, the bypass right-turn lane is set to guarantee there are no conflicts between the vehicles entering the mixed-usage area and the vehicles diverted from the left adjacent approach that turn right. Moreover, a pre-stop line is positioned at the upstream of the work zone to control the traffic flow entering the mixed-usage area.

In terms of signal control, two things should be noticed. Firstly, to avoid the head-on conflict in the mixed-usage lanes, the mixed-usage lanes cannot be used as approach lanes and exit lanes simultaneously. Therefore, the through movements from the two opposing legs cannot discharge simultaneously if mixed-usage lanes are set in one of the two opposing legs. The one phase per leg design should be used. Secondly, to increase the discharge flow rate of the main signal, the vehicles should aggregate in the mixed usage area in advance. Therefore, no conflicting movements should be allowed to use the mixed-usage lanes in the phase before the green phase of the leg with mixed-usage lanes, including the left turn from the right adjacent leg and the through movement from the opposing leg. Under these considerations, the feasible phase plan schemes for a four-leg intersection with work zone are limited.

When the mixed-usage lanes are set in only one leg of the intersection, there are two options for the phase plan, as shown in Fig. 2 (using the mixed-usage lanes set in leg 4 as an example). One is the one phase per leg design for all legs. The other is the combined design of one phase per leg and dual-ring concept. In Fig. 2(b), the dual-ring concept is used in the two opposing legs without mixed-usage lanes. The left-turn phase must lead the through movement phase to ensure vehicles in leg 4 can aggregate in the mixed usage area in advance.

When the mixed-usage lanes are set in two or more legs, the one phase per leg design should be used in all legs. The reason is explained as follows. If the mixed-usage lanes are set in two legs, there are two sub-conditions: two adjacent legs and two opposing legs. For two adjacent legs with mixed-usage lanes condition, all the legs should use the one phase per leg design according to the principle that the one phase per leg design should be used for the two opposing legs if the mixed-usage lanes are set in any of the two opposing legs as mentioned above. For two opposing legs with mixed-usage lanes condition, it is impossible to set both phases from the two legs should follow the through movement phase of the adjacent legs when the phase scheme 2 is in place. Therefore, all the legs also should use one phase per leg design. The same conclusion can be drawn when mixed-usage lanes are set in more than two legs.

The two schemes of phase plan shown in Fig. 2 are considered in the hereafter analysis.

3. Development of the optimization model

A model is established in this section to produce an optimal operational scheme for the proposed design. It is applicable when the work zone is either on the approach or exit at an intersection.

3.1. Objective function

The optimization objective is the maximization of the practical capacity (Allsop, 1972) under the assumption that the proportion among the traffic volumes of movements is constant (Gallivan and Heydecker, 1988), as shown in Eq. (1). As Allsop (1972) stated, if the q are existing arrival rates at the junction, the arrival rates $\mu^{*}q$ correspond to be the practical capacity of the junction. The practical capacity requires that the degree of saturation of all traffic lanes/movements should not exceed the maximum acceptable degree of saturation (C. K. Wong and Heydecker, 2011; Jing Zhao, Gao, & Knoop, 2019). Therefore, the common flow multiplier (μ) will be restricted by the traffic lanes/movements with the highest degree of saturation.

$$\max_{\mu,\, n_{ik},\, L_i^m,\, L_i^t,\, \xi, g_{ij}, \lambda_{ij},\, g_i^p,\, \lambda_i^p} \sum_{i\in\mathcal{L}} \sum_{j\in\mathcal{T}} \mu q_{ij} \tag{1}$$

where, μ is the common flow multiplier of the intersection; $\mathcal{L}$ is the set of legs; $i \in \mathcal{L}$ represents the leg, $i = 1,2,3,$ and 4 for north, west, south, and east leg, respectively, as shown in Fig. 3; $\mathcal{T}$ is the set of movements; $j \in \mathcal{T}$ represents the movement, $j = 1, 2,$ and 3 for left-turn, through movement, and right-turn, respectively, as shown in Fig. 3; k represents the lane type, $k = 1, 2, 3, 4,$ and 5 for exclusive left-turn lane, shared left-turn and through lane, exclusive through lane, shared through and right-turn lane, and exclusive right-turn lane, respectively; n_{ik} is the number of lanes of lane type k in leg i; L_i^m is the length of the mixed-usage area, m, as shown in Fig. 3; L_i^t is the length of the transition area, m, as shown in Fig. 3; ξ is the reciprocal of cycle length, 1/s; g_{ij} is the beginning of green of movement j in leg i at the main signal; λ_{ij} is the green ratio of movement j in leg i at the main signal; g_i^p is the start of green in leg i at the pre-signal; λ_i^p is the green ratio in leg i at the pre-signal; q_{ij} is the traffic volume of movement j in leg i, veh/h.

3.2. Constraints

The constraints of the lane assignment, the signal timing of the main signal and pre-signal, the distance of the mixed-usage area and the transition area, and the degree of saturation are considered.

3.2.1 Lane assignment

According to the layout of the proposed design (see Fig. 3), the lanes in the mixed-usage zone can be utilized methodologically as approach and exit lanes while the right-turn bypass lane should be set exclusively.

When the lanes in the mixed-usage area are used as approach lanes, they should be assigned for different movements to match the traffic volume. The number of approach lanes or lanes in the mixed-usage area is given externally, as shown in Eq. (2).

$$n_i = \sum_{k=1}^{5} n_{ik}, \forall i \in \mathcal{L} \quad (2)$$

where, n_i is the number of approach lanes or lanes in the mixed-usage area in leg i.

According to the analysis result of the phase plan, the one phase per leg design should be used in all legs when the mixed-usage lanes are set in two or more legs, as illustrated in Fig. 2(a). Then, the shared left-turn + through lane and the shared through + right-turn lane can be used, but the number of lanes cannot larger than 1, as shown in Eq. (3). When the mixed-usage lanes are set in only one leg, there is another option for phase plan, as illustrated in Fig. 2(b). In this case, the lane-use of shared left-turn + through should be prohibited in the adjacent legs of the leg with mixed-usage lanes, as shown in Eq. (4).

$$n_{ik} \leq 1, \forall i \in \mathcal{L}, k \in \{2,4\} \text{ for } N_l \geq 1 \quad (3)$$

where, N_l is the number of legs with mixed-usage lanes.

$$n_{ik} = 0, \forall i \in \mathcal{L}'', k \in \{2\} \text{ for } N_l = 1 \quad (4)$$

where, $\mathcal{L}''$ is the set of legs adjacent to the leg with mixed-usage lanes.

To guarantee the smooth running of the intersection, Eqs. (5)-(7) restrict that the lane count specified to a movement at an approach should not be larger than the number of the corresponding receiving lanes.

$$n_{ij}^{e} \geq \sum_{k=1}^{2} n_{ik}, \forall i \in \mathcal{L}, j = 1 \tag{5}$$

where, n_{ij}^{e} is the number of the corresponding receiving lanes of movement j in leg i.

$$n_{ij}^{e} = \sum_{k=2}^{4} n_{ik}, \forall i \in \mathcal{L}, j = 2 \tag{6}$$

$$n_{ij}^{e} = \sum_{k=4}^{5} n_{ik}, \forall i \in \mathcal{L}, j = 3 \tag{7}$$

3.2.2 Length of the mixed-usage area and transition area

The intersection with work zone is the research object of the paper. It is assumed that the work zone begins from the intersection. The length of the work zone is an input parameter for the model, which is determined according to the need of the construction. We can change the length of the mixed usage area. The longer the mixed-usage area, the more clearance time should be set, which leads to a lower green ratio and capacity. The queue length will not become a problem under the assumption that the number of lanes beyond the work zone is sufficient. The queue length can overflow the mixed-usage area. However, it should not be shorter than the length of the work zone. Therefore, the length of the mixed-usage zone territory can be set equivalent to the length of the work zone, as shown in Eq. (8).

$$L_i^m = L_i^w, \forall i \in \mathcal{L}' \tag{8}$$

where, L_i^w is the length of the work zone, m, as shown in Fig. 3; $\mathcal{L}'$ is the set of legs with mixed-usage lanes.

There is an offset when vehicles run from the lanes upstream of the pre-signal to the mixed-usage lanes. The length of the transitional area should be sufficiently long to guarantee the smooth running of vehicles. The code for layout of urban road traffic signs and markings of China (MOHURD, 2015) sets the minimum requirements of the length of the transitional area for this kind of offset, as shown in Eq. (9).

$$L_i^t = \begin{cases} \frac{V^2 W_i}{155} & (V \leq 60) \\ 0.625 V W_i & (V > 60) \end{cases}, \forall i \in \mathcal{L}' \tag{9}$$

where, V is the desired speed, km/h; W_i is the width of the work zone, m, as shown in Fig. 3.

3.2.3 Signal timing of the main signal

As illustrated in Fig. 2(a), the one phase per leg design is adopted with the phase sequence of counterclockwise at the main signal when the mixed-usage lanes are set in two or more legs. It can be specialized as in Eqs. (10)-(12). The cyclical signal timing at the intersection describes the green as a fraction within a signal cycle of a range somewhere in the range of 0 and 1. The start of green of the north leg is set to 0 without loss of generality.

$$g_{ij} = 0, \forall i = 1, j \in \mathcal{T} \text{ for } N_l \geq 1 \tag{10}$$

$$g_{(i+1)j} = g_{ij} + \lambda_{ij} + I\xi, \forall i \in \{1,2,3\}, j \in \mathcal{T} \text{ for } N_l \geq 1 \tag{11}$$

where, I is the intergreen interval between the phases, s.

$$g_{ij} + \lambda_{ij} + I\xi = 1, \forall i = 4, j \in \mathcal{T} \text{ for } N_l \geq 1 \tag{12}$$

As illustrated in Fig. 2(b), the phase scheme 2 is an option when the mixed-usage lanes are set in only one leg. It can be specialized as in Eqs. (13)-(18). Without loss of generality, leg 4 is assumed to be the only leg with the mixed-usage lanes, and the start of green of the left-turn at the north leg is set to 0.

$$g_{11} = g_{31} = 0 \text{ for } N_l = 1 \tag{13}$$

$$g_{12} = g_{31} + \lambda_{31} + I\xi \text{ for } N_l = 1 \tag{14}$$

$$g_{32} = g_{11} + \lambda_{11} + I\xi \text{ for } N_l = 1 \tag{15}$$

$$g_{4j} = g_{12} + \lambda_{12} + I\xi = g_{32} + \lambda_{32} + I\xi,\ \forall j \in \mathcal{T} \text{ for } N_l = 1 \tag{16}$$

$$g_{2j} = g_{4j} + \lambda_{4j} + I\xi,\ \forall j \in \mathcal{T} \text{ for } N_l = 1 \tag{17}$$

$$g_{2j} + \lambda_{2j} + I\xi = 1,\ \forall j \in \mathcal{T} \text{ for } N_l = 1 \tag{18}$$

The cycle length of the intersection should not be beyond a reasonable range of maximum and minimum cycle length. The reciprocal of the cycle length is used to establish the model and also to ensure its linearity (C. Wong and Wong, 2003a), as shown in Eq. (19).

$$\frac{1}{C_{min}} \geq \xi \geq \frac{1}{C_{max}} \tag{19}$$

where, C_{max} and C_{min} are the maximum and minimum cycle length, respectively, s.

3.2.4 Signal timing of the pre-signal

The pre-signal should be coordinated with the main signal. Firstly, to avoid the head-on conflicts in the mixed-usage area, the time gap between the beginning of green of the pre-signal and end of the green of the opposing leg should be no less than the clearance time of the opposing through movement, as shown in Eqs. (20)-(22) for two phase plans.

$$g_i^p \geq g_{(i-2)j} + \frac{3.6(L_i^m + L_i^t)}{V}\xi,\ \forall i \in \mathcal{L}', j \in \mathcal{T} \text{ for } N_l \geq 1 \tag{20}$$

$$g_i^p \geq g_{(i-3)2} + \frac{3.6(L_i^m + L_i^t)}{V}\xi,\ \forall i \in \mathcal{L}' \text{ for } N_l = 1 \tag{21}$$

$$g_i^p \geq g_{(i-1)2} + \frac{3.6(L_i^m + L_i^t)}{V}\xi,\ \forall i \in \mathcal{L}' \text{ for } N_l = 1 \tag{22}$$

Secondly, to guarantee the vehicles entering the mixed-usage area can effectively pass the main stop line during the green time and prevent being caught in the mixed-usage area, the capacity of the main signal should not be less than that of the pre-signal, as shown in Eq. (23).To provide enough clearance time, the end of green of the pre-signal should precede that of the main signal, as shown in Eq. (24). According to Eqs. (20)-(22) and (24), one can find that the clearance time ($\frac{3.6(L_i^m + L_i^t)}{V}\xi$) increases with the increase of the length of the mixed-usage area (L_i), which causes a negative impact on the effective green time.

$$s_i n_i \lambda_i \geq s_i^p n_i^p \lambda_i^p, \forall i \in \mathcal{L}' \tag{23}$$

where, s_i is the saturation flow rate per lane at the main signal, veh/h; s_i^p is the saturation flow rate per lane at the pre-signal, veh/h; n_i^p is the number of lanes in leg i at the pre-stop line.

$$g_{ij} + \lambda_{ij} - \frac{3.6(L_i^m + L_i^t)}{V}\xi \geq g_i^p + \lambda_i^p, \forall i \in \mathcal{L}' \tag{24}$$

3.2.5 Degree of saturation

Eqs. (25) and (26) restrict that the degree of saturation cannot exceed the maximum acceptable limits for the main signal and pre-signal, respectively. The y_{ik} in Eq. (25) is the flow ratio at the main signal, which equals to the ratio of the assigned traffic flow and the capacity of a movement. The flow ratio of the five lane types can be calculated by Eqs. (27)-(31), respectively. The green ratio of the five lane types can be calculated by Eqs. (32)-(36), respectively. Eqs. (37)-(39) restrict the sum of the assigned flows on different lanes for the left turn, through movement, and right turn should be equal to the multiplied demand for that movement, respectively.

$$y_{ik} \leq d_{max}\lambda_{ik}, \forall i \in \mathcal{L}, k \in \{1, \dots, 5\} \tag{25}$$

where, y_{ik} is the glow ratio of lane type k in leg i; d_{max} is the maximum acceptable degree of saturation; λ_{ik} is the green ratio on lane k in leg i.

$$\frac{\sum_{j \in \mathcal{T}} \mu q_{ij}}{s_i^p n_i^p} \leq d_{max}\lambda_i^p, \forall i \in \mathcal{L}' \tag{26}$$

$$y_{ik} = \frac{Q_{ijk}}{s_i n_{ik}}, \forall i \in \mathcal{L}, j = 1, k = 1 \tag{27}$$

where, Q_{ijk} is the assigned flow of movement j on lane type k in leg i, veh/h.

$$y_{ik} = \frac{\sum_{j=1}^{2} Q_{ijk}}{s_i n_{ik}}, \forall i \in \mathcal{L}, k = 2 \tag{28}$$

$$y_{ik} = \frac{Q_{ijk}}{s_i n_{ik}}, \forall i \in \mathcal{L}, j = 2, k = 3 \tag{29}$$

$$y_{ik} = \frac{\sum_{j=2}^{3} Q_{ijk}}{s_i n_{ik}}, \forall i \in \mathcal{L}, k = 4 \tag{30}$$

$$y_{ik} = \frac{Q_{ijk}}{s_i n_{ik}}, \forall i \in \mathcal{L}, j = 3, k = 5 \tag{31}$$

$$\lambda_{ik} = \lambda_{ij}, \forall i \in \mathcal{L}, j = 1, k = 1 \tag{32}$$

$$\lambda_{ik} = \lambda_{ij}, \forall i \in \mathcal{L}, j \in \{1,2\}, k = 1 \tag{33}$$

$$\lambda_{ik} = \lambda_{ij}, \forall i \in \mathcal{L}, j = 2, k = 3 \tag{34}$$

$$\lambda_{ik} = \lambda_{ij}, \forall i \in \mathcal{L}, j \in \{2,3\}, k = 4 \tag{35}$$

$$\lambda_{ik} = \lambda_{ij}, \forall i \in \mathcal{L}, j = 3, k = 5 \tag{36}$$

$$\textstyle\sum_{k=1}^{2} Q_{i1k} = \mu q_{i1}, \forall i \in \mathcal{L} \tag{37}$$

$$\textstyle\sum_{k=2}^{4} Q_{i2k} = \mu q_{i2}, \forall i \in \mathcal{L} \tag{38}$$

$$\textstyle\sum_{k=4}^{5} Q_{i3k} = \mu q_{i3}, \forall i \in \mathcal{L} \tag{39}$$

3.3. Solution

The above presentation of the optimization model is a mixed-integer non-linear program with the objective function of Eq. (1). For the two kinds of phase schemes, there are two sets of constraints, which form two sub-programmings. Programming 1 is formed by the objective function of Eq. (1) and constraints (2)-(3), (5)-(12), (19)-(20), and (23)-(39). Programming 2 is formed by the objective function of Eq. (1) and constraints (2), (4)-(9), (13)-(19), and (21)-(39). When the mixed-usage lanes are set in two or more legs, the Programming 1 should be adopted to get the optimal design. When the mixed-usage lanes are set in only one leg of the intersection, the results of Programming 1 and 2 should be compared, and the better one should be chosen as the optimal design. Two factors make the model non-linear: the piecewise function of Eq. (8) and the decision variable n_{ik}.

Notwithstanding Eq. (8) is a piecewise function, it can be linearized by using a binary variable, δ_i. Eq. (8) can be replaced by Eqs. (26) and (27). When $V > 60$, δ_i

should equal to 1 according to Eq. (20). Then, $L_i^t = 0.625VW_i$. When $V \le 60$, δ_i should equal to 0. Then, $L_i^t = \frac{V^2W_i}{155}$.

$$L_i^t = (1 - \delta_i)\frac{V^2W_i}{155} + 0.625VW_i\delta_i, \forall i \in \mathcal{L} \tag{26}$$

$$M(\delta_i - 1) < V - 60 \le M\delta_i, \forall i \in \mathcal{L} \tag{27}$$

where, δ_i is a binary variable; M is a large positive constant number.

For the decision variable n_{ik}, it makes the constraints (18)-(22) non-linear. Fortunately, the feasible solutions for lane assignments are limited. We can enumerate them. Then, for a given lane assignment scheme, the model becomes linear. The branch and bound method can be used to solve the mixed-integer linear program from the optimization model.

We solve the model by Matlab R2018a. The computation times under the various number of approach lanes and phase plans are shown in Fig. 4. The number of lanes on each leg is set to be the same. The computation time is mainly affected by the number of lanes. With the increase in the number of lanes, more feasible solutions of the lane assignments exist, which takes more time to find the optimal solution. Overall, the computation time is less than two minutes for all tested cases, which is acceptable for an offline optimization algorithm.

4. Case study

A case study is applied to validate the availability and effectiveness of the model. The intersection of Longhua Road - Longhuaxi Road in Shanghai, China, was selected as a case for analysis. Due to the sewage pipeline construction, there was a work zone at the west-north corner of the intersection, which lasted 105 days. The work zone occupied one traffic lane at the west leg. The photo of the building site and the original design of the intersection is illustrated in Fig. 5 and Fig. 6(a), respectively. The length of the work zone is 70m. The traffic demand during peak hours was surveyed on 23th Mar 2018, as shown in Table 1. The practical capacity is the capacity under a given maximum acceptable degree of saturation, which is changeable according to the designer's preference. If the maximum acceptable degree of saturation equals 1, the practical capacity is equal to the capacity (the maximum amount that can depart). In this paper, we choose 0.85 as the maximum acceptable degree of saturation according to the previous study (S. Wong, 1996). The other design parameters are set as follows: the top and bottom limitation of the cycle length is 180 s and 60 s; the saturation flow rate for every lane is 1600 veh/h; the designed speed is 30 km/h; the intergreen interval is 4 s.

The proposed design model is implemented, and the optimized layout for the intersection is illustrated in Fig. 6(b). Listed in Table 2 are the optimized signal timing designs. Since the existing signal timing may not be the optimal scheme for the existing layout and the surveyed traffic demand, for a fair comparison, the signal timing under the original layout scheme is optimized by using the dual-ring phase plan, as shown in Table 3.

The VISSIM simulation package evaluates the performance of the intersection. The average vehicle delay and total throughput are the performance indicators used for evaluation. Comparison results are shown in Table 4, which are the average results of 20 simulation runs.

Critical movements, including the left-turn from the east, through from the west, left-turn from the north, and through from the south, are over-saturated under the conventional design because the throughput of these movements is significantly lower than the input (surveyed) traffic demand. The proposed design can maintain the intersection under-saturated. The overall throughput is improved by 4.97%. Accordingly, the average vehicular delay is reduced by 11.62%.

Please note, in this case study, only one traffic lane in one leg is occupied by the work zone. The proposed design can improve the operation of the intersection without the need for intersection expansion, which demonstrates its cost-effectiveness in capacity enhancement for intersections with the work zone.

5. Sensitivity Analyses

A comprehensive sensitivity analysis is conducted to identify the best utilization of the proposed design. A four-leg intersection comprising of seven traffic lanes on each leg (four approach lanes and three exit lanes) is used for the analyses. The number of legs with work zone is 1. There are two lanes occupied by the work zone. The length of the work zone is 100m. The total traffic volume per leg is 1500 veh/h. The left-turn proportion is 30%. The traffic volumes for each leg are equal. The saturation flow rate is 1800 veh/h/ln. The desired speed is 30 km/h. The top and bottom limitation of the cycle length is 180 s and 60 s. The intergreen interval is 4 s. The acceptable degree of saturation is 0.85. Please note that these parameters will change as the requirement of the sensitivity analysis.

The two commonly used conventional designs, the "dual-ring" phase plan (see Fig. 7a) and "one phase per leg" phase plan (see Fig. 7b), are used for comparison. The optimal signal settings of conventional designs are obtained based on the optimization models proposed by C. Wong and Wong (2003b). The practical capacity and the average vehicular delay of the intersection are used as performance indicators for comparison. Please note, when calculating the improvement of the proposed design, the better one of the two conventional designs will be used as the benchmark.

5.1. Number of legs with work zone impacts

As shown in Fig. 8, the number of legs with work zone is set from 1 to 4. Under the conventional design, the practical capacity decreases with the expansion of the number of legs with work zones. Under the proposed design, the reduction is not significant. As expected, more benefits can be obtained in improving practical capacity with the increase in the number of legs with work zone. On average, the proposed design can obtain a 7.5% increase in practical capacity relatively, when there is an additional leg with work zone.

Accordingly, the delay can be reduced. On average, the proposed design can obtain a 12.1% decrease in delay relatively, when there is an additional leg with work zone. The highest reduction obtained in this numerical experiment is about 50% when the work zone exists in all the legs.

5.2. Number of lane closures impacts

The number of lanes occupied by work zone is set from 1 to 4 as shown in Fig. 9. With the increase in the number of lane closures, fewer traffic lanes are available. Therefore, the practical capacities of both conventional designs and the proposed design decrease with the increase of the number of lane closures. However, the proposed design can always outperform the conventional design in practical capacity and average delay.

The improvement in practical capacity obtained by the proposed design firstly goes up with the increase of the number of lane closures, then goes down. The reason is that the more the number of lanes closures, the more negative effect in reducing the practical capacity for a conventional design. Accordingly, a more significant improvement can be obtained from the proposed design. However, when the work zone occupies lots of lanes, lanes can be used for the mixed-usage area is also limited. Then, the percentage of the increment in practical capacity decreases when the number of lane closures equals to 4. In this numerical experiment, the proposed design can obtain more than 20% increase in practical capacity and more than 40% decrease in average delay when the work zone occupies half of the lanes in a leg.

5.3. Length of work zone impacts

As shown in Fig. 10, the length of the work zone is set from 50 m to 250 m. Under the conventional design, the practical capacity remains the same because the layout of the intersection will not change under different work zone length cases. Under the proposed design, an increase in the work zone length leads to an increase in the clearance time of the mixed-usage area, which will lead to a gradual decrease in the green time of the pre-signal.

For the proposed design, the capacity is limited by the main-signal when the work zone is not quite long. It is because the pre-signal can be green during the two phases of the main-signal (green phase of the leg and left adjacent leg). The green time of the pre-signal can be longer than the main signal. Therefore, the practical capacity remains the same. However, when the length of the work zone is longer than 150 m, the green time at the pre-signal will be less than that of the main signal. Then, the critical spot of the intersection moves to the pre-signal. Accordingly, the practical capacity reduces with the increase of the work zone length. More seriously, it may become lower than the conventional design. By using the 5% improvement in the practical capacity as a threshold for the application recommendation, the length of the work zone should be no more than 160 m.

5.4. Traffic volume impacts

The traffic volume is set from 50% to 150% of the initial volume, as shown in Fig. 11. The practical capacity remains the same because the traffic volumes of all movements increase in proportion. Please note the capacity can be increased by increasing the cycle length. However, the cycle length is restricted to be no more than the maximum cycle length according to Eq. (12). Since the optimization objective is the maximization of the practical capacity, the cycle length in the optimal scheme will always be the maximum cycle length, which is consistent with previous studies (C. Wong and Wong, 2003b; C. K. Wong and Heydecker, 2011). Therefore, the cycle length does not change when increased demands are present. The practical capacity remains the same.

However, the advantage of the proposed design in deducing delay will be reflected more significantly with an escalation in the traffic volume. As shown in Fig. 11(b), the percentage of the decrement in average delay obtained by the proposed design can be divided into three stages depending on the increase of the traffic volume. First, if the traffic volume is low, the conventional design can handle the input volume and keep the average delay in a low value. The benefit of the proposed design in reducing average delay is not significant. Second, when the traffic volume is higher than the capacity of the conventional design but lower than the capacity of the proposed design, the percentage of the decrement in average delay obtained by the proposed design grows rapidly with the increase of the traffic volume. Finally, when the traffic volume is higher than the capacity of the proposed design, the increase in the percentage of the decrement in average delay slows down.

5.5. Imbalanced demand impacts

There are two feasible phase plans when the mixed-usage lanes are set in only one leg of the intersection. The selection of the phase plan is mostly affected by the traffic flow pattern, including the imbalanced demand between the left-turn and through movement and the imbalanced demand between the two opposing legs. Therefore, in this section, the left-turn proportion is set from 5% to 50%, while the ratio of the total traffic volume between the two opposing legs is set from 0.1 to 1.

With the increase of the imbalanced demand between the two opposing legs and left-turn proportion, the practical capacity of the proposed model decreases and then reaches a platform, as shown in Fig. 12(a). It is because there are two kinds of phase plans to choose. The imbalanced traffic demand has little effect on the practical capacity when the phase plan of one phase per leg (phase plan 1) is adopted. However, in some cases (lower left-turn proportion and more balanced demand between the two opposing legs), the phase plan 2 performs better. Higher practical capacity can be obtained accordingly. As a result, one can find the area of the higher practical capacity in Fig. 12(a) is the same as the area of choosing phase plan 2 in Fig. 12(c). Comparing with the conventional design, the improvement in practical capacity is approximately 10%, as shown in Fig. 12(b). It indicates that the proposed method has a stable efficacy in increasing operational efficiency under various traffic demand conditions.

6. Conclusions

An innovative design to increase the capacity of intersections with work zone by using pre-signals is presented. An optimization model for the geometric layout and signal timing design is established. Detailed numerical analysis and a case study were used to gauge the performance of the suggested design. The conclusions drawn are listed below:

(1) The proposed design can lead to an increment in the practical capacity of the intersection with a work zone (by up to 30%) and reduce the average vehicular delay accordingly (by 50%) without necessitating an expansion of the intersection. Thus it is cost-effective.

(2) From the view of a geometric condition, progressively improvements in practical capacity could be gained from the proposed design where more work zone exists, and more lanes are occupied. On average, the proposed design can respectively obtain 7.5% increase in practical capacity when there is an additional leg with work zone. It should also be noticed that the proposed design is applicable when the length of the work zone is less than 160 m by using the 5% improvement in the practical capacity as a threshold.

(3) From the view of traffic volume conditions, the advantage of the proposed design in reducing delay will be reflected more significantly with the growth of the traffic volume, especially when the intersection is over-saturated under the conventional design.

In practice, the overhead reversible lane control signs are suggested to provide the drivers with more navigation information. The driving guidance facilities, including traffic signs and markings, should be carefully studied to streamline the traffic flow. The study on driving behavior under the innovative design scheme is also needed in future studies.

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Disclosure statement

No potential competing interest was reported by the authors.

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Table 1. Traffic demand.

Leg	Left-turn (veh/h)	Through (veh/h)	Right-turn (veh/h)
East	238	436	196
West	266	448	162
South	-	422	169
North	285	296	72

Table 2. Optimal signal timing under proposed layout.

Leg	Main / pre signal	Cycle length (s)	Start of green (s)	Duration of green (s)	End of green (s)
East	Main signal	180	142	34	176
West	Main signal		48	36	84
	Pre-signal		24	36	60
South	Main signal		88	50	138
North	Main signal		0	44	44

Table 3. Optimal signal timing under original layout.

Leg	Movement	Cycle length (s)	Start of green (s)	Duration of green (s)	End of green (s)
East	Left-turn	180	83	25	108
	Through		128	48	176
	Right-turn		128	48	176
West	Left-turn		83	41	124
	Through		112	64	176
	Right-turn		112	64	176
South	Left-turn		-	-	-
	Through		34	45	79
	Right-turn		0	180	180
North	Left-turn		0	30	30
	Through		0	79	79
	Right-turn		0	79	79

Table 4. Performance comparison.

Throughput analysis (veh/h)				
Leg	Movement	Conventional design	Proposed design	Improvement
East	Left-turn	215	241	12.09%
	Through	437	438	0.23%
	Right-turn	194	192	-1.03%
West	Left-turn	268	279	4.10%
	Through	405	450	11.11%
	Right-turn	149	158	6.04%
South	Left-turn	-	-	-
	Through	388	429	10.57%
	Right-turn	168	168	0.00%
North	Left-turn	267	279	4.49%
	Through	297	297	0.00%
	Right-turn	71	70	-1.41%
Overall		2859	3001	4.97%
Delay analysis (s)				
Leg	Movement	Conventional design	Proposed design	Improvement
East	Left-turn	142.18	90.53	36.32%
	Through	74.88	91.91	-22.74%
	Right-turn	73.37	87.52	-19.28%
West	Left-turn	87.85	91.33	-3.96%
	Through	108.28	89.49	17.35%
	Right-turn	103.52	85.38	17.53%
South	Left-turn	-	-	-
	Through	115.12	77.90	32.33%
	Right-turn	5.13	5.05	1.49%
North	Left-turn	121.07	65.66	-5.77%
	Through	65.07	80.16	-23.20%
	Right-turn	63.26	76.46	-20.87%
Average		89.99	79.54	11.62%

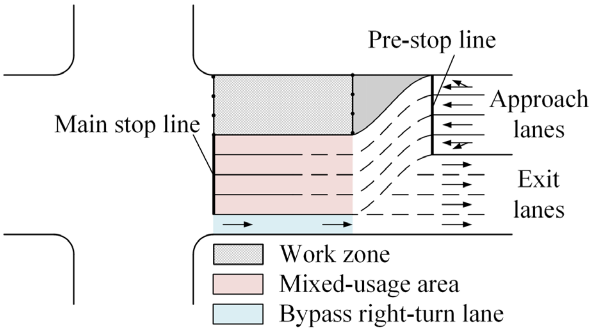
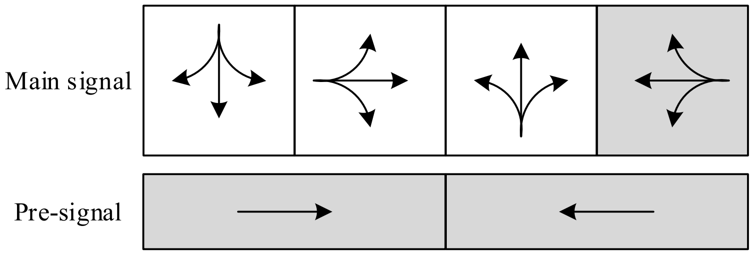
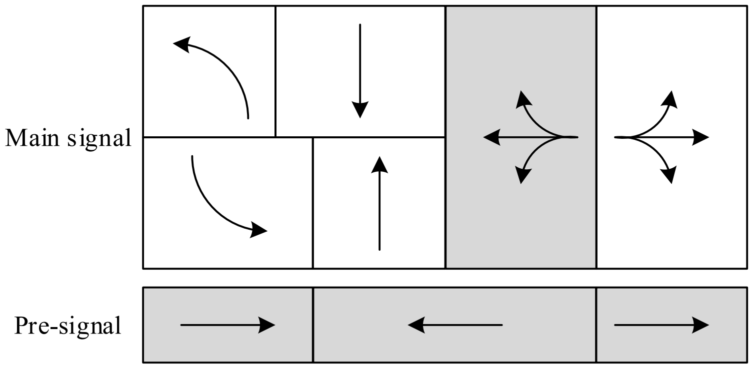


Figure 1. Layout of the proposed design.



(a) Phase scheme 1: One phase per leg design



(b) Phase scheme 2: Combined design of one phase per leg and dual-ring concept

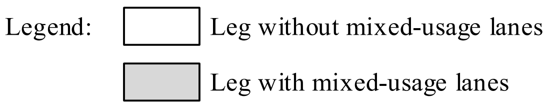


Figure 2. Phase plan schemes of the proposed design.

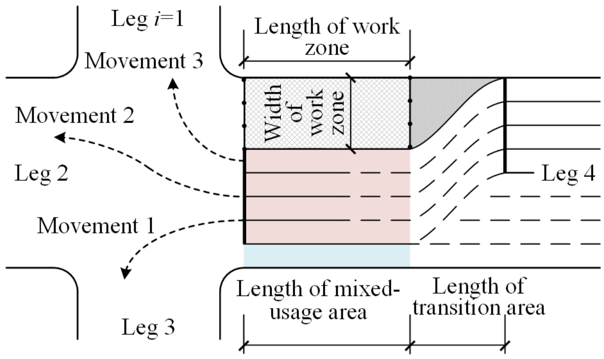


Figure 3. Layout parameters.

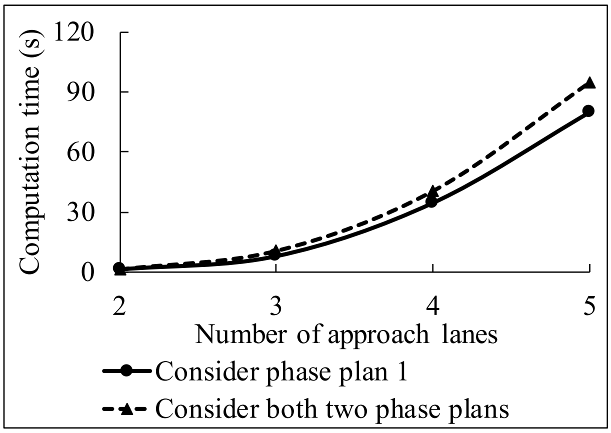


Figure 4. Computation time analysis.

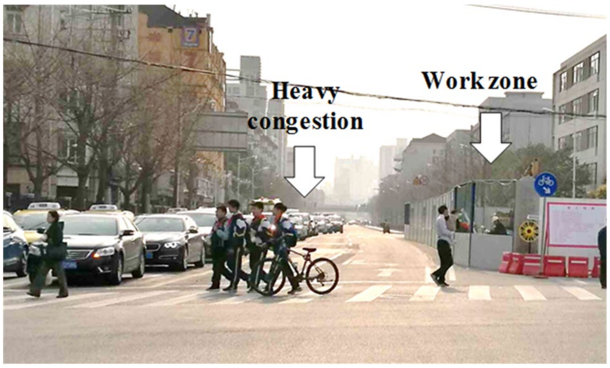
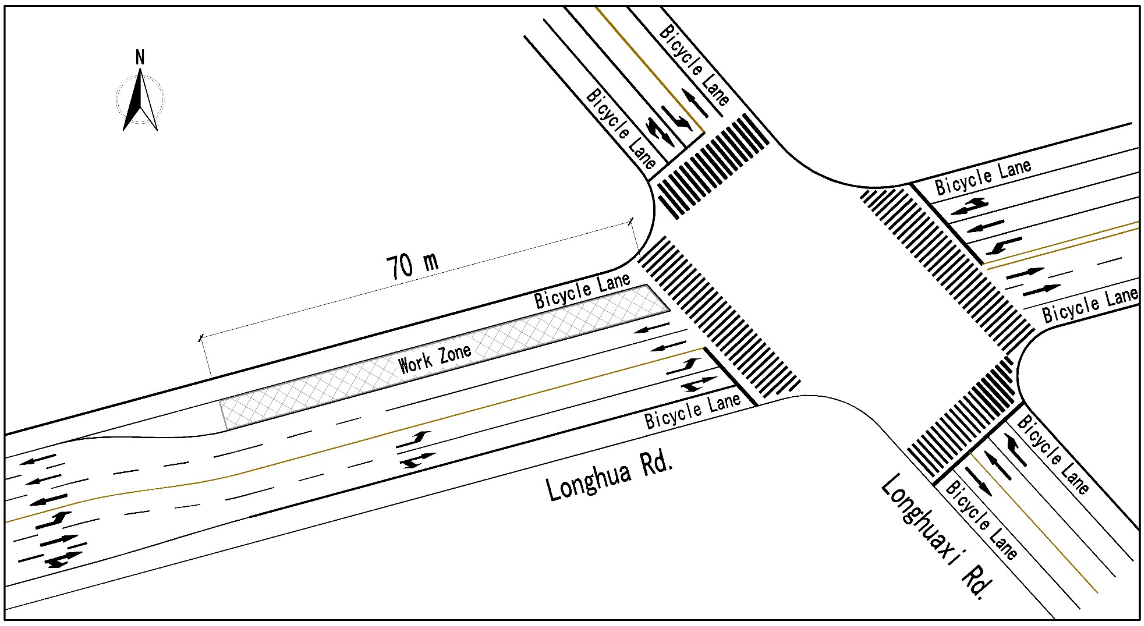
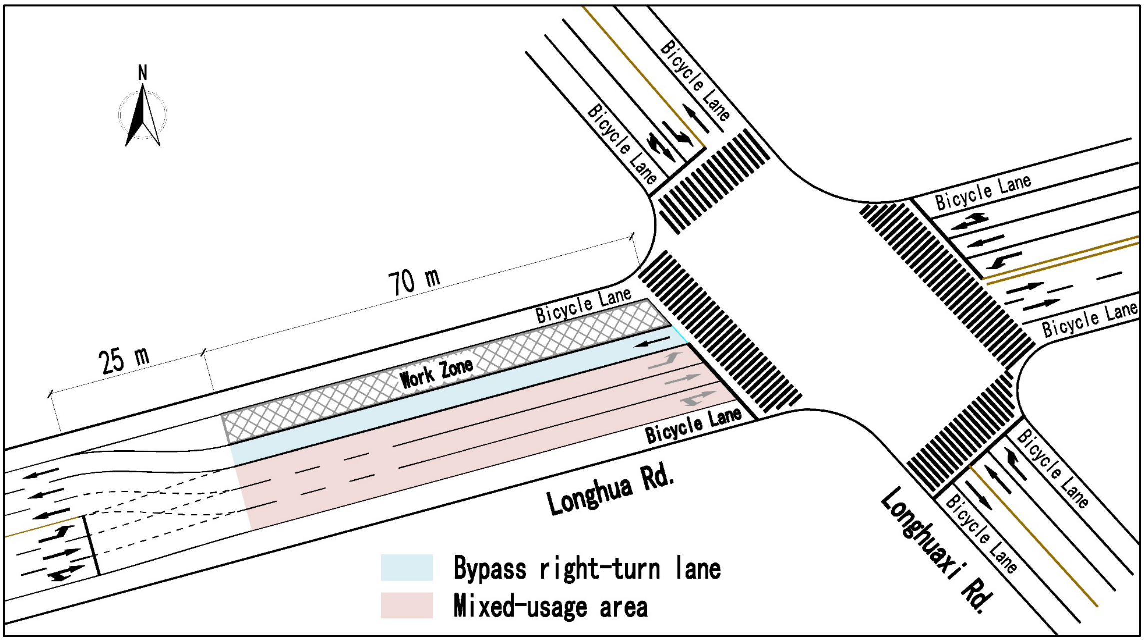


Figure 5. The case study intersection.

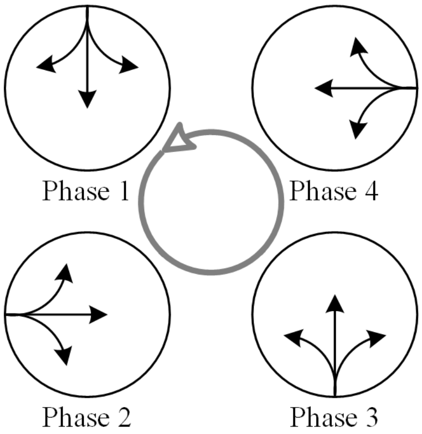


(a) Original layout

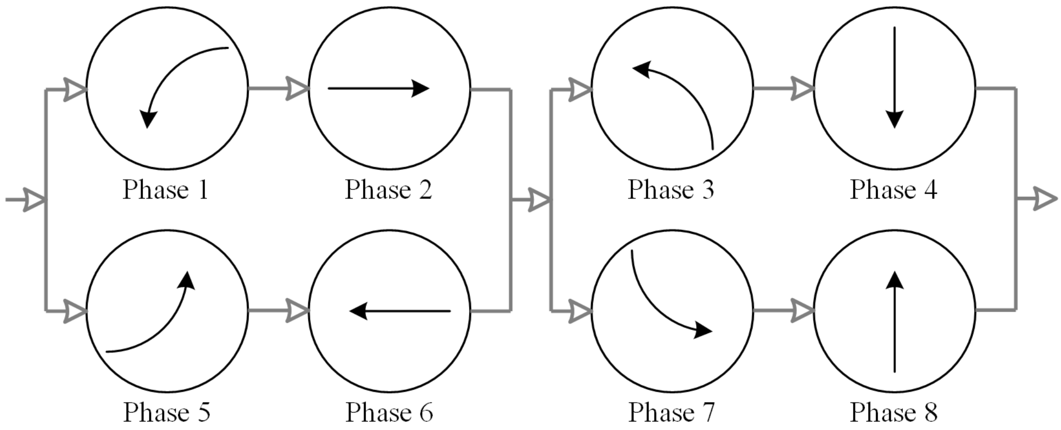


(b) Optimized layout

Figure 6. Layout design.

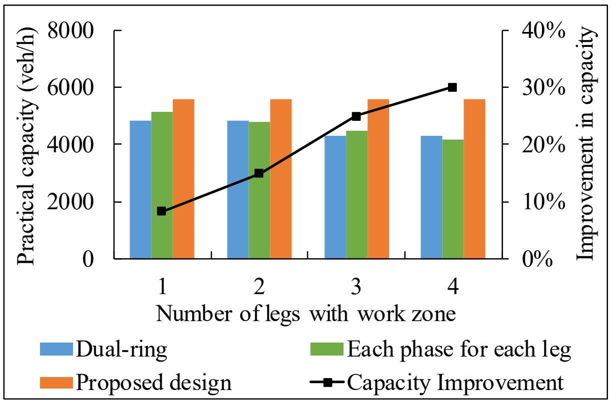


(a) One phase per leg phase plan

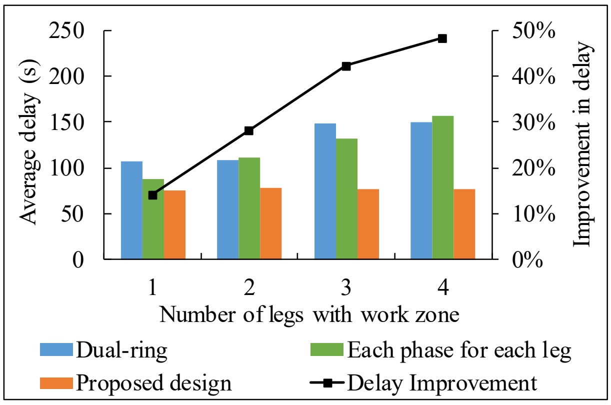


(b) Dual-ring phase plan

Figure 7. Phase plan for conventional designs.

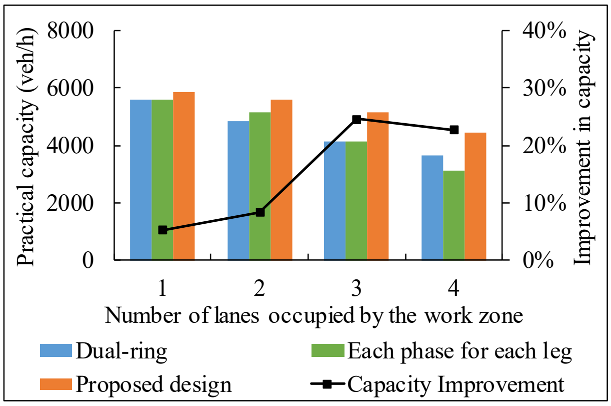


(a) Practical capacity analysis

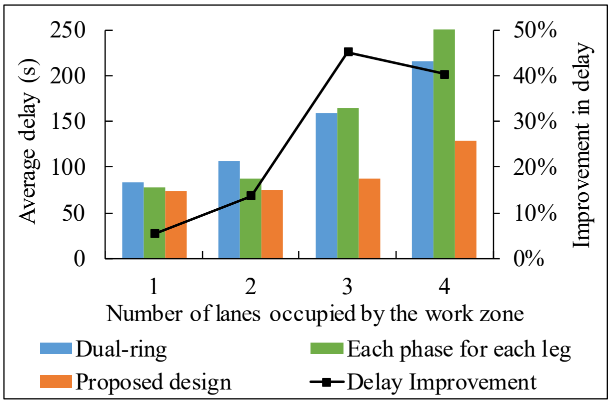


(b) Average delay analysis

Figure 8. Impact of the number of work zones in the intersection.

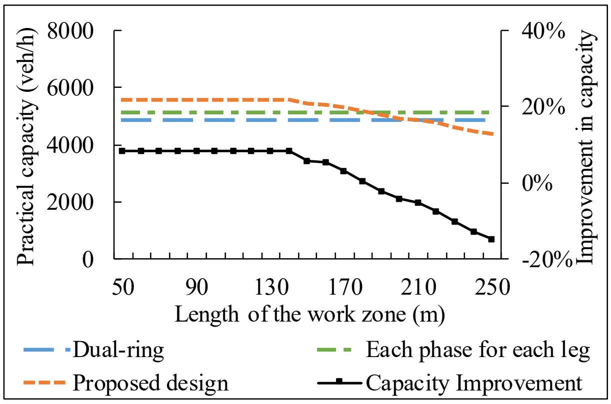


(a) Practical capacity analysis

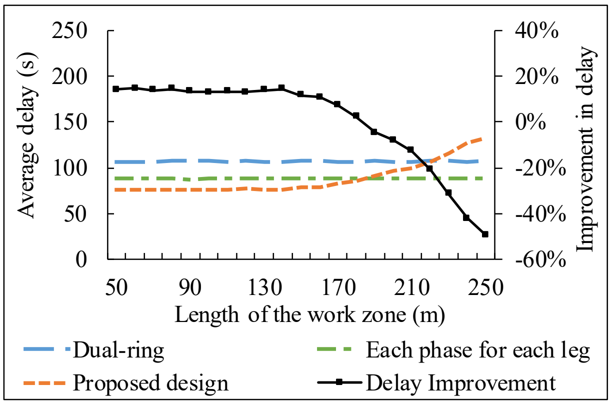


(b) Average delay analysis

Figure 9. Impact of the number of lanes occupied by the work zone.

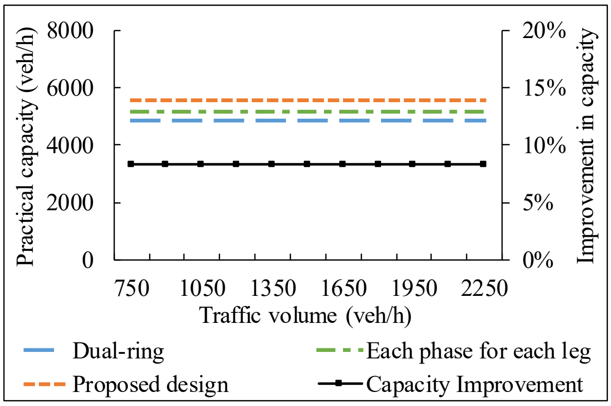


(a) Practical capacity analysis

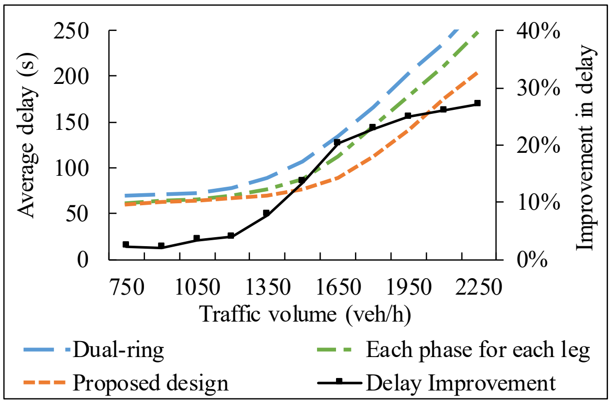


(b) Average delay analysis

Figure 10. Impact of the length of work zone.

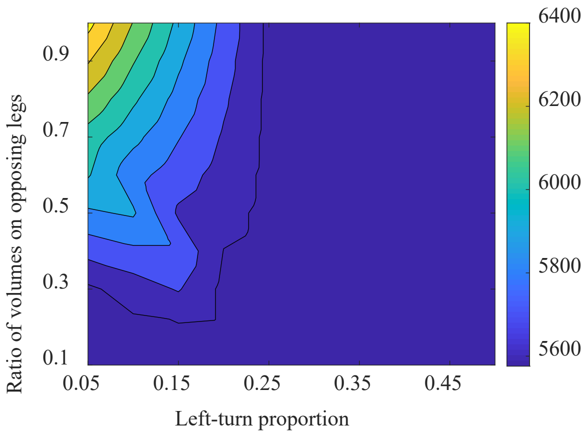


(a) Practical capacity analysis

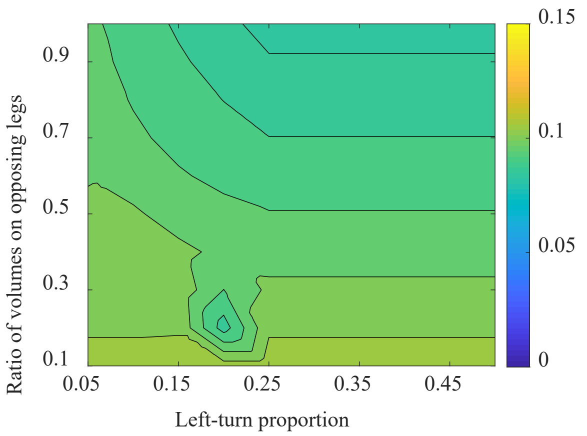


(b) Average delay analysis

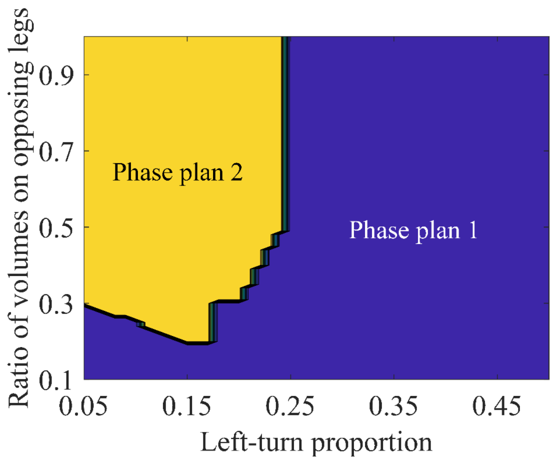
Figure 11. Impact of the traffic volume.



(a) Practical capacity of the proposed design (veh/h)



(b) Improvement in practical capacity



(c) Selection of the phase plans

Figure 12. Impact of the imbalanced demand.