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OPTIMISATION OF SIGNAL TIMING AT INTERSECTIONS WITH WAITING AREAS

ABSTRACT

Unconventional geometric designs such as continuous-flow intersections, U-turns, and contraflow left-turn lanes have been proposed to reduce left-turn conflicts and improve intersection efficiency. Having a waiting area at a signalised intersection is an unconventional design that is used widely in China and Japan to improve traffic capacity. Many studies have shown that waiting areas improve traffic capacity greatly, but few have considered how to improve the benefits of this design from the aspect of signal optimisation. Comparing the start-up process of intersections with and without waiting areas, this work explores how this geometric design influences vehicle transit time, proposes two signal optimisation strategies, and establishes a unified capacity calculation model. Taking capacity maximisation as the optimisation function, a cycle optimisation model is derived for oversaturated intersections. Finally, the relationship among waiting-area storage capacity, cycle time, and traffic capacity is discussed using field survey data. The results of two cases show that optimising the signal scheme helps reduce intersection delays by 10–15%.

KEYWORDS

waiting area; optimisation; traffic capacity; signal timing.

1. INTRODUCTION

In many cities, a place where two major streets intersect can easily become a bottleneck during peak hours, leading to oversaturation. This situation has been researched for more than 50 years, and much effort has been made to address the problem of oversaturation [1–6]. If the traffic efficiency of bottleneck intersections cannot be improved quickly, other intersections may be affected and vehicle queues may sprawl all over the arterial network, causing a so-called network gridlock [4, 7, 8]. Many studies have indicated that improving the capacity of intersections is effective for alleviating oversaturation [1–4, 7, 9, 10].

The conflict between left-turn movement and opposite through movement (driving on the right) is the main cause of the inefficiency of at-grade intersections [8], with left-turn conflicts having a significant impact on traffic capacity, delays, and traffic safety at intersections. Therefore, one of the challenges of traffic management is organising and controlling the left-turn movement of vehicles, and the elimination of conflicts is generally considered in terms of geometric design and the separation of transit times.

Traffic signal control is a highly typical way to separate different movements. If the traffic volume is low enough that left-turning vehicles can use the acceptable gaps between opposite through vehicles to clear the intersection safely, then using permissive phasing makes for an efficient intersection. However, with increasing traffic volume at the intersection, the gaps may become unacceptable for left-turning vehicles, thereby delaying them considerably and impacting intersection safety negatively. For most high-volume intersections, protected phasing is a more secure and effective signal strategy. However, optimising signal schemes to improve intersection operation efficiency has been researched for more than 80 years [11–18], and the optimisation effect may have reached its theoretical limit [8]. In recent years, optimisation based on machine learning [19] and traffic flow collection based on consortium blockchain [20] have been introduced into adaptive signal control, but these methods are yet to be incorporated into conventional design. Because of the limits of conventional design, researchers have proposed some unconventional geometric designs to improve intersection capacity, such as the median U-turn [21–25], the displaced left-turn lane (DLL) [23], the contraflow left-turn lane [26] and the continuous-flow intersection (CFI) [8, 21].

Having been used for at least 50 years, the median U-turn is not a new geometric design [21]. At bottleneck-prone intersections, left turns are often prohibited to reduce the phases and improve the capacity of through-moving traffic. On a major road, drivers of left-turning vehicles are required to travel straight through the main intersection first, make a U-turn at the median opening downstream, and then turn right at the main intersection. Correspondingly, vehicles turning left onto the major road will first turn right at the main intersection and then make a U-turn at the median opening downstream. The median U-turn design can reduce the phases and improve the traffic efficiency of through vehicles, but it may increase the delays and travel distances of left-turning vehicles and lead to additional time cost [21]. In addition, the space required for the U-turns is relatively large, and loops may have to be added [21, 27].

The CFI is an unconventional design that improves the capacity of intersections [27–29]. This design adjusts the location of left-turning vehicles and uses the opposite lanes to reduce and separate conflict points. The main advantage is that left-turning and through vehicles can move without conflicts during the same signal phase [21]. However, the CFI design requires the installation of two new sub-intersections and the design and installation of two traffic signals at the sub-intersections for safety, thereby increasing the construction and operation costs [21]. To overcome the disadvantages of the CFI, Sun et al. [8] proposed a simplified design called CFI-lite that uses existing upstream intersections to allocate left-turning traffic to DLLs instead of new sub-intersections; however, this approach requires left-turning vehicles to be transferred to the DLLs in advance, which is not in line with driving habits and is likely to cause other problems. In China, conflicts between a large number of bicycles (including pedestrians) and left-turning motor vehicles are very prominent and continue to plague traffic engineers. The CFI and CFI-lite designs cannot eliminate this conflict, which may be why they appear rarely in China (at only three intersections in Shenzhen and Haikou).

Obviously, unconventional left-turn designs such as the median U-turn, the contraflow left-turn lane, and the CFI can reduce the conflict between left-turn movement and through movement to a certain extent and increase traffic capacity. However, because of the high cost of reconstruction and inconsistency with driving habits, the application of these designs is limited in China (especially in cities in central China).

At signalised intersections, a protected left-turn phase can be used to eliminate left-turn conflicts, which is considered effective for providing safe operation and handling large left-turn volumes with less delay [30]. However, simply setting up a protected left-turn phase increases the cycle time and reduces the capacity of the intersection. To overcome this issue, installing waiting areas (WAs) at intersections is known to increase traffic capacity [31–37]. Also, with low construction cost, low operation cost, and simple driving operation, installing WAs to improve the efficiency of signalised intersections is being done increasingly in Chinese cities. In addition, the right-turn WA design (driving on the left) is also used in Japanese cities (such as Tokyo and Kawasaki).

Previous studies have shown that installing WAs can improve the traffic capacity of signalised intersections [31–34, 38–41]. Yang et al. [31] simulated the effect of WAs and showed that using left-turn WAs (LWAs) could improve the capacity of left-turn lanes. Chen et al. [42] established a capacity calculation model for left-turn lanes with WAs and showed that the capacity could be increased by 10–20%.

Yang et al. [32] showed that installing LWAs with a storage capacity of three cars could increase the capacity by 22.39% with an effective green time of 15 seconds. In summary, installing WAs can increase traffic capacity by 10–30% [31, 32, 34, 39–41].

Yang et al. [33] showed that WAs help to reduce vehicle delays and improve the utilisation of approach lanes, and You et al. [31] showed that delays could be reduced by 5.6%. Through theory or simulation, other studies [30, 33, 40] have also shown that installing WAs can reduce delays to some extent.

In addition, the impact of WAs on safety is controversial. Yang et al. [39] reasoned that installing through-movement WAs (TWAs) could ensure pedestrian safety, a view also supported by You et al. [34]. However, Jiang et al. [35, 36] used the traffic conflict technique and the ordered probit model to show that both LWAs and TWAs have a negative impact on safety, especially when drivers behave illegally in WAs, which will intensify conflicts.

Based on the capacity model provided by Highway Capacity Manual (HCM) [44], Ma et al. [30] and Yang et al. [31–33] established capacity models for intersections with WAs. In addition, some studies used simulation methods to quantify and analyse the capacity and delay of WAs [33, 37, 38, 41].

The consensus among traffic researchers and engineers is that setting up WAs can improve traffic capacity and reduce intersection delays. Nevertheless, installing WAs increases the number of vehicle stops, which is considered to be its weakness [38, 43]. In conclusion, previous studies examined the effect of various WA methods and showed that they (i) improve traffic capacity, (ii) reduce intersection delays, (iii) reduce queue lengths and prevent overflow, and (iv) increase the number of stops required by a vehicle. In China, urban road networks are increasingly plagued by traffic jams, high crash rates, and long delays. To overcome these issues, WAs are becoming more popular with traffic engineers.

Previous studies have focused on the geometric WA design and how it impacts capacity. As an unconventional left-turn geometric design, it must be used with a signal control strategy, but how the signal scheme influences the capacity of an intersection with WAs remains to be researched. The view that increasing the capacity of intersections is an effective way to alleviate oversaturation is widespread [1–4, 7, 9, 10], but the issue of optimising the signal scheme to maximise traffic capacity at an intersection with WAs is yet to be discussed.

To solve the aforementioned problems, this paper presents a series of WA design patterns and derives a capacity model for intersections with WAs. Based on this model, the relationship between the signal length and the capacity of an intersection with WAs is explored. In particular, this paper focuses on (i) the design patterns of WAs, (ii) establishing a capacity model, and (iii) modelling the optimisation of the maximum capacity.

The remainder of this paper is organised as follows. The WA design concept is described in Section 2, a capacity model based on the installation of WAs at signalised intersections is established in Section 3, and a case study using real-world data is examined in Section 4. Finally, a discussion is presented in Section 5 and conclusions are drawn in Section 6.

2. DESIGN CONCEPT

To ensure safe road conditions, the intersection space should be utilised fully when installing WAs. Typically, the spaces outside the trajectories of the various movements in the previous phase are designated as WAs; these spaces are usually at the front of certain lanes.

LWAs can be installed at large-scale intersections where many vehicles wish to turn left. *Figure 1* shows a typical four-leg intersection. Approaches 1 and 3 have been equipped with LWAs, and some practical conditions were assumed: (i) there should be exclusive left-turn lanes in the approaches; (ii) a protected left-turn phase is required; (iii) the lagging left-turn phase should be used; (iv) adequate line of sight should be ensured.

Phase 1 is the period of through movement and pedestrian traffic, and the right-turn movement adopts the yield control mode. The conflict zone is caused by the entering left-turn movement and the clearing-through movement from the opposite approach (the movement trajectories are shown by the dashed lines in *Figure 1*). The LWA can extend, at most, to the front of the conflict zone. If there are multiple left-turn lanes, then multiple LWAs could be set up. At this time, to ensure that the driver of the first vehicle in each WA has an adequate line of sight, the stop lines for WAs near the centre line cannot go beyond those of the outside lanes.

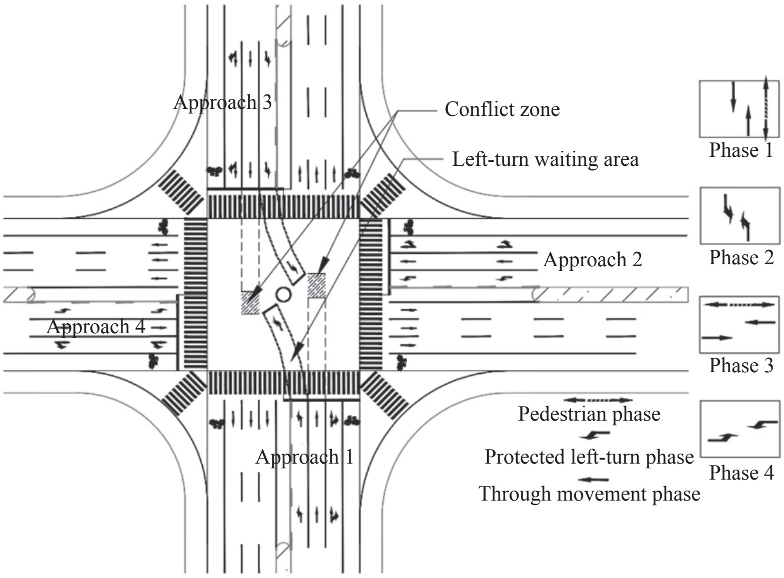


Figure 1 – Left-turn waiting area (LWA)

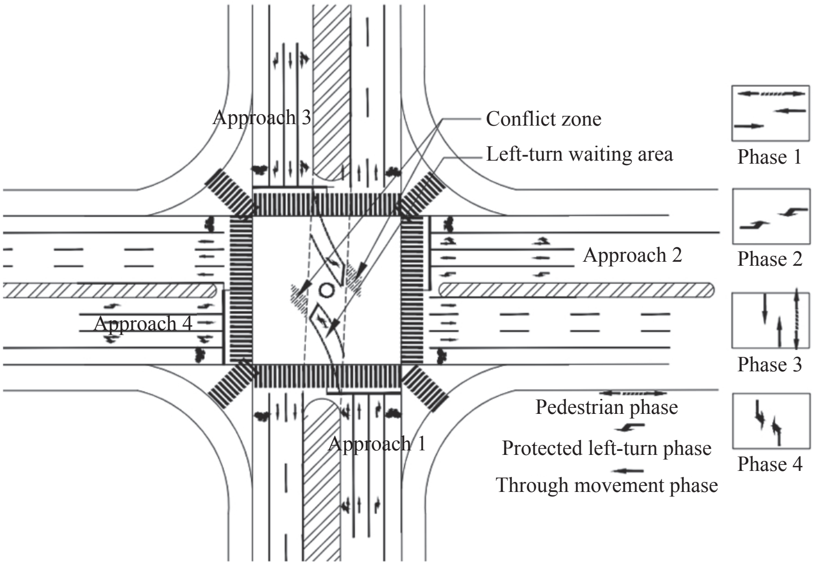
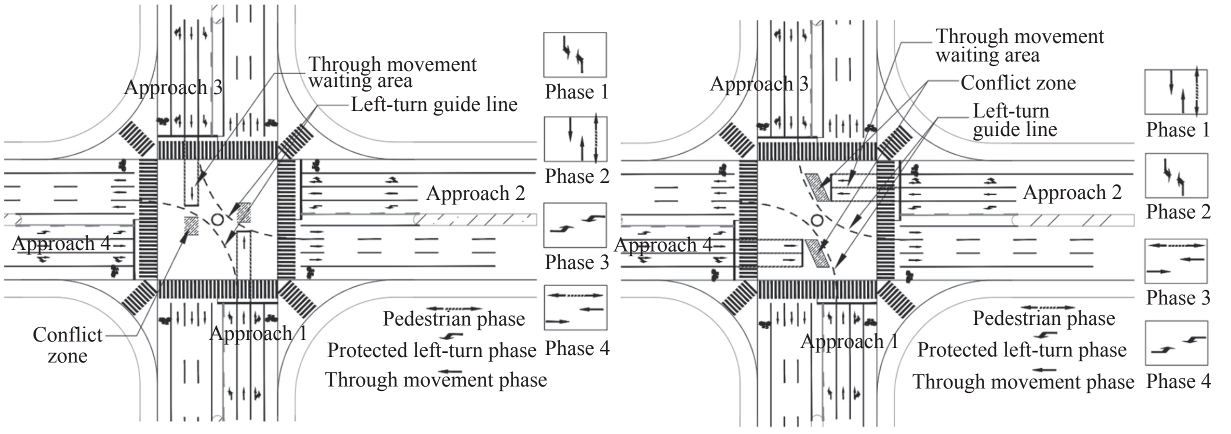


Figure 2 – LWA at shared lane

In general, exclusive left-turn lanes are required for installing LWAs. However, if there is a sufficiently wide median belt and the through movement is unaffected by vehicles stopped in free areas, then LWAs can also be installed in front of shared lanes for through movement and left-turn movement. The layout is shown in *Figure 2*. This design is only suitable for intersections with low left turn movement demand (the left-turn traffic that arrives during a cycle period cannot exceed the storage capacity of the WAs). In this case, the protected left-turn phase is not the best strategy, and the permissive left-turn phase or the permissive/protected left-turn phase may make the intersection more efficient.

Although left-turning vehicles can enter the intersection and stop in front of the conflict zone and wait for an acceptable gap at an intersection with the permitted left-turn phase, the throughput is limited by the amount of acceptable gaps. When the left-turn demand or the opposite through traffic volume is relatively large, the amount of acceptable gaps is insufficient to meet the left-turn demand, which seriously affects the operation efficiency and safety of the intersection. In contrast, the method of installing LWAs does not have these restrictions.

TWAs can be installed at large-scale intersections where there is high demand for through movement. There are two ways of setting up TWAs.



a) TWA for leading left-turn phase *b) TWA for lagging left-turn phase*

Figure 3 – Through-movement waiting area (TWA)

First, the WA may be installed in the vacant space of the opposing left-turn movement. An intersection with leading protected left-turn phase and the phase diagram are described in *Figure 3a*. Approaches 1 and 3 are equipped with TWAs. Similar to the traffic rules of intersections with LWAs, when the signal of phase 1 turns green, through vehicles in approaches 1 and 3 can enter WAs. The following requirements must be satisfied: (i) there should be exclusive left-turn lanes at the intersection; (ii) a protected left-turn phase is required; (iii) the leading left-turn phase should be used; (iv) adequate line of sight should be ensured. The conflict zone is caused by the entering through movement and the clearing left-turn movement from the opposite approach.

The second approach places the TWA in the vacant space of the crossing left-turn movement (as shown in *Figure 3b*). In this way, the lagging and protected left-turn phase should be used in all approaches, with the other conditions similar to those described above. Through vehicles at approaches 2 and 4 can enter WAs when the signal of phase 2 turns green. Because through vehicles at approaches 2 and 4 may not see the arrow light of phase 2 turning green, an additional signal should be set to guide them into the WAs. The conflict zone is caused by the entering through movement of approach 2 (resp. approach 4) and the clearing left-turn movement from crossing approach 3 (resp. approach 1). If multiple TWAs are installed, the stop lines for the WAs of outside lanes cannot extend beyond those of lanes near the centre line to ensure that the driver of the first vehicle in each WA has a good line of sight.

When the lagging and protected left-turn phase is used in all the approaches of a signalised intersection, each approach can contain both LWAs and TWAs if conditions permit. *Figure 4* shows a four-leg intersection in which each approach is equipped

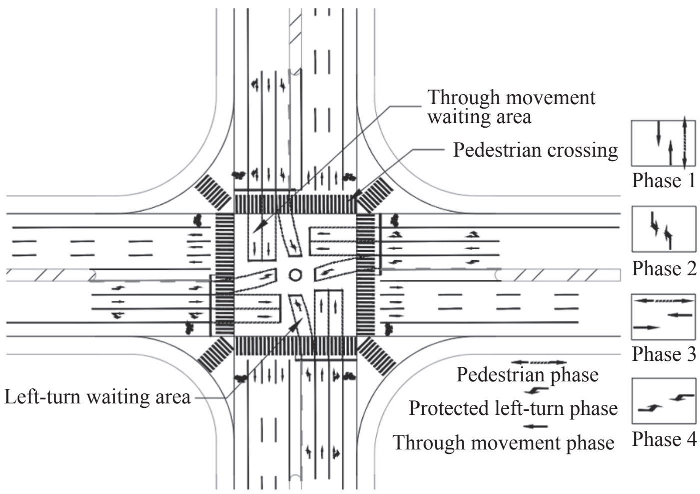


Figure 4 – Four-leg intersection with LWAs and TWAs

with an LWA and two TWAs. However, because of the complexity of the ground markings and the potential for driver confusion, this system is rarely used in practice.

There are two issues that need special attention. First, the traffic rules change when WAs are installed. When the previous phase signal turns green, vehicles are guided into WAs, which is fulfilled by installing signs or signals. China's national standard (GB 5768.3-2009) stipulates that the marking line of an LWA is a white dotted line, which is used to indicate where left-turning vehicles should enter the WA to turn left during the through duration. In other words, the through signal is the guidance signal. For the case of installing TWAs, the guidance sign "through vehicles enter waiting area during left-turn duration" is usually installed to guide vehicles into WAs. Second, the clearance interval should avoid traffic conflicts because vehicles in WAs are near the trajectories of crossing vehicles.

3. ANALYSIS METHODOLOGY

Many studies examined vehicle operation characteristics in the presence of WAs. Setting up WAs is known to improve the traffic capacity of intersections and reduce the delay time. The main purpose of installing WAs is to improve the traffic capacity of intersections. In the case of unsaturated road networks, it is appropriate to consider delays or stops as the optimisation objective. However, the most severe oversaturation occurs during peak periods, when serious traffic jams may occur. The control strategy for intersections should be based on maximising capacity, as long as this does not cause the next intersection to overflow [1–4, 7, 9, 10].

3.1 Start-up process

The start-up process of vehicles at an intersection with WAs differs from that at one without WAs. *Figure 5* shows the start-up processes of vehicles. *Figure 5a* shows the layout of a lane with no WA; when the signal turns green, the first vehicle behind the stop line starts up immediately after the reaction time and then crosses the stop line. Correspondingly, in *Figure 5b*, a WA is installed in front of the stop line. Before the signal turns green, vehicles w_1–w_n are waiting in the WA. When the signal turns green, the first vehicle o_1 behind the stop line starts up not first but after vehicle w_n. In fact, o_1 becomes vehicle n+1 in the whole queue.

The Traffic Engineering Handbook [45] (TEH2016, Institute of Transportation Engineers) and the Highway Capacity Manual [41] (HCM2010, Transportation Research Board) provide a method for determining the start-up lost time and saturation headway. The timing starts when the signal turns green. The time for the front bumper (or front wheel) of vehicle k to reach the stop line is t_k, and the time for the last vehicle in the queue to cross the stop line is t_n. The saturation headway h_0 and start-up lost time l_1 are calculated as follows:

$$h_0 = \frac{t_n - t_k}{n - k} \quad (1)$$

$$l_1 = t_k - k \cdot h_0 \quad (2)$$

where HCM2010 sets k=4 and TEH2016 sets k=3. This method is also applicable to intersections with WAs. Based on this method, the measured start-up lost time is greater than that of intersections without WAs.

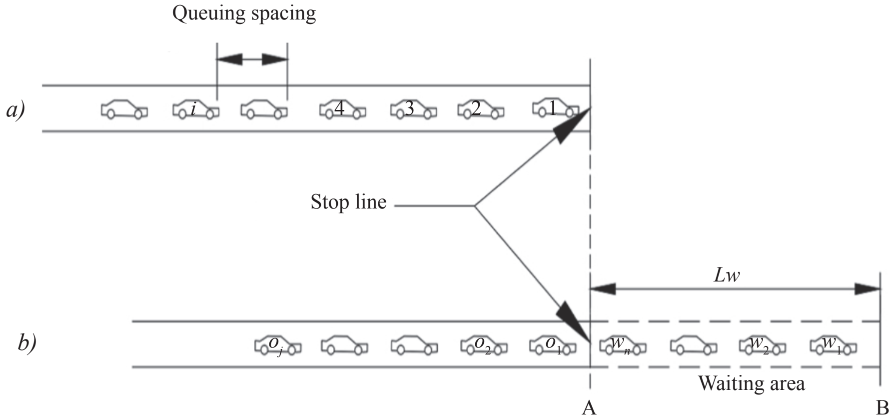


Figure 5 – Vehicles queuing in front of stop line

The time for the front bumper (or front wheel) of vehicle o_k to reach the stop line is t_{ok}, and the time for the last vehicle in the queue to cross the stop line is t_{on}. The saturation headway h_{w0} and start-up lost time l_{w1} at an intersection with WAs are calculated as follows:

$$h_{w0} = \frac{t_{on} - t_{ok}}{on - ok} = \frac{t_{(n+n_w)} - t_{(k+n_w)}}{(n+n_w) - (k+n_w)} = \frac{t_n - t_k}{n - k} = h_0 \qquad (3)$$

$$l_{w1} = t_{ok} - k \cdot h_{w0} = t_{ok} - k \cdot h_0 \qquad (4)$$

As shown in *Figure 5b*, the storage capacity n_w of the WA is calculated as follows:

$$n_w = \frac{L_w}{qs} \qquad (5)$$

where L_w is the length of the WA and qs is the queuing spacing.

Figure 6 shows the cumulative curve of vehicle release at a signalised intersection. In *Figure 6b*, at time t_w, vehicle o_5 (or o_4) crosses the stop line at the saturation flow rate. In fact, o_5 becomes vehicle n_w+5 in the whole queue. Correspondingly, if no WA is installed, then vehicle n+5 crosses the stop line at time t, as shown in *Figure 6a*. In the remaining time for the green light, the discharge patterns are identical at intersections with and without WAs That is, $t-t_w$ is the time saved by installing WAs. Therefore, the green time of this phase can be reduced by time $t-t_w$ in the unsaturation state.

According to *Equations 1–4*, the times t and t_w are calculated as follows:

$$t = l_1 + \frac{5 + n_w}{h_0} \qquad (6)$$

$$t_w = l_{w1} + 5h_0 \qquad (7)$$

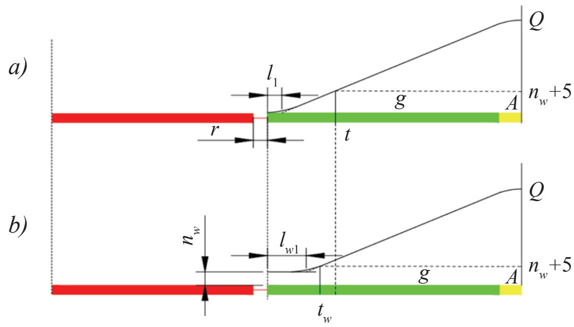


Figure 6 – Cumulative curve of vehicle release

and hence

$$t - t_w = l_1 - l_{w1} + n_w h_0 \qquad (8)$$

3.2 Capacity model

A typical four-leg intersection is shown in *Figure 7*. There are four phases, and each approach includes LWAs and TWAs. The lane-setting rules are shown in *Figure 7*.

To facilitate the discussion in this section, each phase and lane is assigned a unique number or number/letter combination. Phase 1 denotes the through movement of approaches 1 and 3 (the other phase settings are shown in *Figure 7*). The through-movement lane in approach 1 is denoted by L11 (lane 1 of phase 1); if there are other through-movement lanes, these are denoted by L12, L13 etc. from left to right. If there are two through-movement lanes in approach 1, those in approach 3 are denoted by L13 (lane 3 of phase 1); if approach 1 has n through-movement lanes, these are denoted by

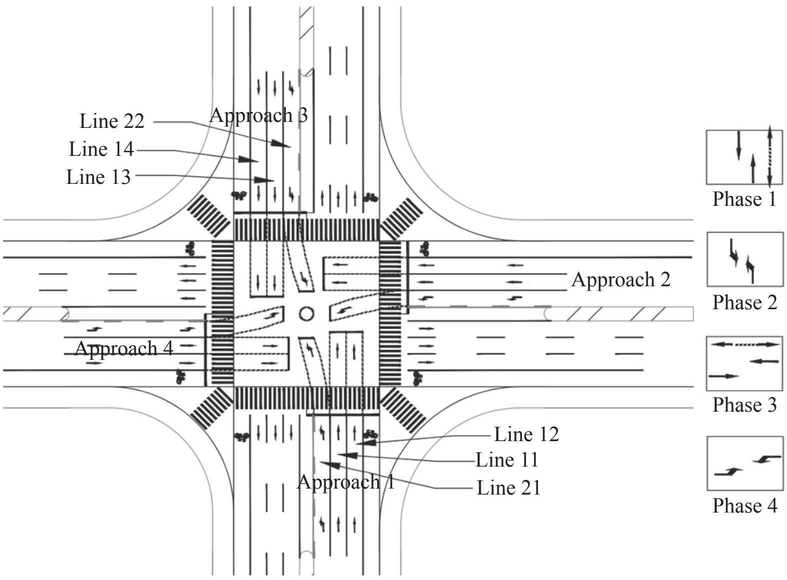


Figure 7 – Illustration of intersection with waiting areas

L1(n+1) and L14 from left to right. The one left-turn lane in approach 1 is denoted by L21 (lane 1 of phase 2; if there are other left-turn lanes, the method of assignment is the same as that for phase 1). The lane-assignment method for the other approaches is the same as that for approaches 1 and 3.

The saturation flow rate s of each lane is either given by HCM2010 or is computed as follows:

$$s = \frac{3600}{h_0} \tag{9}$$

Hence, the saturation flow rate S of each phase is computed as

$$S_i = \sum_j \frac{3600}{h_{ij}} \tag{10}$$

The phase ratio of input flow to saturation flow is given by

$$\lambda_i = \max \frac{Q_{ik}}{S_{ik}} \tag{11}$$

where Q_{ik} is the input flow rate of approach k in phase i. According to Webster's theory, the effective green time of each phase should be proportional to the phase flow rate, i.e.,

$$\frac{g_{ei}}{\sum g_{ei}} = \frac{\lambda_i}{\sum \lambda_i} \tag{12}$$

where g_e is the effective green time and λ is the green time ratio. The cycle lost time L is computed as follows:

$$L = \sum_i l_{pi} \tag{13}$$

where l_{pi} is the total lost time of phase i. Hence,

$$\sum g_{ei} = T_c - L \tag{14}$$

where T_c is the cycle length. The effective green time of each phase can be obtained from *Equations 12–14* as follows:

$$g_{ei} = \frac{\lambda_i}{\sum \lambda_i} \sum G_{ei} = \frac{\lambda_i}{\sum \lambda_i} [T_c - L] \tag{15}$$

The releasable traffic flow c_{ij} of each lane in a cycle can then be calculated as follows:

$$c_{ij} = \delta \left(n_{ij} + \frac{g_{ei}}{h_{ij}} \right) \tag{16}$$

where δ is the reduction factor and n_{ij} is the storage capacity of the WA for L_{ij}. The releasable traffic flow of an intersection in a given cycle is calculated as follows:

$$c = \sum_i \sum_j c_{ij} \tag{17}$$

The capacity C of an intersection with WAs is computed as follows:

$$C = \frac{3600}{T_c} c \tag{18}$$

Equation 19 is obtained by substituting *Equations 15–17* into *Equation 18*:

$$\begin{aligned} C &= \frac{3600}{T_c} c = \frac{3600}{T_c} \sum_i \sum_j c_{ij} \\ &= \frac{3600}{T_c} \sum_i \sum_j \delta \left(\frac{G_{ei}}{h_{ij}} + n_{ij} \right) \\ &= \frac{3600}{T_c} \sum_i \sum_j \left(\frac{\delta \lambda_i (T_c - L)}{h_{ij} \sum \lambda_i} + \delta n_{ij} \right) \end{aligned} \tag{19}$$

where n_{ij} is obtained by observation, δ is obtained from HCM, L and h_{ij} are obtained either by observation or from HCM, and λ_i is calculated by using *Equation 12*. Therefore, the capacity C is only related to the cycle T_c.

3.3 Cycle optimisation for unsaturated intersections

The theory and method of signal optimisation under low saturation are well developed. The traditional approach involves establishing optimisation models based on traffic flow theory and obtaining signal parameters by establishing models. In previous studies, optimisation with the lowest delay as the objective function was the most popular [11–16].

The signal-scheme optimisation methods of Webster [12], Akcelick [15], and HCM [44] are used widely by traffic engineers in various countries. Intersections with WAs are dealt with as those without WAs before optimisation with these methods. The green time of phases with WAs can be reduced by t–t_w, and two optimisation ideas are provided here: (i) keep the cycle length unchanged and extend the green time of the next phase by t–t_w; (ii) keep the green time of the other phases unchanged and reduce the cycle length.

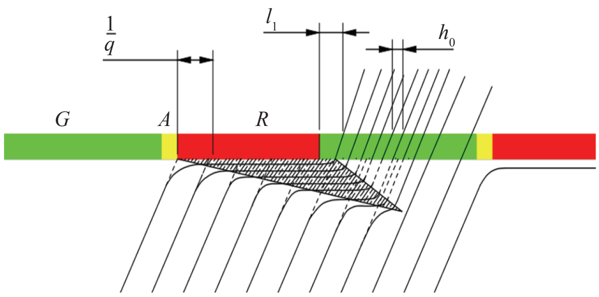


Figure 8 – Vehicle arrival and departure trajectories

Figure 8 shows the vehicle trajectories in the case of uniform arrival, and the shaded triangular area is the total delay. The average delay d is calculated as follows:

$$d=\frac{s\cdot R_e^2}{2T_c(s-q)}=\frac{T_c(1-\lambda)^2}{2(1-\lambda x)} \tag{20}$$

where R_e is the effective red time, q is the traffic flow and x is the volume-to-capacity ratio.

If random fluctuation of vehicle arrival is taken into account, then the average delay can be calculated by Webster's delay model:

$$d=\frac{T_c(1-\lambda)^2}{2(1-\lambda x)}+\frac{x^2}{2q(1-x)}-0.65\left(\frac{T_c}{q^2}\right)^{\frac{1}{3}}x^{2+5\lambda} \tag{21}$$

3.4 Cycle optimisation for oversaturated intersections

At oversaturated intersections, increasing capacity is an effective way to alleviate congestion. Therefore, the following optimisation model can be established:

$$\begin{aligned}&f=\max(C)\\&\text{s.t}\begin{cases}G_i\in[G_{i\min},G_{i\max}]\\T\in[T_{\min},T_{\max}]\\T_{\min}\geq L+\sum G_{i\min}\end{cases}\end{aligned} \tag{22}$$

Suppose $\Lambda_i=\delta\lambda_i/\sum_i\lambda_i$, so that

$$C=\frac{3600}{T_c}\sum_i\sum_j\left(\frac{\Lambda_i}{h_{ij}}(T_c-L)+\delta n_{ij}\right) \tag{23}$$

Suppose $H_i=\sum_j\frac{1}{h_{ij}}, N_i=\sum_j\delta n_{ij}$ so that

$$\begin{aligned}C&=\frac{3600}{T_c}\sum_i(\Lambda_i\cdot H_i(T_c-L)+N_i)\\&=\frac{3600}{T_c}\sum_i(\Lambda_i,H_i,T_c-\Lambda_i,H_i,L+N_i)\\&=3600\sum_i(\Lambda_iH_i)+3600\sum_i\frac{N_i-\Lambda_i,H_i,L}{T_c}\end{aligned} \tag{24}$$

Suppose $\Lambda=\sum_i\Lambda_iH_i, N=\sum_i N_i$ and substitute these expressions into *Equation 24*:

$$C=3600\Lambda+3600\frac{N-\Lambda L}{T_c} \tag{25}$$

Hence, the optimised model becomes

$$f=\max(C)=\max\left(3600\Lambda+3600\frac{N-\Lambda L}{T_c}\right) \tag{26}$$

the solution to which is

$$T_c=\begin{cases}T_{\min}, & N>\Lambda L\\\text{Any value}\in[T_{\min},T_{\max}] & N=\Lambda L\\T_{\max}, & N<\Lambda L\end{cases}$$

4. CASE STUDY

In this section, we consider three four-leg intersections with WAs in Zhengzhou (China), and their geometric characteristics are given in *Table 1*. The intersection of Ping'an Road and Wenyuan Road (Intersection 1) and the intersection of Jinshui Road and Mingli Road (Intersection 2) have LWAs, and the investigation periods for both intersections were when they were unsaturated. The intersection of Ping'an Road and Dongfeng Road (Intersection 3) has TWAs, and there were long queues of vehicles

Table 1 – Characteristics of intersections

Site	Intersection	Approach	Lane configuration	Lane width [m]	Number of WAs	Lengths of WAs [m]
1	Wenyuan Road and Ping'an Road	East	1L + 3T + 1R	3.5	1L	29
		West	1L + 3T + 1R		1L	26
		South	1L + 3T + 1R		1L	27
		North	1L + 3T + 1R		1L	25
2	Jinshui Road and Mingli Road	East	1L+4T+1B+1R	3.5	1L	21
		West	1L+4T+1B+1R		1L	25
		South	2L + 3T + 1R		2L	41
		North	1L + 3T + 1R		1L	44
3	Dongfeng Road and Ping'an Road	East	1L + 3T + 1R	3.5	3T	18.8,18.3,18
		West	1L + 3T + 1R		3T	17,17,16.6
		South	1L + 4T + 1R		3T	28.4,25.2,21.4
		North	1L + 4T + 1R		3T	27.4,27,24.4

L: left-turn lane; T: through lane; R: right-turn lane; B: bus lane in three approaches during the investigation period. The intersection layouts are shown in *Figure 9*, and the traffic flows at these three intersections are given in *Table 2*.

Drones (Mavic Air2; DJI, China) and video cameras (DS-2CD; Hikvision, China) were used to record traffic data during the peak period of a weekday with fine weather, as shown in *Figure 10*. In total, 5 hours of valid video was recorded. Each second of video contained either 25 (DS-2CD) or 30 (Mavic Air2) frames, and the research team recorded the number of frames in which each car was crossing the stop line. The headway is calculated based on the difference in the number of frames between two adjacent cars crossing the stop line. In total, 246 groups of uninterrupted traffic flows were collected. The statistical results are presented in *Figure 11* and *Tables 3 and 4.*

Table 2 – Input flow [veh]

Site	Movement	East	West	South	North
1	L	187	75	198	28
	T	1028	1171	112	153
2	L	184	96	140	223
	T	1432	1364	224	488
3	L	355	247	362	324
	T	1488	265	1678	1533

The statistical results show a striking phenomenon: the saturation headway at the intersections with WAs is smaller than that at the intersection without WAs. There may be two reasons for this: (i) the small sample sizes may have produced errors; (ii) drivers must start their vehicles in advance at intersections with WAs, so they perhaps pay more attention. In addition, the results show that the start-up lost time is correlated positively with the WA length.

Intersection 1 Intersection 2 Intersection 3

Figure 9 – Satellite images of three intersections (from Google Earth)

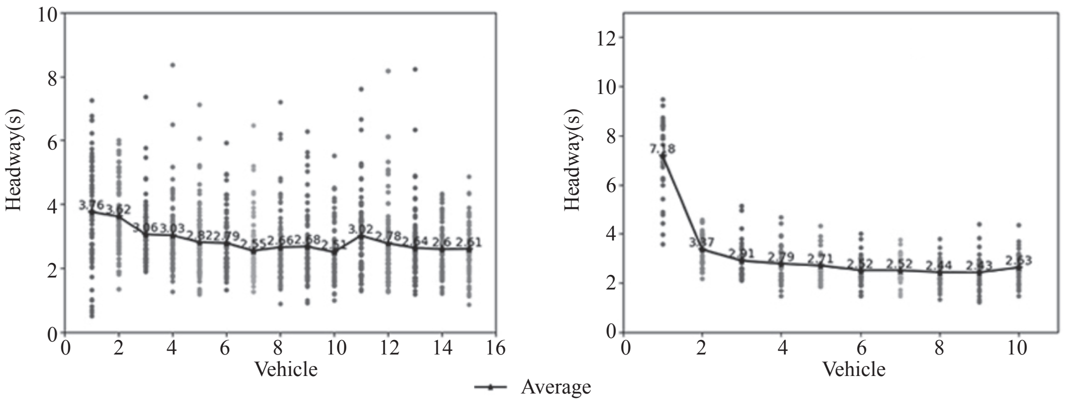
a) Human–machine interface of drone

b) Image from recorded video

c) Image from recorded video

d) Image from recorded video

Figure 10 – Survey field



a) Without WAs *b) With WAs*

Figure 11 – Statistics of headway

Table 3 – Summary statistics of saturation headway

	Length of WA [m]	Sample size	Min [s]	Max [s]	Average [s]	SD*
Without WAs	0	76	2.03	3.67	2.74	0.359
	0	80	2.09	4.09	2.74	0.420
	0	37	2.01	3.62	2.82	0.352
Total					2.76	
With WAs	25	23	1.97	2.86	2.39	0.238
	21	13	2.24	3.24	2.77	0.284
	41	17	192	2.92	2.45	0.278
Total					2.51	

**SD – standard deviation*

Table 4 – Summary statistics of start-up lost time

	Length of WA [m]	Sample size	Min [s]	Max [s]	Average [s]	SD
Without WAs	0	76	−0.93	9.61	2.47	2.225
	0	80	−2.79	7.27	2.66	1.960
	0	37	−3.41	8.62	2.53	2.580
Total					2.56	
With WAs	25	23	4.01	9.58	6.30	1.445
	21	13	3.38	9.01	5.81	1.747
	41	17	4.43	12.13	8.16	1.844

Queuing spacing can be obtained through statistics by using satellite images from Google Maps. Queuing cars stop before the stop line at a signalised intersection, and the queue length and each car can be identified clearly. The spacing is equal to the queue length divided by the number of vehicles. The statistical results are presented in *Figure 12* and *Table 5*.

Table 5 – Summary statistics of queuing spacing

Sample size	Min [m]	Max [m]	Average [m]	SD
163	5.6	8.4	6.9	0.49

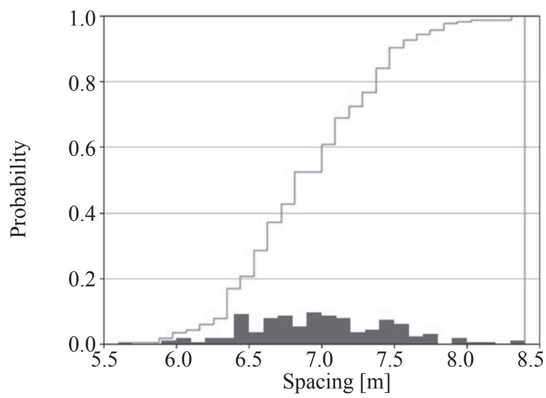


Figure 12 – Cumulative probability curve of queuing spacing

4.1 Results for unsaturated intersections

Intersections 1 and 2 did not reached saturation, and the signal schemes from 16:00 to 18:00 on a weekday are given in *Table 6*. Installing WAs reduces the transit time of the left-turn phase; the reduced time is obtained according to *Equation 8* and *Tables 4 and 7*, and the results are given in *Table 8*.

The reduced time of installing WAs is rounded down, and two strategies are used to check the calculations by Webster's model. The calculation results are given in *Table 9*. Under the two strategies, the delay is reduced. For the two intersections, the effect of mode 2 is better than that of mode 1, and the average delay of through vehicles is reduced by more than 10%. The first term (stop delay) in *Equation 21* is the main part of the average delay, and the cycle length has a linear relationship with the stop delay. Therefore, reducing the cycle time appropriately can reduce the delay. For an intersection with an unconventional geometric design, optimising the signal scheme is effective for improving the operation efficiency of the intersection.

Table 6 – Signal schemes [s]

Site	Phase 1	Phase 2	Phase 3	Phase 4	A	Cycle
1	60	30	33	25	3	160
2	60	30	45	30	3	177

Table 7 – Storage capacity of each WA [veh]

Site	East	West	South	North
1	4.2	3.8	3.8	3.6
2	3	3.6		5.9

Table 8 – Reduced time of each WA [s]

Site	East	West	South	North
1	7.05		6.75	
2	5.03	6.2		10.68

4.2 Results for oversaturated intersection

During the on-site investigation, intersection 3 became oversaturated and the queues were very long. The lengths of the WAs and the numbers of vehicles that could enter them are given in *Table 10*.

The yellow change interval A at this intersection was 3 seconds, and the red clearance interval was 2 seconds. The phase lost time is computed using the following equation (HCM, 2010):

$$l_i = l_1 + l_2 = l_1 + A + r - e \tag{27}$$

where l_2 is the red clearance lost time, r is the red clearance interval and e is the extension of the effective green interval, which was 2.0 s in this study (HCM, 2010). Hence, l_i=5.56 seconds and so L=22.24 seconds from *Equation 13*. Because the saturation headway is the average result obtained from the statistics, we have δ=1.

Table 9 – Delay comparison

Site	Phase	Current	Mode 1		Mode 2	
			Delay	Reduction rate	Delay	Reduction rate
1	1	40.5	36.8	9.0%	34.7	14.2%
	3	57.6	53.6	6.8%	51.6	10.3%
2	1	51.9	46.0	11.3%	44.5	14.3%
	3	60.8	57.8	4.9%	53.4	12.2%

Table 10 – Storage capacity of each WA

	Phase 2		Phase 4	
	Length [m]	n_{ij} [veh]	Length [m]	n_{ij} [veh]
$line_{i1}$	28.4	4.1	18.8	2.7
$line_{i2}$	25.2	3.7	18.3	2.7
$line_{i3}$	21.4	3.1	18	2.6
$line_{i4}$	27.4	4.0	17	2.5
$line_{i5}$	27	3.9	17	2.5
$line_{i6}$	24.4	3.5	16.6	2.4

From the substitution factors, it can be obtained Λ=13.15 and N=37.7, i.e. $N<\Lambda L$. Therefore, the cycle time should be maximised to maximise the capacity. *Equation 25* can be converted to C=47,340 – 917,121/T_c.

In this case, the capacity increases as the cycle time increases. The maximum capacity is 24.5% higher than the minimum capacity. Because of the lost time, the relationship among traffic capacity, WA storage capacity, and cycle time in traditional designs is similar to that in *Figure 13*. These results show that the model is effective.

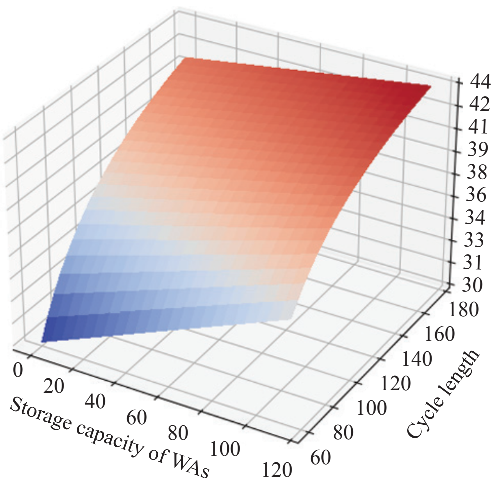


Figure 13 – Relationship among intersection capacity, cycle length and WA storage capacity

5. DISCUSSION

The conflict caused by left turns is the main factor affecting the safety and operation efficiency of intersections. Many unconventional geometric designs are effective for eliminating conflict points and improving intersection operation efficiency. However, because of the advantages of low construction cost, having no impact on other intersections and being more in line with the driving habits of Chinese drivers, the practice of installing WAs is more common than other unconventional designs in China.

This paper covers the following main issues: (i) comparative analysis is used to discuss the difference in vehicle start-up process between intersections with and without WAs; (ii) a model for estimating the capacity of intersections with WAs is proposed; (iii) results for two cases are presented to demonstrate the effectiveness of the proposed signal optimisation strategies for the unsaturated state; (iv) the relationship among WA storage capacity, cycle time, and traffic capacity is discussed using field survey data.

However, the research on optimising the signal schemes for intersections with WAs can be developed further. Various factors such as vehicle composition, proportion of large vehicles, driving behaviours, and environments affect the efficiency and safety of intersections, but these factors are beyond the scope of this work. In addition, only three cases were selected in this paper; had more intersections and a longer on-site investigation period been selected, the statistical results and model analysis may have been more in line with reality. These limitations of the present study should be considered in any future investigation.

6. CONCLUSION

In this paper, the location and implementation of WAs was discussed. Such designs can be used to enhance both through-movement and left-turn movement, with different layouts for leading and lagging left-turn phasing. This study analysed the start-up process of vehicles, compared the difference in start-up lost time of intersections with and without WAs, and proposed control strategies for unsaturated and oversaturated intersections. Using real-world data, this study examined three intersections in Zhengzhou and found that the proposed model is effective. Based on the results presented herein, the following conclusions are obtained: (i) installing WAs can improve the capacity of signalised intersections; (ii) optimising the signal scheme is effective for reducing the delay of through vehicles at unsaturated intersections with LWAs; (iii) the traffic capacity increases as the WA storage capacity increases; (iv) installing WAs can reduce traffic delays; (v) compared with permissive phasing, the LWA design can handle high-volume traffic with less delay and higher safety.

Installing WAs has become one of the main methods for improving the efficiency of intersections in Chinese cities. However, a more reasonable way to discuss how installing WAs influences intersection efficiency must be proposed. Future studies should include the impact of installing WAs on driving behaviours, the strategy, and optimisation of the signal scheme, as well as a performance comparison between other unconventional designs and the WA design. In the future, more-extensive field investigations and experiments will be required to evaluate the effectiveness of installing WAs with different intersection geometric structures. Moreover, the optimal design scheme will be explored from multiple perspectives such as traffic safety, traffic coordination, and energy.

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有等待区交叉口信号配时优化

摘要

为减少左转弯冲突，提高交叉口通行效率，交通工程师提出了一些非常规几何设计，例如连续流交叉口、中间掉头以及逆向左转车道设计。而在中国和日本，在信号交叉口设置等待区以提高通行能力是一种很普遍的做法。许多研究已经表明等待区可以很大程度上提高通行能力，然而很少有从信号优化角度去考虑如何提高这种设计的优势。本文通过对比车辆在有等待区和无等待区交叉口的启动过程，探讨等待区设计对车辆通行时间的影响，提出两种信号优化策略，并建立了统一的有等待区交叉口通行能力计算模型。以通行能力最大化为优化目标，推导出适应过饱和交叉口的周期优化模型。最后，利用实地调查的数据讨论等待区存储容量、周期时间与通行能力的关系。两个案例交叉口的计算结果表明，通过优化信号方案，可以减少*10-15%*的交叉口延误。

关键词
等待区；优化；通行能力；信号配

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