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Analysis of saturation flow rate at tandem intersections using field data

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Abstract: A tandem intersection is an unconventional intersection design that possesses the important property of increasing the traffic capacity using pre-signals and sorting areas. However, the operational efficiency of the lanes in the sorting areas may be affected by driver unfamiliarity and confusion. This study evaluates the effect of the tandem control on the saturation flow rate using field data. Statistical analyses were conducted to identify the difference in the saturation flow rate of the approach lanes when the tandem control was open and closed. A saturation flow rate adjustment model for tandem control was established in accordance with three factors: unequal distribution of traffic, red light violations at the pre-signal, and incomplete discharge of vehicles at the sorting area. The results indicate that the tandem control decreases the saturation flow rate of the approach lanes in the sorting area. Most of the observed reductions are caused by the first factor, i.e. the unequal distribution of traffic. The other two factors, red light violations and incomplete discharge, can be controlled by using appropriate traffic signs, markings, and signal timing design.

1 Introduction

Reducing congestion at intersections is a continuing problem in urban environments owing to the ever-increasing traffic demand. For many years, traffic engineers have been investigating how to control and manage conflicts among turning movements in a manner that ensures safety and improves operational efficiency.

Conventionally, congestion problems at intersections were addressed using signal controls, which include three approaches: the stage-based method [1–4], group-based method [5–9], and lane-based optimisation method, which combines the design of lane assignments and signal settings [10–13]. To enhance the capacity of intersections, many unconventional intersection designs have been proposed. These include median U-turn intersections [14, 15], superstreet intersections [14, 16, 17], bowtie [14], paired intersections [18], jug-handle [18, 19], quadrant roadway intersections [20, 21], hamburger intersections [20], displaced left-turn intersections [22, 23], exit-lanes for left-turn intersections [24, 25], special width approach lanes [26], and tandem intersections [27–29].

One of the suggested unconventional intersection designs is the tandem intersection [27], which is the focus of this study. The definition of the tandem intersection is that left-turn and through vehicles enter the approach lanes in tandem. As shown in Fig. 1, the approach lanes function as a sorting area, which can be used as left-turn lanes and through lanes during their corresponding signal phases. A pre-signal upstream of the intersection reorganises the traffic. The lanes upstream of the pre-signal are marked by movements to control the permission of vehicles advancing into the sorting area. Then, all approach lanes can be used to discharge the left-turning and through-moving vehicles. The operational procedure of the tandem intersection using the phase swap sorting strategy is shown in Fig. 1. The left-turning and through-moving vehicles use the sorting area alternately while those in the east–west direction and south–north direction discharge alternately. Vehicles that are allowed to enter the sorting area at the pre-stop line in the previous phase will be allowed to discharge at the main stop line in the later phase. In Phase 1, the main signal at the east and west approach turns green for left-turning vehicles that are waiting at the main stop line in the sorting area; the pre-signal at the south and north approach turns green for left-turning vehicles to allow them to enter the sorting area. In Phase 2, the main signal at the south and north approach turns green for left-turning vehicles, and the pre-signal at the east and west approach turns green for through-moving vehicles. In Phase 3, the main signal at the east and west approach turns green for through-moving vehicles, and the pre-signal at the south and north approach turns green for through-moving vehicles. In Phase 4, the main signal at the south and north approach turns green for through-moving vehicles, and the pre-signal at the east and west approach turns green for left-turning vehicles.

The tandem intersection can increase the capacity of the entire intersection owing to the increase in the number of traffic lanes for both left-turning and through-moving vehicles. In conventional intersections, only the lanes assigned to left-turning vehicles discharge during the protected left-turn phase. Similarly, during the through phase, only the traffic in the through lanes discharges. However, in tandem intersections, all lanes can completely discharge during both phases. Therefore, the tandem intersection is effective in increasing the capacity of the entire intersection, particularly when the demand in different traffic movements is identical and the percentages of through, left-turn, and right-turn movements are not more than 65% on all arms [29].

The tandem intersection was first proposed by Xuan in 2011 [27]. Then, Ma *et al.* [28] developed an optimisation model for an isolated intersection approach with pre-signals to explicitly capture the interaction between the pre-signal and main signal and to optimise signal timing for the entire intersection. The queue-evolving process and capacity in the sorting area were formulated in the model with respect to different types of phase sequences, durations of green signals, and offsets between the main signal and pre-signal. Furthermore, Yan *et al.* [29] implemented the phase swap sorting strategy and developed an optimisation model that produces capacity maximisation decisions, in which the through, left-turn and right-turn movements on all legs of an intersection were explicitly taken into consideration.

In these optimisation methods, the saturation flow rate is an important input. Many efficiency indices, such as capacity, delay, waiting time, and queuing length, are calculated based on the saturation flow rate. For conventional intersections, research has

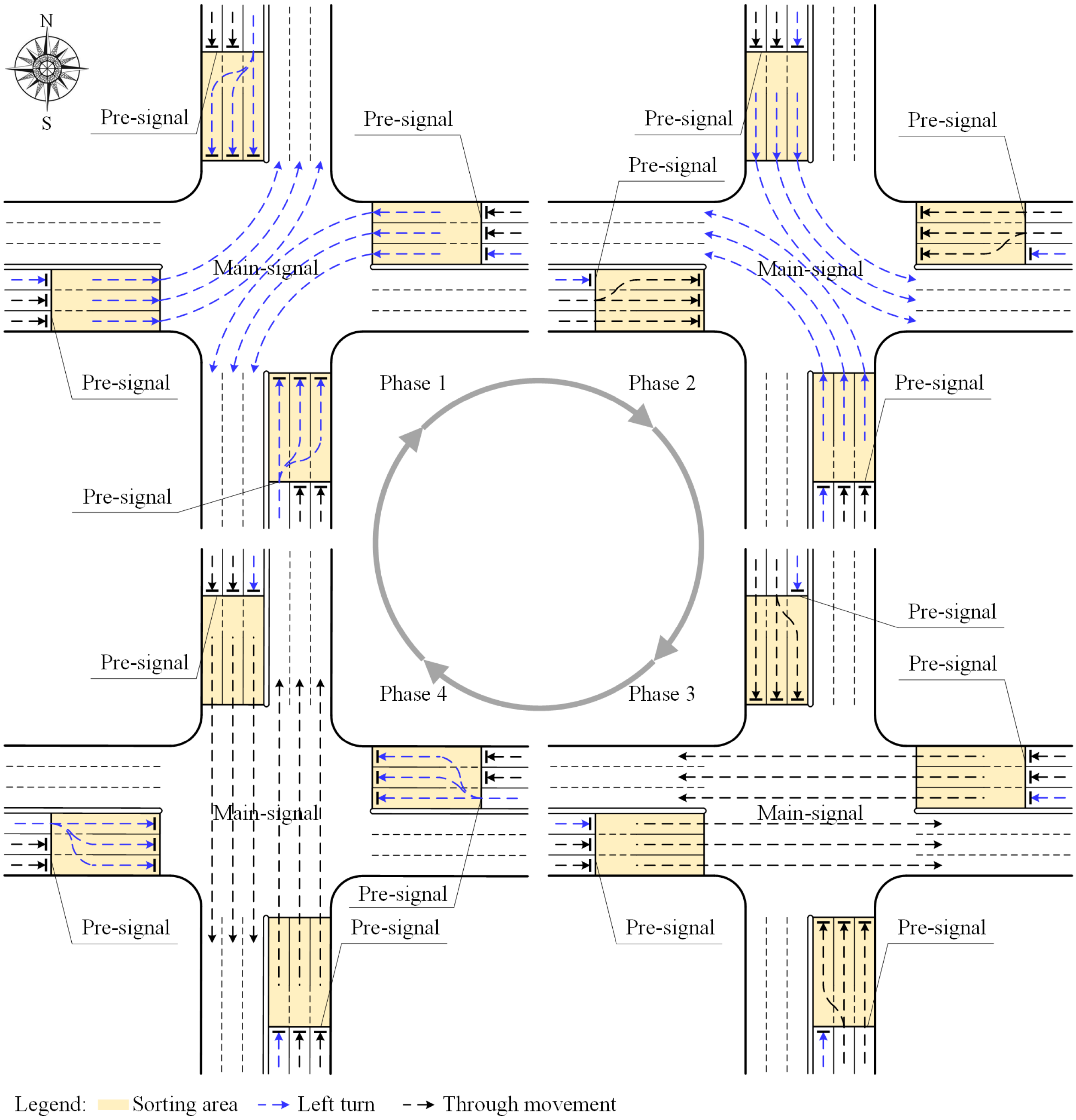


Fig. 1 *Operational procedure of the tandem intersection*

been conducted to establish adjustment factors for the saturation flow rate. In HCM2010 [30], the adjustment factors include lane width, heavy vehicles, grade, parking, bus blockage, area type, lane utilisation, right turns, left turns, and pedestrians and bicycles. Other adjustment factors, such as short lanes [31, 32], weather conditions [33], lighting conditions [34], access flows [35], the stochastic nature of queue discharge headways [36], and signal countdown devices [37] are discussed. However, for tandem intersections, few or no studies have been conducted up to the present time regarding the effect of this control method on the saturation flow rate. The saturation flow rate of the lanes at tandem intersections is assumed to be the same as the lanes at conventional intersections. Despite the positive effects of pre-signals and sorting areas in reorganising traffic and improving intersection capacity, it is argued that drivers may be confused and may violate the rules intentionally or unintentionally owing to its unconventional design. Many traffic flow models also indicate significant changes in the driving behaviour under different traffic control and management conditions [38–41]. Consequently, the promising benefits that are anticipated in existing theoretical analyses may not occur in a real-life setting.

To overcome this deficiency, this study aims to analyse the saturation flow rate at tandem intersections. The following critical operational issues are addressed: (i) are there significant differences in the saturation flow rates among the lanes in the sorting area and normal approach? (ii) If significant differences exist, what are the influencing factors (unequal distribution of traffic, red-light violations at the pre-signal, and incomplete discharge at the sorting area) and their degree of influence?

The methods for operational evaluation include the use of field data and driving simulators. The former is a more direct way and could attain real operational conditions [42–48]. The latter is a cost-effective way of examining driver responses under different traffic conditions, signage, and other design factors without posing any risk to drivers [49–56]. Considering that the driving environment in a simulator generally differs from that in the real world owing to various factors caused by other road users, limited sight distance, marking degradation etc., the field data method was used in this research.

The contribution of this study lies in the quantified analysis of the saturation flow rate for the tandem intersection using field data. A saturation flow rate adjustment model for tandem control is

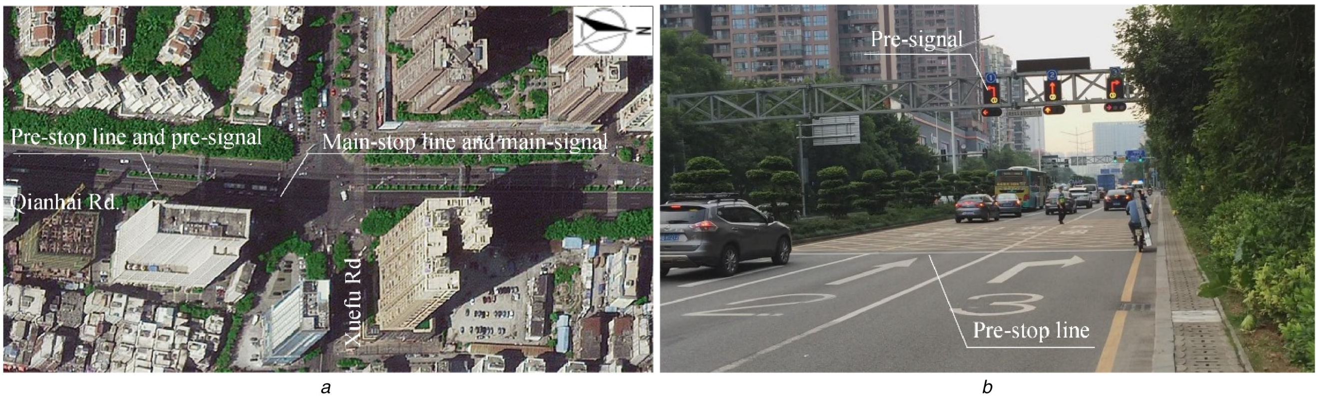


Fig. 2 *Surveyed intersection in Shenzhen, China*
(a) Aerial view, ***(b)*** View at the pre-signal of the south approach

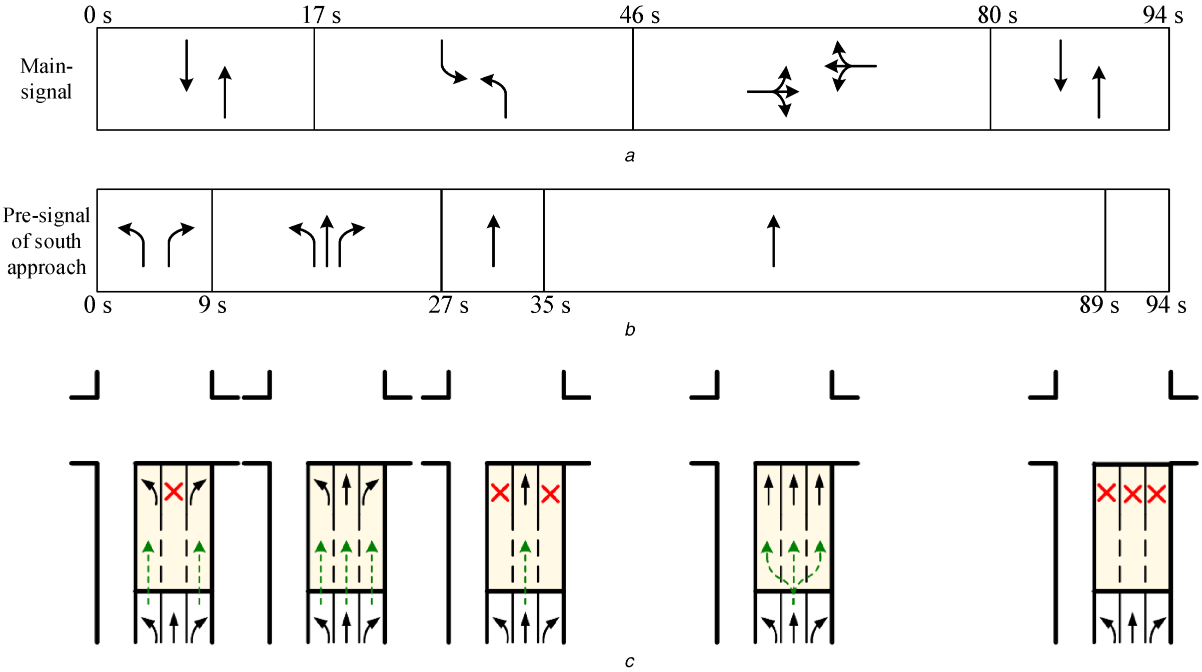


Fig. 3 *Signal timing and operation of the sorting area*
(a) Main signal, ***(b)*** Pre-signal, ***(c)*** Operation of the sorting area

established considering the three influencing factors. The recommendations to relieve the negative impact are discussed.

The rest of this paper is organised as follows. In Section 2, the surveyed intersection and data collection are introduced. In Section 3, the saturation flow rates between the lanes in the sorting area and normal approach are compared and the influencing factors are analysed. Section 4 discusses the potential efficiency issues of the tandem intersection and the recommendations for improvement. Finally, the conclusions drawn are presented at the end of the paper.

2 Materials

2.1 Surveyed intersection

The tandem intersection surveyed herein has been in use at the intersection of Qianhai Road and Xuefu Road in Shenzhen, China, as illustrated in Fig. 2. The pre-signals and sorting areas are at the south and north approaches of the intersection. The length of the sorting area is 65 m. The tandem control is open in the morning and evening peak hours (07:30–09:00 and 17:30–19:00). The tandem control is closed during off-peak hours, and the intersection then operates as a conventional intersection. The traffic operation of the south approach is surveyed and analysed in this study because of the suitable viewing angle of the camera. The layout of the lane assignments in the sorting area and the signal timings are illustrated in Fig. 3. The main signal of the intersection is a three-phase plan. A fully protected left-turn phase is provided for the north–south direction (from 17 to 46 s in a signal cycle). It follows the through phase of the north–south direction (from 80 to 17 s). For the east–west direction, a green phase (from 46 to 80 s), during which all movements are allowed to proceed, is set. The pre-signal is coordinated with the main signal. Left-turning and right-turning vehicles are allowed to drive into the sorting area during the north–south through phase at the main signal (from 0 to 9 s). Only the leftmost and rightmost lanes can be used for left turns and right turns, respectively. Then, the through-moving vehicles are allowed to drive into the middle approach lane (from 9 to 27 s). During the north–south left-turn phase, all left-turning and right-turning vehicles in the sorting area should be cleared (from 27 to 35 s). After clearing the left- and right-turning vehicles, the through-moving vehicles are allowed to drive into all the lanes of the sorting area (from 35 to 89 s). Then, all approach lanes are used as through lanes when the north–south through phase begins. The green phase for the through movement at the pre-signal ends earlier than that at the main signal to ensure the clearance of the through-moving vehicles (from 89 to 94 s). Then, the cycle is repeated by returning to the first step. One can observe that all approach lanes are used as through lanes during the north–south through phase.

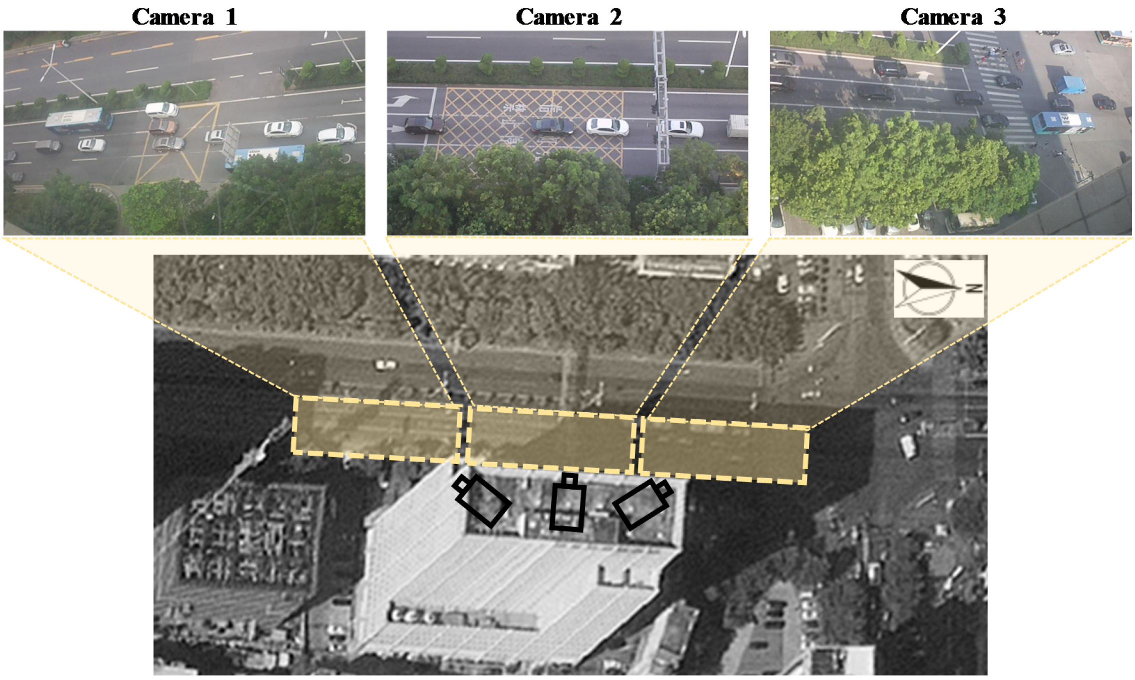


Fig. 4 *Camera views of the surveyed intersections*

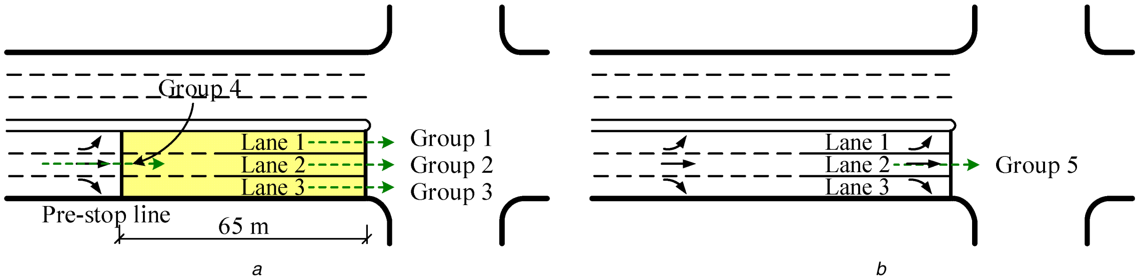


Fig. 5 *Data grouping diagram*
(a) Tandem control is open, ***(b)*** Tandem control is closed

2.2 Data collection

The traffic data used in this study were obtained by video cameras. To capture the entire running process of the tandem control, three cameras were installed to capture data simultaneously, as shown in Fig. 4. The three cameras were mounted at the top of a roadside building. The running characteristics of vehicles upstream of the pre-signal, at the transition section, and at the approach, were recorded by Cameras 1, 2, and 3, respectively. Video-based data collection was performed between the hours of 07:00–10:00 and 16:00–19:00 on 23–26 August 2016. This configuration allowed for the data capture of both the open and closed conditions of the tandem control.

Vehicle arrivals and departures every second were readily obtained using the video cameras. The time-varying traffic data and operational performances such as the saturation flow rate, usage distribution of vehicles among approach lanes, lane changing and selection behaviour, and violations, were collected for subsequent analyses.

2.3 Data grouping

To analyse the impact of the tandem control on traffic operation, the surveyed data were divided into five groups, as illustrated in Fig. 5. When the tandem control is open (see Fig. 5*a*), the left-turning and right-turning vehicles can only use Lane 1 and Lane 3, respectively. Through movements, one can use all three approach lanes. The pre-signal is used to control the allowance of different movements into the sorting area. During the green period of the through movement at the pre-signal, through-moving vehicles can drive into the sorting area and select any of the three approach lanes. When the tandem control is closed (see Fig. 5*b*), the left-turning, through-moving, and right-turning vehicles can only use Lane 1, Lane 2, and Lane 3, respectively. The following analysis focuses on the through movement, as this is the only movement that uses the tandem control for the surveyed intersection. The data of the five groups were then counted as follows. Note that the difference between Group 2 and Group 4 is that Group 2 is the saturation flow rate of Lane 2 at the main stop line while Group 4 is the saturation flow rate of Lane 2 at the pre-stop line.

Group 1: Lane 1 at the main stop line when the tandem control is open, which is used in an alternating manner as a through and left-turn lane.
Group 2: Lane 2 at the main stop line when the tandem control is open, which directly aligns with the pre-signal through lane, and is always used as an exclusive through lane.
Group 3: Lane 3 at the main stop line when the tandem control is open, which is used in an alternating manner as a through and right-turn lane.
Group 4: Lane 2 at the pre-stop line when the tandem control is open.
Group 5: Lane 2 at the main stop line when the tandem control is closed. This is a normal approach lane with the same lane usage as that for all the above four groups. Therefore, Group 5 can be used as a benchmark to analyse the operational characteristics of the tandem control.

3 Saturation flow rate analysis

The saturation flow rate is a key indicator of the operational efficiency of traffic lanes. In this section, multiple comparisons are

Table 1 Statistical description of headways

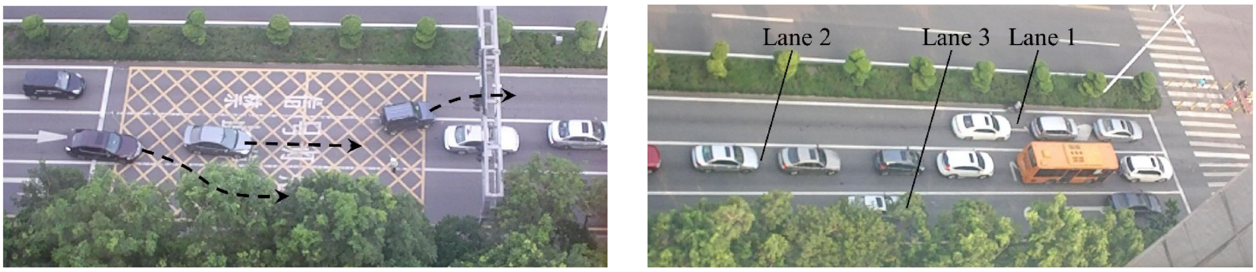
Group	Sample size	Minimum	Maximum	Mean	Standard deviation	Test of normality (1 − sample K–S)	Kruskal–Wallis test	
							χ^2	Sig. (p)
1	1451	0.80	6.06	2.871	1.065	0.000	792.152	0.000
2	1752	0.88	5.95	2.415	0.902	0.000		
3	1485	0.81	6.08	2.782	0.879	0.000		
4	4688	0.73	6.00	2.332	1.103	0.000		
5	5771	0.71	5.98	2.301	0.963	0.000		

Note: Minimum and maximum headways are the minimum and maximum values of the surveyed headways in each group. The Kruskal–Wallis test is a non-parametric method for testing whether samples originate from the same distribution. Sig. is the abbreviation for significance.

Table 2 Mann–Whitney *U* test for the saturation flow rate

Group I	Group J	s_I/s_J	Mann–whitney U	Wilcoxon, W	Z-value	Sig. (two-tailed)
group 1	group 5	0.801	2,711,688.500	19,366,794.50	−20.779	0.000
group 2	group 5	0.953	4,524,274.500	21,179,380.50	−6.671	0.000
group 3	group 5	0.827	2,829,172.000	19,484,278.00	−20.222	0.000
group 4	group 5	0.987	13,440,744.00	24,431,760.00	−0.563	0.573

Note: s_I and s_J refer to the saturation flow rate of Group I and Group J, respectively. U is the statistic value of the Mann–Whitney U test. W is the Wilcoxon rank sum (the rank sum of the smaller group). Z is the standardised value of U. *Sig.* is the abbreviation for significance.



a *b*

Fig. 6 *Example of unequal distribution of traffic*
(a) Lane selection and lane changing behaviour, ***(b)*** Unequal distribution of traffic

first performed to identify whether the differences in the saturation flow rates among the five groups of lanes are significant or not. If they are, further analysis will be conducted to determine where the differences exist.

3.1 Saturation flow rate comparison

The actual saturation flow rate can be measured by calculating the headways between vehicles when their front axles cross the stop line. The headways are recorded after the fourth vehicle in the queue to eliminate the impact of the start-up lost time [30]. Moreover, only the queued vehicles are recorded [30]. The saturation flow rate can be calculated using (1). The mean values of the saturation flow rate of the five groups are equal to 1254, 1491, 1294, 1544, and 1565 veh/h, respectively, which is based on the mean values of the surveyed headways in each group

$$s = \frac{3600}{h}, \tag{1}$$

where s is the saturation flow rate, in veh/h; and h is the headway, in s.

As the results of the normality test (see Table 1) show that the observed headway of each group does not obey the normality distribution, the analysis of variance (ANOVA) cannot be used. Therefore, a non-parametric test, the Kruskal–Wallis test, is used to compare the headway values among the five groups. This test shows that the difference in headway among the different groups is statistically significant ($p < 0.01$ indicates that the difference is significant at a 99% confidence interval).

To determine whether the tandem control causes a negative effect on the saturation flow rate and where the differences exist, we use Table 2 to further test the significance of the headway differences between each pair of groups by using Group 5 (the exclusive through lane at the main signal when the tandem control is closed) as a benchmark. The results show that there are significant differences between the following three group pairs: Groups 1 and 5, Groups 2 and 5, and Groups 3 and 5 ($p < 0.01$ indicates that the difference is significant under a 99% confidence interval), while there is no significant difference between Groups 4 and 5 ($p > 0.05$ indicates that the difference is not significant under a 95% confidence interval). This indicates that the setting of the tandem control affected the saturation flow rate of the lanes in the sorting area. However, the saturation flow rate of the lanes at the pre-signal was not affected significantly by the tandem control. On average, the reduction in the saturation flow rate reaches 19.85, 4.72, and 17.29% (see Table 2), for Groups 1, 2, and 3, respectively.

3.2 Effect of unequal distribution of traffic

In tandem intersections, the lanes in the sorting area do not exhibit a one-to-one correspondence to the lanes at pre-signals. Similarly, in the surveyed intersection, there is one through lane at the pre-signal, while there are three approach lanes in the sorting area. Through-moving vehicles can drive into any lane in the sorting area during the green time of the through movement at the pre-signal. As shown in Fig. 6*a*, through-moving vehicles can enter the approach Lane 2 (Group 2) directly, while vehicles are forced to make a lane change to enter Lanes 1 and 3. Under ideal conditions, the utilisation of the lanes in the sorting area is equal. However, the actual driving behaviours for the lane selection and lane changing must be considered. As a result, there is an unequal distribution of vehicle accumulation among the lanes in the sorting area, as shown in Fig. 6*b*.

To analyse the lane utilisation, the number of through-moving vehicles that use each of the lanes in the sorting area is recorded on a cycle-by-cycle basis. In Table 3, ANOVA is used to compare the vehicle accumulation among the three lanes in the sorting area. To use ANOVA, the samples should obey the following three

Table 3 Traffic distribution

	Group 1	Group 2	Group 3
sample size	440	440	440
average	0.313	0.371	0.316
standard deviation	0.065	0.071	0.063
minimum	0.11	0.19	0.13
maximum	0.49	0.66	0.50
test of normality	0.200	0.200	0.200
test of homogeneity of variance	$F = 1.964$, $p = 0.141$, $\alpha = 0.05$		
ANOVA	$F = 108.433$, $p = 0.000$, $\alpha = 0.05$		

Table 4 Multiple comparisons of traffic distribution (least significant difference (LSD) test)

Group I	Group J	Mean difference (I − J)	Standard error	Sig.	95% confidence interval	
					Lower bound	Upper bound
group 1	group 2	−0.05864[a]	0.00447	0.000	−0.0674	−0.0499
	group 3	−0.00329	0.00447	0.463	0.0121	0.0055
group 2	group 1	0.05864[a]	0.00447	0.000	0.0499	0.0674
	group 3	0.05535[a]	0.00447	0.000	0.0466	0.0641
group 3	group 1	0.00329	0.00447	0.463	−0.0055	0.0121
	group 2	−0.05535[a]	0.00447	0.000	−0.0641	−0.0466

[a]Mean difference (the difference between the mean values of the two groups) is significant at the 0.05 level. Sig. is the abbreviation for significance.

conditions: independence, normality, and homoscedasticity. Therefore, the traffic distribution of each group was examined for normality and homogeneity of variance using the Kolmogorov–Smirnov (K–S) statistics and Levene's test, respectively. The results show that the traffic distributions obey the normality distribution ($p > 0.05$ indicates that the samples follow a normal distribution under a 95% confidence interval) and their variances obey the homogeneity requirement ($p > 0.05$ indicates that the variances of the groups follow the homogeneity assumption under a 95% confidence interval). This indicates that ANOVA can be used. The results show that the differences in the vehicle accumulation of the three approach lanes in the sorting area were statistically significant ($p < 0.01$ indicates that the difference is significant under a 99% confidence interval).

Furthermore, pairwise multiple comparisons were used to determine where the differences exist, as presented in Table 4. The results indicate that Group 2 (approach Lane 2) differs from Groups 1 and 3 (approach Lanes 1 and 3, respectively). However, there is no significant difference between Groups 1 and 3. This indicates that drivers prefer to choose the approach lane that directly aligns with the lane used at the pre-signal, and drivers avoid changing lanes. The saturation flow rates of the other adjacent approach lanes are thus reduced because of demand starvation. The adjustment of the saturation flow rate for the unequal distribution of traffic can be calculated using (2) [30]. The results show an average reduction of 15.34% in the saturation flow rate for the approach lanes that do not directly align with the lane used at the pre-signal

$$f_{t1} = \frac{D_v}{D_{max}}, \tag{2}$$

where f_{t1} is the adjustment for the unequal distribution of traffic under the tandem control; D_v is the demand flow rate on the lane, veh/h; and D_{max} is the demand flow rate on a single lane with the highest volume in the lane group, veh/h.

3.3 Effect of red light violations at the pre-signal

Due to the unfamiliarity with the running characteristics of tandem control, drivers may violate the red light at the pre-signal and enter the sorting area when it is used for other movements. Consequently, the following vehicles will be blocked and will have to make a mandatory lane change to go through the intersection, as illustrated in Fig. 7. This may cause a negative effect on the operational efficiency of the following two aspects.

Case 1: The approach lane is blocked, and the green time of the intersection is wasted when the vehicle that violated the red light at the pre-signal stops and waits for the right-of-way at the main signal.

Case 2: The smooth running of the adjacent lane is affected and maybe interrupted by the slow motion of the mandatory lane changes of the blocked vehicles.

The impact of the red-light violations on the saturation flow rate is determined by the possibility of an event occurrence and its effects, as given by

$$f_{t2} = 1 - P_r\delta_r, \tag{3}$$

where f_{t2} is the adjustment for the red-light violation at the pre-signal under the tandem control; P_r is the possibility of occurrence of the red-light violation at the pre-signal; and δ_r is the percentage of saturation flow rate reduction due to the red-light violation, considering that the two aforementioned cases, δ_r^b and δ_r^a are the percentages of the saturation flow rate reductions under Case 1 (the blocked lane) and Case 2 (the adjacent lane), respectively.

The data regarding the number of signal cycles during which the red-light violations occur are listed in Table 5. Note that Lane 2 (Group 2) is always used as an exclusive through the lane, and therefore, it will never be blocked. One can observe from Table 5 that there are some left-turning and right-turning vehicles that drive into the sorting area lanes during the time that they are used as through lanes. A comparison of Groups 1 and 3 yields non-significant differences ($p = 0.216 > 0.05$ indicates that the difference is not significant under a 95% confidence interval). On average, the possibility of occurrence of red light violations at the pre-signal (P_r) is 8.07%.

When the red-light violation occurs, the extent of the negative effect on the blocked lane depends on the percentage of the wasted green time (Case 1). The distribution of the wasted green time for the 71 vehicles violating the red light follows a normal distribution (see Table 6; $p > 0.05$ for the test of normality indicates that the samples follow a normal distribution under a 95% confidence interval). Therefore, the mean value is used to determine the percentage reduction in the saturation flow rate of the blocked lane due to the red-light violation, which is equal to 0.448 ($\delta_r^b = 0.448$).

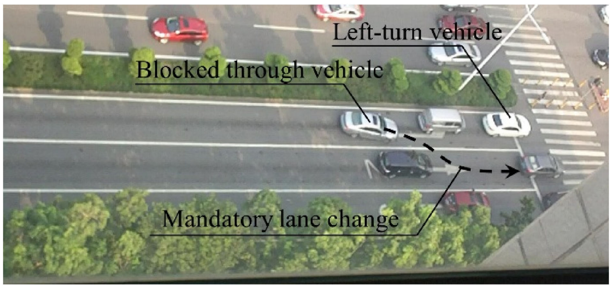


Fig. 7 *Example of lane blockage and mandatory lane change*

Table 5 Number of signal cycles where red-light violations occur

	Sample size (number of signal cycles)	Number of red light violations	Percentage	Average	Chi-square test	
					χ^2	Sig. (two-tailed)
group 1	440	41	9.318%	8.07%	1.827	0.216
group 3	440	30	6.818%			

Table 6 Statistical description of the wasted green time

Sample size	Minimum	Maximum	Mean	Standard deviation	Test of normality (1 − sample K–S)
71	0.21	0.68	0.448	0.102	0.200

Table 7 Statistical description of the number of blocked vehicles

Sample size	Minimum	Maximum	Mean	Standard deviation	Test of Poisson distribution (1 − sample K–S)	
					Z-value	Sig. (two-tailed)
71	1	6	3.338	1.434	0.586	0.882

Table 8 Regression analysis of the reductions in the saturation flow rate

Equation	Model summary			Parameter estimates	
	R^2	*F*	Sig.	Constant	*b*1
linear	0.848	384.654	0.000	17.301	2.554
logarithmic	0.881	510.883	0.000	17.512	7.571
power	0.825	324.700	0.000	18.135	0.102
logistic	0.825	324.700	0.000	0.055	0.903

Table 9 Adjustment of lane saturation flow rate for red light violations at the pre-signal

Lane	P_r	δ_r^b	*q*	δ_r^a	f_{t2}
1	8.07%	0.448	7	—	0.964
2	8.07%	—	—	0.490	0.960
3	8.07%	0.448	7	—	0.964

On the other hand, for the adjacent lane, the degree of the negative effect mainly depends on the number of blocked vehicles that requires a lane change (Case 2). The result of the K–S test shows that the number of blocked vehicles obeys the Poisson distribution, as indicated in Table 7 ($p > 0.05$ for the K–S test indicates that the samples obey the Poisson distribution under a 95% confidence interval). The regression analysis results (see Table 8) show that the logarithmic equation (with the highest value of R^2) exhibits the highest degree of goodness of fit in describing the relationship between the reduction in the saturation flow rate and the number of lane changes. Thus, the percentage of the saturation flow rate reduction at the adjacent lane owing to the red-light violation, δ_r^a, can be calculated using the following equation:

$$\delta_r^a = \sum_{x=1}^{q}\left[(7.571\ln(x) + 17.512)\frac{(q/2)^x e^{-(q/2)}}{x!}\right]\%, \qquad (4)$$

where x is the number of mandatory lane changes and q is the demand flow rate on a lane in a signal cycle, veh/cycle.

Then, according to (3), the saturation flow rate reductions of 3.6, 4.0, and 3.6%, for the three approach lanes will be caused by red light violations at the pre-signal for the tandem control, as indicated in Table 9.

3.4 Effect of incomplete discharge of vehicles at the sorting area

Another potential operational risk of the tandem intersection is the incomplete discharge of vehicles in the sorting area. As the lanes in the sorting area alternate different movements, the vehicles are trapped in the sorting area owing to inadequate coordination of the main and pre-signal blocks in a given approach lane, which affects the running efficiency of the subsequent movement using this approach lane.

The impact of the incomplete discharge on the saturation flow rate is determined by the possibility of an event occurrence and its effects, as given by the following equation:

$$f_{t3} = 1 - P_d\delta_d, \qquad (5)$$

where f_{t3} is the adjustment for incomplete discharge, P_d is the possibility of an incomplete discharge event, and δ_d is the

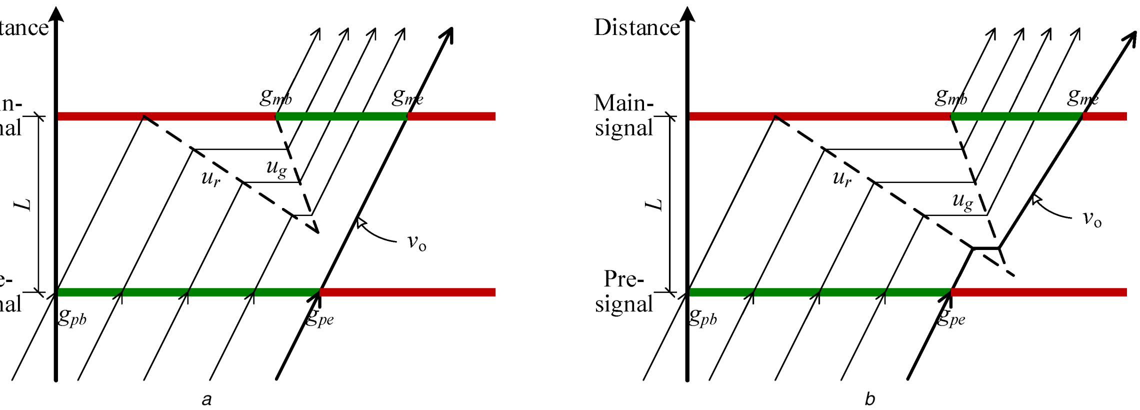


Fig. 8 *Determination of the required minimum travel speed*
(a) Case 1, ***(b)*** Case 2

Table 10 Statistical description of the travel speed of the last through vehicle

Sample size	Minimum	Maximum	Mean	Standard deviation	Test of normality (1 − sample K–S)
440	5.92	14.92	10.28	1.59	0.200

Table 11 Adjustment of lane saturation flow rate for the incomplete discharge

Lane	v_0	$\bar{v}_l$	σ_v	P_d	δ_d	f_{t3}
1	6.96	10.28	1.59	1.83%	1.000	0.982
2				1.83%	0.490	0.991
3				1.83%	1.000	0.982

percentage of saturation flow rate reduction due to incomplete discharge.

The occurrence possibility of an incomplete discharge can be estimated according to the possibility that the last vehicle will successfully pass the intersection before the end of the green time, as indicated in the following equation:

$$P_d = P_l(v_l < v_0), \qquad (6)$$

where P_d is the possibility of an incomplete discharge; P_l is the possibility that the last vehicle in the sorting area will successfully pass the intersection before the end of the green time; v_l is the travel speed of the last vehicle, m/s; and v_0 is the required minimum travel speed of the last vehicle to successfully pass the intersection, m/s.

The required minimum travel speed (v_0) is determined by the offset of the pre-signal and the main signal. As illustrated in Fig. 8, both cases (classified based on whether the shock wave affects the operation of the last vehicle) should be satisfied as given by (7). When the signal is red, the downstream density is higher than the upstream density. Then, shock waves are generated, and queues are generally built. When the signal is green, the density downstream is lower than the density upstream, and there is a diffusion of flow similar to that observed when a queue is discharging. As the number of lanes used for a movement at the pre-stop line is less than that at the main stop line, the absolute value of the shock wave flow speed for a red signal is smaller than that for a green signal. Therefore, the two shock waves will meet at the tail end of the queue

$$v_0 = \max\left(\frac{L}{g_{me} - g_{pe}}, \frac{L}{g_{me} - g_{mb} - (L/|u_g|)}\right), \qquad (7)$$

where L is the length of sorting area, in m; g_{me} is the end of the green time at the main signal, in s; g_{pe} is the end of the green time at the pre-signal, s; g_{mb} is the beginning of the green time at the main signal, s; and u_g is the speed of the shock wave when the signal is green [57], m/s.

In this investigation, the travel speed of the last through-moving vehicle is recorded on a cycle-by-cycle basis. The K–S test results show that the number of blocked vehicles follows a normal distribution, as presented in Table 10 ($p > 0.05$ for the test of normality indicates that the samples obey the normality requirement under a 95% confidence interval). Equation (6) then becomes

$$P_d = \Phi\left(\frac{v_0 - \bar{v}_l}{\sigma_v}\right), \qquad (8)$$

where $\Phi(.)$ is the distribution function of the standard normality distribution; $\bar{v}_l$ is the mathematic expectation of the travel speed, m/s; and σ_v is the standard deviation of the travel speed.

The negative effect of the incomplete discharge (δ_d) is similar, though more severe, to the impact of the red-light violation at the pre-signal, as mentioned in Section 3.3. This is because the entire green time will be affected, while only parts of this green time will be affected for the red-light violation at the pre-signal. Therefore, for the surveyed intersection, reductions in the saturation flow rate for the three approach lanes of 1.83, 0.90, and 1.83% will be caused by the incomplete discharge, as given in Table 11.

3.5 Adjustment for tandem control

Considering the above three factors, the saturation flow rate adjustment for the tandem control of the lanes in the sorting area can be calculated using (9). The factor f_{t1} refers to the adjustment for the unequal distribution of traffic, which can be calculated using (2). The factor f_{t2} refers to the adjustment for the red-light violation, which can be calculated using (3). The factor f_{t3} refers to the adjustment for the incomplete discharge at the sorting area, which can be calculated using (5)

$$f_t = f_{t1} f_{t2} f_{t3}, \qquad (9)$$

where f_t is the adjustment for the tandem control.

A comparison of the results of the developed tandem control adjustment model and the field survey is summarised in Table 12. The mean error is 1.12%. Non-parametric test results (Wilcoxon test) further show that there is no significant difference ($p = 0.285 > 0.05$ indicates that the difference is not significant under a 95%

Table 12 Comparison of results between the proposed model and field survey

Lane	Proposed adjustment model				Field survey	Percentage difference	Two-related-samples non-parametric test	
	f_{t1}	f_{t2}	f_{t3}	f_t			Z	Sig. (2-tailed)
1	0.847	0.964	0.982	0.802	0.801	0.12%	−1.069	0.285
2	1.000	0.960	0.991	0.951	0.953	−0.21%		
3	0.847	0.964	0.982	0.802	0.827	−3.02%		

confidence interval), indicating that the accuracy of the proposed adjustment model is acceptable.

4 Discussion

According to the statistical analysis based on the field data, the use of tandem control decreases the saturation flow rate of the lanes in the sorting area. The negative effect can be caused by three factors: unequal distribution of traffic, red light violations at the pre-signal, and incomplete discharge of vehicles at the sorting area.

The unequal distribution of traffic is the most frequent factor and plays the most important role among the three. Although the tandem control was used in the surveyed intersection for more than two years, unequal distribution of traffic in the sorting area still exists in almost every signal cycle. The drivers are more likely to proceed without changing lanes when entering the sorting area from the pre-stop line. On average, this causes a 15.34% reduction in the saturation flow rate. The main reason for this is that drivers prefer to remain in the same lane, an aspect of driving behaviour, which is fundamentally difficult to change.

Red light violations at the pre-signal occur in 8.07% of the surveyed signal cycles. This causes a reduction in the saturation flow rate of both the blocked approach lanes and the adjacent lane. Considering that this problem is caused by driver unfamiliarity, additional guiding information is necessary to help drivers in correctly navigating the pre-signal control. The following three measures are suggested: (i) a pavement marking ‘STOP ON RED’ can be added at the pre-signal stop line; (ii) the sorting area can be painted using bright colours, such as red or yellow; and (3) a ground-mounted signal light and an overhead signal light can be used to increase driver awareness.

An incomplete discharge of vehicles at the sorting area, when it occurs, causes the greatest negative effect on the smooth flow at the tandem intersection. The occurrence possibility of the incomplete discharge event is closely related to the signal timing. Therefore, this risk can be controlled by setting an adequate clearance time and a suitable offset between the main signal and the pre-signal.

In the proposed model, the effect of the phase plan is not discussed for several reasons. The first two factors, unequal distribution of traffic and red light violations, will not be affected by the phase plan. The unequal distribution of traffic is mainly caused by driving behaviour in lane selection and lane changing. Red light violations are mainly caused by the unfamiliarity of drivers who do not notice the pre-signal upstream from the main intersection. Thus, the phase plan will not affect these two factors. For the third factor, incomplete discharge of vehicles at the sorting area, the phase plan will affect the saturation flow rate of the movement following the blocked lane. For example, under the condition that the left-turn phase is followed by the through phase, the saturation flow rate of the through movement will be affected when the left-turning vehicles are trapped; the saturation flow rate of the left turn at the next cycle will be affected when the through-moving vehicles are trapped. Furthermore, under the condition that the through phase is followed by the left-turn phase, the left-turn and through movements will interact with each other. Therefore, the calculation principle for different phase plans is the same. However, the values of some parameters should be modified for different phase plans and traffic movements, such as the distribution of the travel speed, end of the green time at the main signal (g_{me}), end of the green time at the pre-signal (g_{pe}), and the beginning of the green time at the main signal (g_{mb}).

5 Conclusions

This study analyses the saturation flow rate of the tandem intersection. A saturation flow rate adjustment model for tandem control is established. Three factors of the saturation flow rate are considered: unequal distribution of traffic, red light violations at the pre-signal, and incomplete discharge of vehicles at the sorting area. The accuracy of the model is validated by comparing the results between the proposed model and field data. The mean difference between the two was 1.12%. A quantified analysis of the saturation flow rate was conducted. From the analysis, the following conclusions can be drawn:

(i) Overall, the tandem control decreases the saturation flow rate of the lanes in the sorting area at the main stop line, while the effect on the saturation flow rate of the lanes at the pre-signal is not significant.
(ii) On average, the reduction in the saturation flow rate reaches 5% for lanes where vehicles can directly enter from the pre-stop line without changing lanes and 20% for lanes where vehicles must make a lane change to enter.
(iii) The reduction in the saturation flow rate is mainly caused by the unequal distribution of traffic. For the other two factors, red light violations at the pre-signal and incomplete discharge of vehicles at the sorting area, the occurrence possibility can be controlled by using adequate traffic signs, markings, and signal timing design.

In practice, more guiding information (e.g. a pavement marking ‘STOP ON RED,’ coloured pavements in the sorting area, and a ground-mounted signal light coupled with an overhead pre-signal light) is recommended to improve the noticeability of the pre-stop line and the sorting area. Moreover, a redundant design of the signal timing is recommended to ensure that all vehicles in the sorting area can be fully discharged during their signal sub-phases.

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