Transportation Research Part C 69 (2016) 228–241

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Operational analysis of the contraflow left-turn lane design at signalized intersections in China ☆

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ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 10 June 2016
Accepted 10 June 2016
Available online 16 June 2016

Keywords:
Capacity
Delay
Unconventional design
Left-turn
Signalized intersection

ABSTRACT

The primary objective of the study was to evaluate the impacts of an unconventional left-turn treatment called contraflow left-turn lane (CLL) on the operational performance of left-turn movement at signalized intersections. An analytical model was developed for estimating the capacity of left-turn movement at signalized intersections with the CLL design. The capacity model was calibrated and validated using field data collected at six approaches at five signalized intersections in the city of Handan, China. The results of field data analyses showed that the use of CLL design improved the capacity of left-turn movements. However, the capacity gains with the CLL design were quite stochastic considering the randomness in the arrivals of left-turning vehicles. Analytical delay models were proposed for estimating the delay to left-turning vehicles at intersections with the CLL design. A procedure was also proposed for optimizing the location of the upstream median opening and the green interval of the pre-signal. Simulation analyses were conducted to compare the delay experienced by the left-turning and through vehicles at signalized intersections with the conventional left-turn lane, the CLL and another unconventional left-turn treatment entitled "tandem design". The results showed that both CLL and tandem designs outperformed conventional left-turn lane design; and the CLL design generated less delay to both the left-turning and through vehicles as compared with the tandem design.

1. Introduction

With the dramatic increase in private vehicle ownership, at-grade intersections are becoming more and more congested in China. Numerous treatments have been applied to improve the operational performance of the signalized intersections with heavy left-turn demand (Mirchandani and Head, 2001; Stamatiadis et al., 2015; Hale et al., 2015). Some of the treatments can be considered unconventional as they violate the rules and regulations that have been widely accepted. So far the most widely used unconventional left-turn treatments include median U-turns, jughandles, super streets, quadrant roadways, bowties, continuous flow intersection design, parallel flow intersection design, and more recently, the tandem intersection design (El Esawey and Sayed, 2013; Hummer, 1998; Xuan et al., 2011; Bie and Liu, 2015; Liu and

☆ This article belongs to the Virtual Special Issue on: Innovative Intersection Design and Control for Serving Multimodal Transport Users.

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http://dx.doi.org/10.1016/j.trc.2016.06.011
0968-090X/

Bie, 2015; Rodegerdts et al., 2004; Goldblatt et al., 1994; Krause et al., 2015; Zhao et al., 2015a). Most of these unconventional left-turn treatments require re-routing of left-turning vehicles, which may partly offset the benefits that can be achieved (Xuan et al., 2011).

A new left-turn treatment entitled contraflow left-turn lane (CLL) has recently been implemented at some signalized intersections in the city of Handan, China. With the CLL design, left-turn lanes are setup in the opposing lanes adjacent to the conventional left-turn lanes. The basic idea of the design is to provide additional capacity to left-turning vehicles by making use of the opposing lanes dynamically. The detailed layout of a signalized intersection with the CLL design is illustrated in Fig. 1. The CLL is implemented at the signalized intersections with leading left-turn phases and heavy left-turn demand. A median opening is installed in the upstream of the stop bar to allow left-turning vehicles to enter the contraflow left-turn lanes. A pre-signal is installed at the upstream median opening to control the time window during which left-turning vehicles can enter the contraflow left-turn lanes. Lane markings are also provided to help left-turning drivers understand which receiving lane they should proceed to.

Fig. 2 illustrates the signal timing plan and the traffic movements at a signalized intersection with the CLL design. The main signal on the minor street starts its cycle by giving green signal to the through movements on the minor street, which is denoted as movement 1 and 5. The left-turning vehicles that arrive at the intersections on the major street need to stop and wait in the conventional left-turn lane (see movement 2 and 6 in Fig. 2). A few seconds later, the pre-signals on the major street turns green to allow left-turning vehicles to enter the CLL through the upstream median opening (see movement 9 and 10 in Fig. 2). The left-turning vehicles in the CLL will be discharged together with those in the traditional left-turn lanes during the leading left-turn phase on the major street. Note that the pre-signals will turn red before the initiation of the left-turn phase on the major street, and after that no vehicles can enter the CLL. The purpose is to make sure that the vehicles in the CLL can be fully discharged during the left-turn phase.

The location and timing of the pre-signal are key factors that influence the operations of the CLL design. In fact, the idea of using pre-signals at signalized intersections is not new. Pre-signals have been used for different purposes by previous researchers to improve traffic operations at signalized intersections (Von Stein, 1961; Wu and Hounsell, 1998; Xuan et al., 2011; Guler and Menendez, 2014). Xuan et al. (2011) have recently proposed an unconventional left-turn treatment called "tandem" intersection design, whose basic concept is shown in Fig. 3. Pre-signals are installed upstream of the main signal and alternates giving green time to the two sets of lanes. The area between the pre-signal and the main signal is called the "sorting area" which is intended to contain transient queues. The pre-signal starts its cycle by giving the green time to left-turn movement allowing left-turning vehicles to advance into the sorting area when the main signal is red. Then, the pre-signal allows through vehicles to move into the sorting area lining up behind left-turning vehicles. With the tandem design, both left-turning and through vehicles can make use of more lanes than those at conventional signalized intersections (Xuan et al., 2011).

Guler et al. (2016) proposed a new concept which uses pre-signals together with a contra-flow lane to provide bus priority at signalized intersections. Two pre-signals are placed upstream of the main signal in the direction of bus travel. The

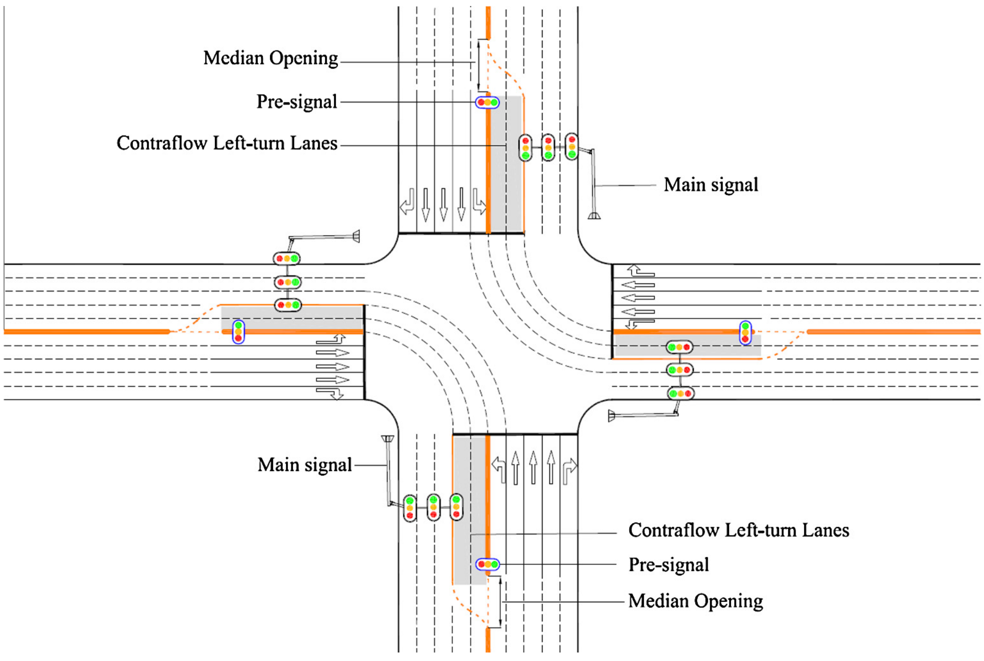


Fig. 1. Layout of the CLL design at a signalized intersection.

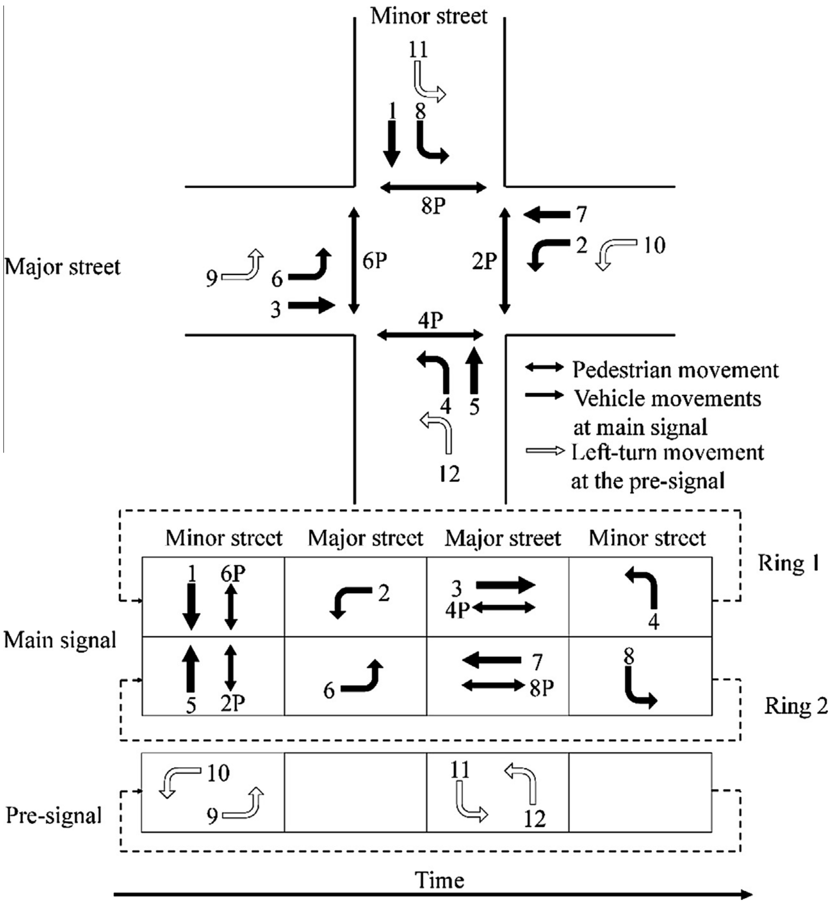


Fig. 2. Signal timing plan and traffic movements at signalized intersection with CLL design.

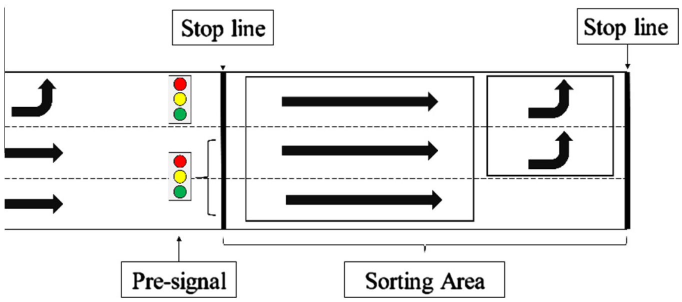


Fig. 3. The tandem intersection concept.

upstream pre-signal affects passenger cars in the subject direction and the downstream pre-signal affects passenger cars in the opposite direction. By stopping passenger cars on the opposing travel lanes, buses can jump a portion of queues using the travel lane in the opposite direction and consequently reduce the delay imposed on bus (Guler et al., 2016). The concept proposed by Guler et al. (2016) is quite different from the CLL design presented in the present paper. In fact, the contra-flow lane in Guler et al.'s concept serves as an extra passing lane exclusive for buses. The purpose is to provide priority to buses at the cost of increasing delay to passenger cars. While with the CLL design, the contra-flow lanes can be used by all of the left-turning vehicles that arrive at the intersections during a specific time window determined by a pre-signal. The purpose is to increase left-turn capacity without posing significant impacts on other traffic movements.

Several studies have also been conducted to evaluate the safety and operational performance of the CLL design (Zhao et al., 2013, 2015b; Su et al., 2016). Zhao et al. (2013) proposed an optimization procedure for the CLL design in which all the variables including geometric design characteristics and signal timing for both main and pre-signals were integrated into an optimization problem. Simulation analysis based on the VISSIM simulation model was conducted to evaluate the effects of CLL on the capacity and delay of the whole intersection. The results of both numerical analysis and VISSIM simulation indicated that the CLL design outperforms the conventional design in terms of intersection capacity (Zhao et al., 2013). Zhao et al. (2015b) further investigated how drivers responded to the CLL design based on an experiment conducted using a driving simulator. The results indicated that drivers show a certain amount of confusion and hesitation when encountering a CLL design for the first time. However, drivers' confusion can be relieved by increasing exposure through driver education or by the information provided from other vehicles. Moreover, the experiments suggested that the concern of head-on collision in the CLL may not be warranted since no driver ran red light at the pre-signal. And the concern of vehicle being trapped in the contraflow left-turn lanes is also not warranted since only a slight reduction in travel speed was measured which could be addressed by coordinating of the main signal and pre-signal (Zhao et al., 2015b).

Although several studies have been conducted regarding the operational and safety performance of the CLL design, there are still research gaps that need to be addressed. Unlike the situation considered by previous studies in which the timing of the pre-signal and main signal needs to be considered in a coherent manner, the timing of pre-signals in the CLL design concept does not affect the timing of the main signal. The pre-signal turns green a few seconds after the initiation of the green time on the crossing street and turns red before the initiation of the left-turn phase on the major street. The purpose of doing so is to ensure that that the vehicles in the CLL can be fully discharged during the left-turn phase. In this condition, the most critical question is how to optimize the timing and the location of the pre-signal such that the usage of the CLL can be maximized considering the random arrival of left-turning vehicles. This issue has not been addressed by previous studies.

In addition, previous studies related to the CLL design are based on simulation analyses and conducted under hypothetical conditions. It can be expected that drivers' behavior may be significantly different in a simulated driving environment from that in the real world. Additional research based on field data is needed to help traffic engineers better understand to what extent the CLL design affects the capacity of left-turn movement at signalized intersections. In the present study, an analytical model was developed for estimating the capacity of left-turn movement at signalized intersections with a CLL design. The capacity model was calibrated and validated using field data collected at six locations. Analytical delay models were proposed for estimating the delay to left-turning vehicles at intersections with the CLL design. A procedure was proposed for optimizing the CLL design such that the capacity of left-turn movement can be maximized. Simulation analyses were also conducted to compare the delay experienced by the left-turning and through vehicles at the signalized intersections with the conventional left-turn lane, the CLL design and the tandem design. To the best of our knowledge, it is the first time that the capacity of CLL design is evaluated comprehensively using field data. It is expected that the research results will help traffic engineers develop guidelines that aim at improving traffic operations at signalized intersections with CLL design.

2. Development of the capacity model

The time–space diagrams of the left-turn movement at an intersection installed with a traditional left-turn lane and two contraflow left-turn lanes are illustrated in Fig. 4. The black lines denote the trajectories of the left-turning vehicles in the normal left-turn lane, while the blue[1] lines represent the trajectories of the left-turning vehicles using the contraflow left-turn lanes. It can be clearly identified that the capacity of the left-turn movement with the CLL design consists of two parts: the capacity of the normal left-turn lane and the capacity of CLL. Because the pre-signal turns red before the initiation of the green light in the main signal, the CLL design can hardly affect the operations in the normal left-turn lane. Thus, the capacity of one normal left-turn lane can be approximately estimated using the equation provided by the Highway Capacity Manual (HCM 2010, 2010):

$$c_0 = s_0 \cdot G_e / C \tag{1}$$

where c_0 represents the capacity of the normal left-turn lane (veh/h), s_0 represents the left-turn saturation flow in the normal left-turn lane (veh/h/ln), G_e represents the effective green time for the leading left-turn phase of main signal (s), and C represents the cycle length of the main signal (s).

For the contraflow left-turn lanes, the capacity analysis could be more complex. In practice, the vehicles in the CLL must be discharged during the following left-turn phase. Otherwise, the left-turning vehicles will block the through traffic in the other direction, raising both safety and operational concerns. Fortunately, the clearance of the left-turning vehicles in the CLL can be easily achieved by properly setting up the green time allocated to the left-turn phase of the main signal, and by controlling the number of vehicles that can get access into the CLL through the pre-signal. Thus, theoretically, when estimating the capacity of left-turn movements at an intersection with the CLL design, the number of vehicles that enter the CLL can be directly considered capacity gains. Note that the capacity gains represent the additional capacity of left-turn movement that is achieved using the CLL design as compared with the conventional left-turn lane design. The key question is: how many vehicles can get access into the CLL. The answer to the question needs to take into consideration the impacts of numerous factors, including the location of the upstream median opening through which left-turning vehicles enters the CLL, which determines the maximum number of left-turning vehicles that can stop in the left-turn lane between the stop bar and the pre-signal (n), the total number of left-turning vehicles that arrive at the intersection before the termination of the green

[1] For interpretation of color in Fig. 4, the reader is referred to the web version of this article.

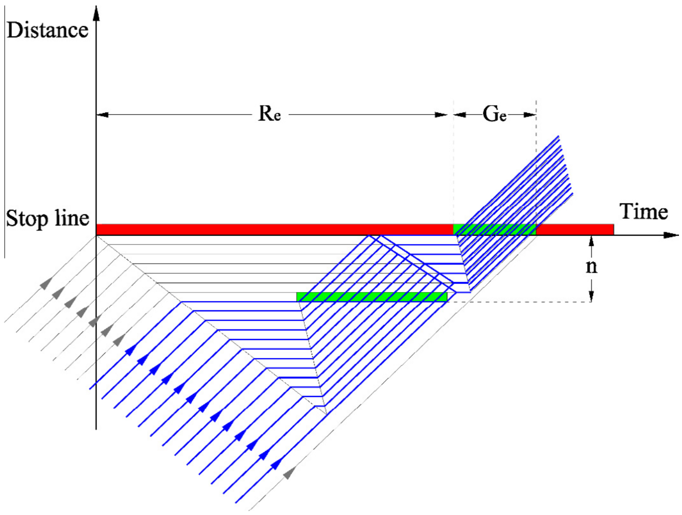


Fig. 4. Time–space diagram of the left-turn movement with CLL design.

light of the pre-signal (K), the initial queue in the left-turn lane (I), the effective green time of the pre-signal (g_e), and the saturation flow rate for the traffic flow that enters the CLL under the control of the pre-signal (s_1).

The number of left-turning vehicles that crosses the intersection using the CLL in one cycle can be calculated with Eq. (2).

$$V = \min(s_1 \cdot g_e, \max(K - n + I, 0)) \tag{2}$$

Eq. (2) can be further expressed as:

$$\begin{cases} V = 0 & K < n - I \\ V = K - n + I & n - I < K < n + s_1 \cdot g_e - I \\ V = s_1 \cdot g_e & K > n + s_1 \cdot g_e - I \end{cases} \tag{3}$$

where V denotes the number of left-turning vehicles that are discharged through the CLL.

From Eqs. (2) and (3) it is clear that the arrival pattern of left-turning vehicles may heavily affect the number of vehicles that can get access into the CLL. Accordingly, when estimating the capacity of left-turn movement the arrival pattern of left-turning vehicles need to be carefully considered. In the present study, it is assumed that the arrival of the left-turning vehicles follows a Poisson distribution. Note that the Poisson distribution has been widely used for modeling the arrival pattern of vehicles at isolated intersections where the influence from upstream intersections is minor (McNeil, 1968). In this condition, the capacity of the left-movement can be estimated as:

$$c = [p_0 \cdot s_1 \cdot g_e + p_1 \cdot (K - n + I) + s_0 \cdot G_e]/C \tag{4}$$

$$c = [(p_0 + p_1) \cdot s_1 \cdot g_e + p_1 \cdot (K - n - s_1 \cdot g_e + I) + s_0 \cdot G_e]/C \tag{5}$$

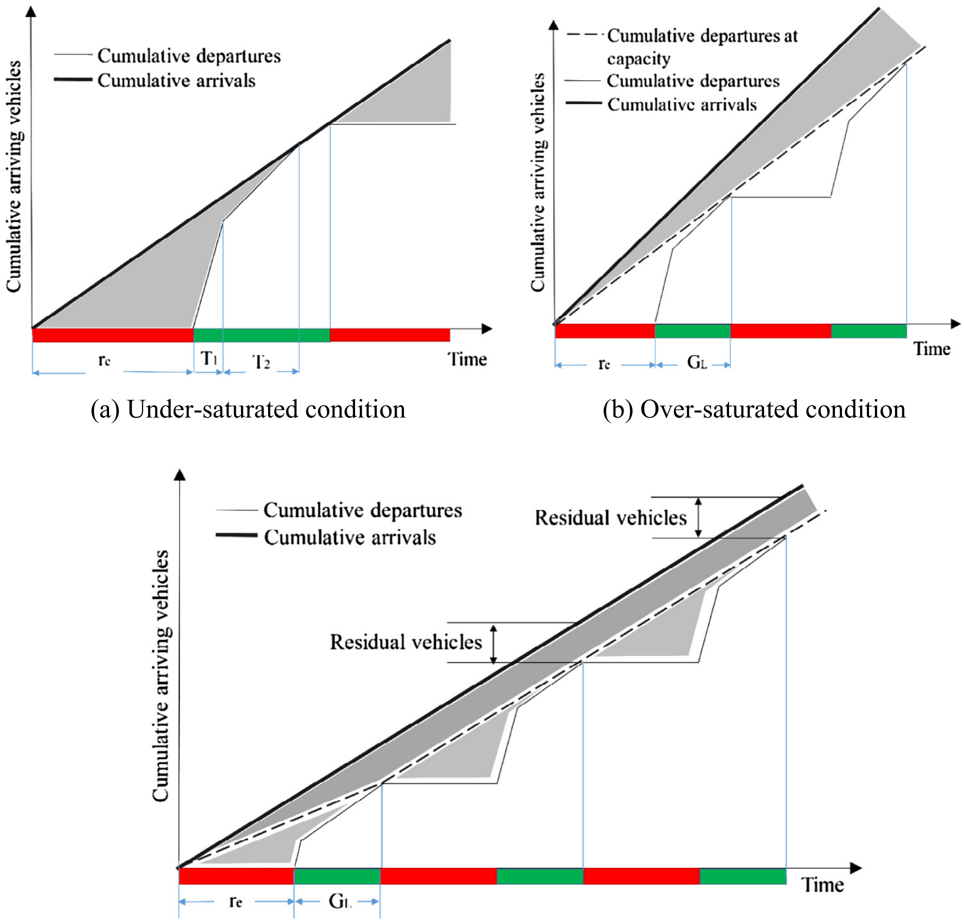
$$c = [s_1 \cdot g_e + p_1 \cdot (K - n - s_1 \cdot g_e + I) + s_0 \cdot G_e]/C \tag{6}$$

$$c = \left[s_1 \cdot g_e + \sum_{x=0}^{n+s_1 \cdot g_e} [P(x) \cdot (x - n - s_1 \cdot g_e + I)] + s_0 \cdot G_e \right] \Big/ C \tag{7}$$

where c denotes the capacity of the left-movement, which equals the capacity of the normal left-turn lane plus the number of vehicles that use the CLL to cross the intersection (veh/h), p_0 denotes the possibility of $K > n + s_1 \cdot g_e$, p_1 denotes the possibility of $n < K < n + s_1 \cdot g_e$. Note that p_0 and p_1 can be estimated using Poisson distribution. In addition, considering the fact that the intersections with CLL design usually suffer from heavy left-turn traffic demand, the possibility of having $K < n - I$ is negligibly small, indicating that in most cases $p_0 + p_1$ is close to 1.

3. Development of the delay model

The arrival and departure curves of left-turning vehicles at an intersection with a traditional left-turn lane and two contraflow left-turn lanes are depicted in Fig. 5. As mentioned before, the contra-flow left-turn lane can be considered an extra left-turn lane, and the use of which is influenced by the arrival pattern of left-turning vehicles. As shown in Fig. 5, only part of the left-turning vehicles can be discharged at a rate that equals three times the saturation flow rate of a conventional left-turn lane.



(a) Under-saturated condition (b) Over-saturated condition

(c) Under-saturated condition with residual queue

Fig. 5. Arrival and departure pattern of left-turn movement.

A unique phenomenon is observed in the field that vehicles lining up in the conventional left-turn lane might not be fully discharged even when the demand is smaller than the capacity, (see Fig. 5(c)). Considering that the pre-signal is turned off during the green phase of the main signal, the residual queue would line up at the conventional lane. Unlike the over-saturated condition at conventional left-turn lanes, the residual queue would not grow up in the following cycles because the presence of vehicles in the conventional left-turning lane would enable more vehicles to move into CLL in the next cycle and increases the throughput volume. The phenomenon is an inherent characteristic of the CLL design, and it is caused by the random arrival of left-turning vehicles and the use of the pre-signal. A more detailed discussion of this phenomenon will be provided in Section 5.1. However, the delay experienced by the residual vehicles needs to be considered when estimating delay to left-turn movement.

The total uniform delay experienced by left-turning vehicles is represented by the gray area in Fig. 5. Based on Fig. 5, Eqs. (8)–(13) were proposed for estimating the delay to left-turn movement at intersections with the CLL design:

$$d_u = [(T_1 + r_e - 3T_1 \cdot s_0/v) \cdot (3T_1 \cdot s_0 + T_2 \cdot s_0) + 3T_1 \cdot s_0 \cdot r_e]/(2v \cdot C) + d_{re} \quad (8)$$

$$d_{re} = \max[T_p(C \cdot v/3600 - T), 0] \quad (9)$$

$$T = p_0 \cdot s_1 \cdot g_e + p_1 \cdot (K - n + I) + s_0 \cdot G_e \quad (10)$$

$$T_1 = h(v \cdot r_e/3600 - n)/2 \quad (11)$$

$$T_2 = \min\{[v \cdot r_e + T_1(v - 3s_0)]/(s_0 - v), G_e - r_e - T_1\} \quad (12)$$

$$d_o = T_p(v/c - 1)/2 \quad (13)$$

where d_u denotes the average control delay in under-saturated condition (s); d_o denotes the average control delay in over-saturated condition (s); d_{re} denotes the average control delay experienced by residual queues (s); v denotes the arrival flow rate (veh/h); h denotes the saturation headway (s); r_e denotes the duration of the effective red interval (s); T denotes the number of left-turning vehicles that can be discharged in one cycle which could be calculated based on Eq. (4); T_1 represents the time period from when the initiation of the left-turn phase until the time when the last left-turning vehicle in the contra-flow lanes crosses the stop bar (s); T_2 represents the time period from the time when the rear-end of the last left-turning vehicle in the contra-flow lanes crosses the stop bar until the time when the rear-end of the last left-turning vehicle in the conventional left-turn lane crosses the stop bar (s).

4. Field data collection

Field data collection was conducted at six approaches at five signalized intersections in the city of Handan, China. When selecting the sites for field data collection, the following criteria were applied: (a) The selected intersection should be a four-leg pre-timed signalized intersection installed with CLL design; (b) there is no bus station or roadside parking within 100 m upstream and downstream of the stop bar; (c) the left-turn traffic demand at the selected sites should be high. The average queue length for left-turning vehicles at the selected intersections should be greater than eight vehicles per cycle. According to the Highway Capacity Manual, an initial queue with more than eight vehicles is typically required in each cycle for estimating saturation headways (TRB, 2010); (d) the intersections are not located in central business district area; (e) the approach grade is level; and (f) the distance to upstream signalized intersection should be at least 1000 m such that the arrival of left-turning vehicles can be considered random.

Three types of data, including geometric design characteristics, signal timing and traffic flow data were collected. The geometric design characteristics, including the lane configuration, the lane width, and the distance between the stop bar and the pre-signal, were directly measured in the field. Some of the geometric design characteristics of the selected sites are given in Table 1. Of the selected sites, two sites are installed with single CLL, while the other four sites are installed with dual CLL. A video camera was set up in the field for recording data. The videos were later reviewed in the laboratory for data reduction. While reviewing the recorded videos, the following information was obtained: (a) the signal timing, including the cycle length, the phase sequence, the green interval of the main signal, the green interval of the pre-signal, the yellow change of the main signal, and the yellow change of the pre-signal; and (b) the traffic flow characteristics, including the arrival time of each left-turning vehicle, the initial queue of left-turning vehicles, the number of vehicles that use the CLL to cross the intersection, the discharge headways of the normal left-turn lane, and the discharge headways of the left-turning vehicles that enter the CLL land under the control of the pre-signal.

In total, the research team recorded 40 h of traffic data, including 783 cycles. The cycle length of the selected intersections varies from 145 s to 195 s. The green time duration of the left-turn phase of the main signal varies from 15 s to 25 s. The green time duration of the left-turn phase of the pre-signal varies from 15 s to 35 s. The research team also measured the discharge headways of left-turning passengers at the main and pre-signals using a stopwatch. The first headway was defined as the time between the initiation of the green signal and when the front wheel of the first passenger car crossed over the reference line. The second headway was measured as the time interval between the first and the second vehicles crossed over the reference line. Note that for the left-turning vehicles in the normal left-turn lane the stop bar at the intersection was set to be the reference line; while for those entering the CLL, the yellow line that separates the road was considered the reference line. The start-up lost time and saturation headway at the main signal and the pre-signal was calculated by following the method proposed by the Highway Capacity Manual (TRB, 2010). For estimating the arrival rate of the left-turning vehicles, the arrival time was measured as the time when vehicles crossed the reference point which was set up 150 m upstream of the stop bar. Note that the reference point was selected to make sure that the arrival vehicles were not affected by the queue. According to the proposed capacity model, the saturation headways of the normal left-turn lane

Table 1
Selected sites for field data collection.

Site	Intersection	Direction	D (m)[a]	Number of lanes				
				LT[b]	TM[c]	RT[d]	CLL	SL[e]
1	Fudong. RD & Lianfang. RD	NB	50	1	4	1	2	0
2	Fuheng. RD & Lianfang. RD	WB	50	1	3	0	2	1
3	Fuheng. RD & Lianfang. RD	EB	50	1	3	0	2	1
4	Lianfang. RD & Zhonghua. RD	SB	43	1	3	1	1	0
5	Renmin. RD & Fudong. RD	SB	53	1	4	1	2	0
6	Renmin. RD & Zhonghuabei. RD	WB	50	1	4	1	1	0

[a] D represents the distance between the stop bar and the pre-signal.
[b] LT represents the conventional left-turn lane.
[c] TM represents the through traffic lane.
[d] RT represents the exclusive right-turn lane.
[e] SL represents the shared lane for right-turn and through traffic.

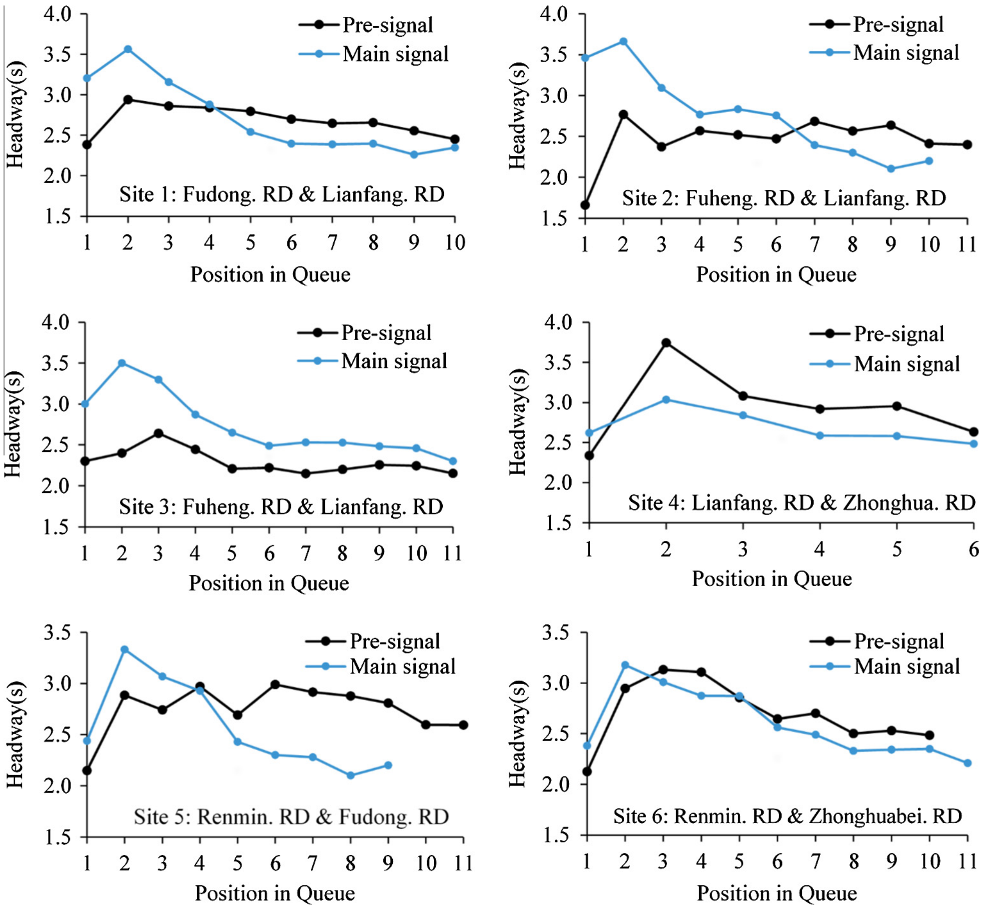


Fig. 6. Discharge headways of left-turning passenger cars at the selected sites.

at the main signal and those at the pre-signal are crucial factors that influence the capacity gains. The mean discharge headway by queue position for the six selected approaches are plotted in Fig. 6.

It is found that saturation headways at the pre-signal are generally larger than those at the main signal. The reason for this discrepancy is that drivers have to make continuous turning operations when advancing into the CLL, resulting in a decrease in speed. The only exception is observed at Site 3, where the saturation headway at the pre-signal is smaller than that at the main signal. Field observation shows that the width of the median opening at Site 3 is much greater than that at other sites. Thus, it provides left-turning vehicles with larger flexibility for entering the CLL. Note the first discharge headway at all selected sites are relatively small which is due to the existence of countdown timers (Liu et al., 2012). In addition, there are also significant differences between the start-up lost time at pre-signals and main signals. A possible explanation is that there are no safety concerns or disturbances from other movements when vehicles start to enter the CLL.

5. Model calibration and validation

5.1. Capacity model

The data collected at the selected sites were used for calibrating crucial parameters in the capacity model. First, K–S tests were conducted to identify if the number of left-turning vehicles that arrive at an intersection during a 15-s time interval follows a Poisson distribution. The results suggested that with a 95% level of confidence the null hypothesis about Poisson distribution cannot be rejected. Descriptive statistics of the saturation headway and start-up lost time are summarized in Table 2. With the parameters estimated from field data, Eqs. (4)–(7) were used for estimating the capacity of left-turn movements at signalized intersections with CLL design.

The proposed capacity models were also validated using field measured data. At a conventional signalized intersection without CLL, the capacity of the left-turn movement can be measured in the field as the maximum number of left-turning vehicles that can be discharged during over-saturated conditions. Theoretically, if the left-turn traffic demand is less

Table 2
Saturation headways and start-up lost time of left-turning passenger cars at main signals and pre-signals.

Site	Intersection	Direction	Position	Saturation headway (s)			Start-up lost time (s)		
				Mean	Std.	Sample size[a]	Mean	Std.	Sample size[b]
1	Fudong. RD & Lianfang. RD	NB	Main signal	2.39	0.33	160	3.5	1.91	165
			Pre-signal	2.67	0.32	91	1.19	1.93	93
2	Fuheng. RD & Lianfang. RD	WB	Main signal	2.39	0.31	56	3.12	1.8	56
			Pre-signal	2.42	0.34	43	1.3	1.82	43
3	Fuheng. RD & Lianfang. RD	EB	Main signal	2.49	0.28	76	2.86	1.75	77
			Pre-signal	2.2	0.4	62	1.0	1.85	62
4	Lianfang. RD & Zhonghua. RD	SB	Main signal	2.52	0.46	75	2.4	1.63	79
			Pre-signal	2.88	0.47	41	1.5	1.69	41
5	Renmin. RD & Fudong. RD	SB	Main signal	2.13	0.25	101	3.22	1.64	104
			Pre-signal	2.83	0.47	27	1.0	1.39	27
6	Renmin. RD & Zhonghuabei. RD	WB	Main signal	2.48	0.29	59	1.72	1.67	62
			Pre-signal	2.71	0.5	29	0.43	2.0	30

[a] Sample size is defined as the number of cycles that are used for calculating saturation headway.
[b] Sample size is defined as the number of cycles that are used for calculating start-up lost time.

than the capacity, the left-turning vehicles can always get discharged. However, it is not the case at a signalized intersection with CLL. As mentioned before, the capacity of the left-turn movement at the site with CLL design consists of two parts, including the capacity of the normal left-turn lane, and the number of left-turning vehicles that can get access into the CLL. The capacity of the normal left-turn lane is quite deterministic, while the number of vehicles that can get access into the CLL is heavily affected by the arrival pattern of left-turning vehicles and the signal timing of the pre-signal. Accordingly, the number of vehicles that can get access into the CLL is quite stochastic, resulting in large variances in the maximum number of left-turning vehicles that can be discharged. In other words, the capacity estimated using analytical models may not always equal the maximum number of left-turning vehicles that can be discharged through CLL.

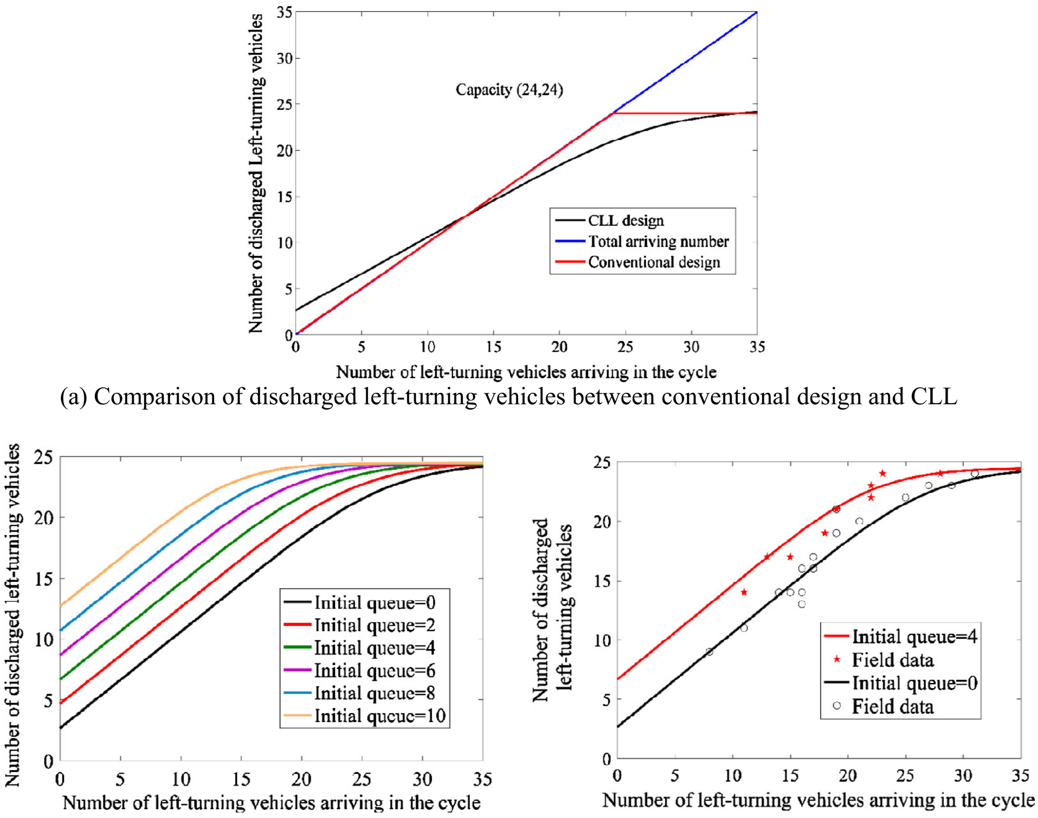
An example is given here to help readers better understand the aforementioned phenomenon associated with the CLL design. With the proposed model and the data collected from site 1, the relationship between the arrival rate and the number of discharged left-turning vehicles is shown in Fig. 7. It is clear that the maximum discharged vehicles in CLL may be lower than the estimated capacity even under over-saturated conditions (see Fig. 7(a)). However, after queue starts forming in the normal left-turn lane, the maximum discharged left-turning vehicles are approaching the capacity with the increased number of vehicles in the initial queue (see Fig. 7(b)). This phenomenon can also be validated using field data (see Fig. 7(c)). The explanation is that the presence of initial queues may reduce the number of left-turning vehicles that can stop between the stop bar and the pre-signal. In this condition, it is more likely that left-turning vehicles will enter the CLL, leading to a reduction in the randomness in the use of the CLL.

Considering the randomness in the maximum discharged left-turning vehicles, the capacity model validation was conducted by making a comparison between the number of discharged left-turning vehicles that was estimated using the capacity model and that directly measured in the field. Both the mean absolute error (MAE) and the mean absolute percent error (MAPE) were used as measures for capacity model validation. The MAE generated by the proposed capacity model varies from 0.83 to 1.26 with a mean of 0.98 at the selected sites. The MAPE generated by the proposed capacity model varies from 3% to 10.6% with a mean of 6.46% at the selected sites.

5.2. Delay model

Considering the fact that the delay directly measured in the field is quite stochastic, simulation results based on the VISSIM simulation models were used to validate the proposed delay models. The simulation models were developed based on the traffic demand scenarios and the geometric design characteristics obtained from one of our selected sites which was located at the intersection between Renmin. Rd & Fudong. Rd in Handan, China. The simulation models were calibrated and validated using the data measured from the site. Two traffic demand scenarios were considered, including a medium demand scenario in which the left-turn traffic demand varied from 270 to 720 veh/h with an increment of 90 veh/h, and a heavy demand scenario in which the left-turn traffic demand varied from 270 to 1080 veh/h with an increment of 90 veh/h. For the medium demand scenario, the ratio between left-turn traffic demand and through traffic demand was set to be 1:3, while for the heavy demand scenario the ratio was set to be 1:2. In total, the simulation analyses considered sixteen different traffic conditions. The simulation time was set to be equal to 45 cycles for each traffic condition considered. The lane configurations and signal timing settings for CLL design are illustrated in Table 3.

The comparison between analytical models and simulation results is shown in Fig. 8. It was found that the analytical models and simulation analyses generated similar results in most cases. The mean absolute percentage error of the analytical model varies from 11% for the medium demand scenario to 12% for the heavy demand scenario. The results could be considered reasonable according to previous studies (Dion et al., 2004).



(a) Comparison of discharged left-turning vehicles between conventional design and CLL

(b) Number of discharged left-turning vehicles under different initial queues

(c) Comparison of the theoretical results and field data

Fig. 7. Number of discharged left-turning vehicles under different initial queues.

Table 3
Signal timing plan and geometric structure for CLL design.

	N_{CLL}[a]	G_L[b] (s)	G_T[c] (s)	g[d] (s)	n	Cycle length (s)
Medium demand	2	30	45	41	9	150
Heavy demand	2	30	45	59	13	150

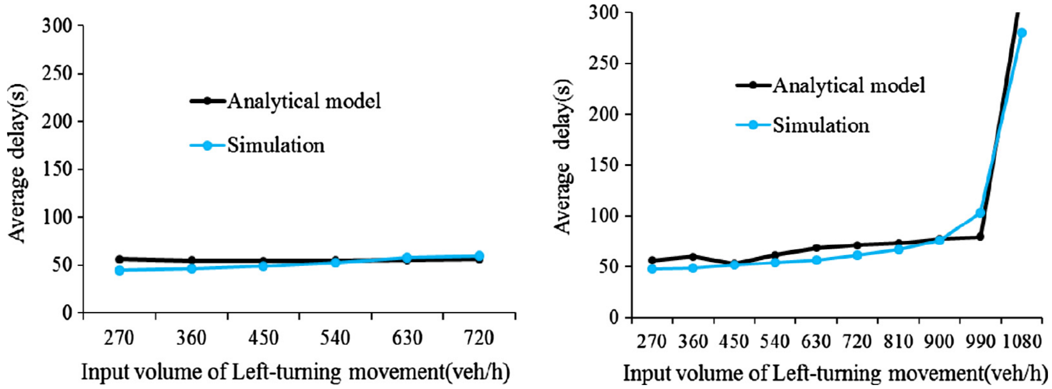
[a] N_{CLL} = the number of contraflow left-turn lanes.
[b] G_L = the effective green time of the left-turn phase in the main signal.
[c] G_T = the effective green time of the through phase in the main signal.
[d] g = the effective green time duration of the pre-signal.

6. Optimization of the CLL design

As mentioned before, the effective green time of the pre-signal and the distance between the stop bar and the pre-signal heavily affect the number of left-turning vehicles that can use the CLL to cross the intersection, and accordingly, the capacity of the left-turn movement. In the present study, a procedure was proposed for optimizing these two parameters such that the capacity of left-turn movement can be maximized. The only constraint that needs to be considered is that the number of left-turning vehicles in the CLL must be discharged successfully during the left-turn phase in the main signal. Considering the selected site 1 where a traditional left-turn lane and dual contraflow left-turn lanes are installed, the following relationship needs to be satisfied:

$$N_g \geqslant n \geqslant s_1 \cdot g_e/2 \tag{14}$$

where N_g denotes the maximum number of left-turning vehicles that can be discharged. Note that in the real world the start-up lost time and saturation headways are stochastic variables which may vary in different conditions. As a result, N_g is also stochastic. To fully ensure that the vehicles in the CLL can be discharged, it is recommended that N_g here should be estimated as the maximum number of left-turning vehicles that can be discharged with a certain level of confidence in a CLL during the



(a) Medium demand scenario (b) Heavy demand scenario

Fig. 8. Comparison between analytical models and simulation results.

effective green time of the left-turn phase. For example, if a 97.5% level of confidence is used, N_g can be easily estimated as $\overline{N_g} + 1.96\sigma_{Ng}$, where $\overline{N_g}$ represents the average number of left-turning vehicles that can be discharged during the green phase and σ_{Ng} represents the standard deviation of N_g. Both parameters can be directly measured in the field. Also note that for the sites with single contraflow left-turn lane, the expression $s_1 \cdot g_e/2$ should be replaced with $s_1 \cdot g_e$. Note that T denotes the number of left-turning vehicles that can be discharged in one cycle, according to Eq. (4), T can be further estimated as:

$$T = s_1 \cdot g_e + \sum_{x=0}^{n+s_1 \cdot g_e - I} [P(x) \cdot (x - n - s_1 \cdot g_e + I)] + s_0 \cdot G_e \tag{15}$$

Because we assume that the arrival of left-turning vehicles follow a Poisson distribution, $P(x)$ can be estimated as:

$$P(x = k) = \frac{e^{-\lambda t} \cdot (\lambda t)^k}{k!} \tag{16}$$

where λ represents the expected arrival rate of left-turning vehicles. Eq. (15) can be further expressed as:

$$T = s_1 \cdot g_e - (n + s_1 \cdot g_e - I)e^{-\lambda t} \sum_{x=0}^{n+s_1 \cdot g_e - I} \frac{(\lambda t)^x}{x!} + \lambda t e^{-\lambda t} \sum_{x=0}^{n+s_1 \cdot g_e - I - 1} \frac{(\lambda t)^x}{x!} + s_0 \cdot G_e \tag{17}$$

where t represents the elapsed time from the end of the left-turn phase in the previous cycle to the initiation of the green light in the pre-signal (s).

Then Eq. (17) can be further expressed as:

$$T = s_1 \cdot g_e + e^{-\lambda t} \sum_{x=0}^{n+s_1 \cdot g_e - I - 1} \frac{(\lambda t)^x}{x!} \left(\lambda t - (n + s_1 \cdot g_e - I) \cdot \sum_{x=0}^{n+s_1 \cdot g_e - I} \frac{(\lambda t)^x}{x!} \Big/ \sum_{x=0}^{n+s_1 \cdot g_e - I - 1} \frac{(\lambda t)^x}{x!} \right) + s_0 \cdot G_e \tag{18}$$

Now the optimization procedure can be considered a basic mathematical problem, that is: Max T subject to Eq. (14). Considering the constraint given in Eq. (14), let us assume that no initial queue exists, the following relationship can be defined:

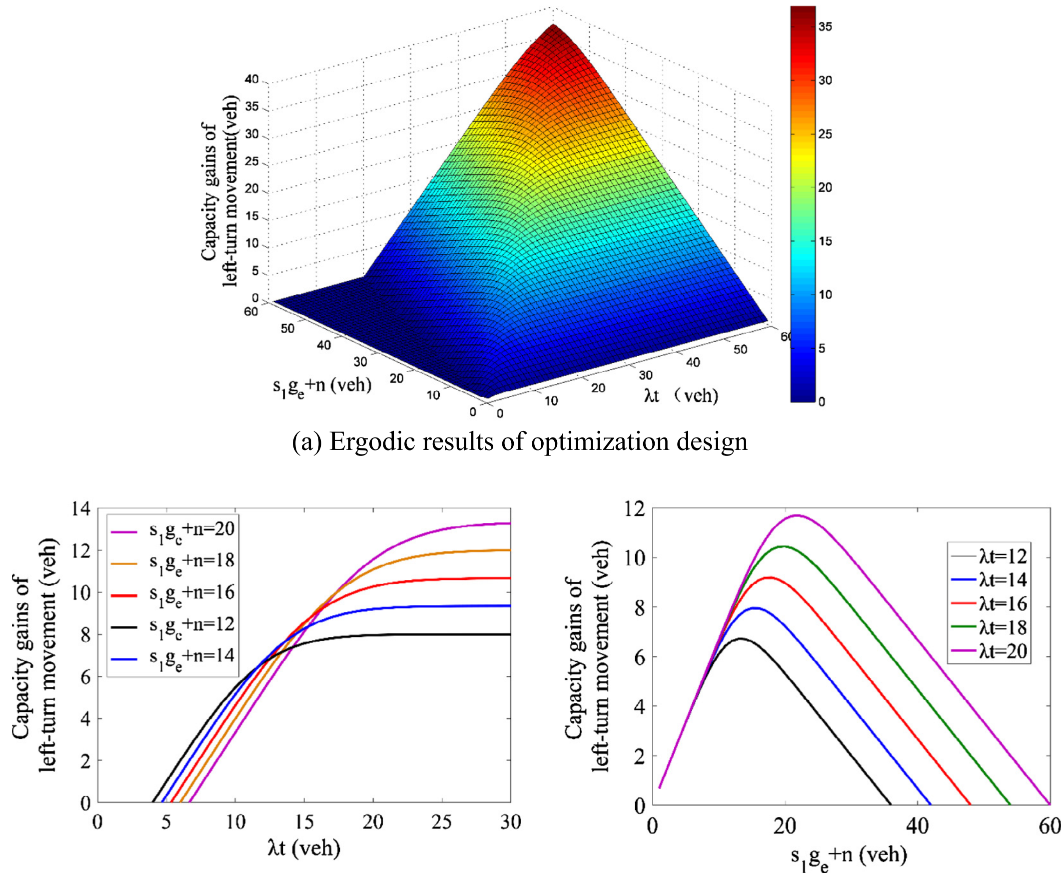
$$s_1 \cdot g_e + n \geqslant 3s_1 \cdot g_e/2 \tag{19}$$

Given Eqs. (18) and (19) the following relationship can be established:

$$T \leqslant 2(s_1 \cdot g_e + n)/3 + e^{-\lambda t} \sum_{x=0}^{s_1 \cdot g_e + n - 1} \frac{(\lambda t)^x}{x!} \left(\lambda t - (s_1 \cdot g_e + n) \cdot \sum_{x=0}^{n+s_1 \cdot g_e} \frac{(\lambda t)^x}{x!} \Big/ \sum_{x=0}^{n+s_1 \cdot g_e - 1} \frac{(\lambda t)^x}{x!} \right) + s_0 \cdot G_e = T_{\max} \tag{20}$$

Based on the analysis mentioned above, the maximum value of T can be estimated using Eq. (20). The question is, how to select the value of $s_1 g_e + n$ such that $T_{\max}$ can be maximized? The problem can be easily resolved given the ergodic result of $T - s_0 \cdot G_e$ calculated by Matlab, as shown in Fig. 9(a). It is found that when $s_1 \cdot g_e$ equals $n/2$, the maximum value of $T_{\max}$ can be achieved.

Given the discussion mentioned above, curves were developed in Fig. 9(b) and (c) to illustrate the relationships among capacity gains and $s_1 g_e + n$ and λt. A procedure is also proposed to help traffic engineers determine the location of the upstream median opening through which the left-turning vehicles enter the CLL, which determines (n) and the green time for pre-signal (g_e):



(a) Ergodic results of optimization design

(b) Capacity gains with different arrival rates

(c) Capacity gains with different values of s_1g_e+n

Fig. 9. Capacity gains with different arrival rates and $s_1g_e + n$ value.

Step 1: estimate the expected arrival rate of the left-turning vehicles, and the elapsed time from the end of the left-turn phase in the previous cycle to the initiation of the green light in the pre-signal;
Step 2: estimate the value of $s_1g_e + n$ that maximizes T with Matlab;
Step 3: estimate n and ge using Eq. (13), given that the discharged left-turning vehicles reach the maximum when $s_1 \cdot g_e$ equals $n/2$.
Step 4: identify if the constraint given in Eq. (8) can be satisfied.

An example is given here to explain the optimization process. Assuming that a site design with single normal left-turn lanes and dual CLL with $C = 150$ s, $G_e = 25$ s, $N_g = 10$, $s_1 = 0.4$ (veh/h), and the average arrival rate at peak hour is 2.5 pcu per 15 s. The calculation procedure is given below.

Step 1: $\lambda t = \lambda(C - G_e) = 2.5 \times 125/15 = 20.8 \approx 21$
Step 2: $T_{\max} \Rightarrow s_1g_e + n = 23$
Step 3: $g_e = 2(s_1g_e + n)/3s_1 \approx 37.5$; $n = (s_1g_e + n)/3 = 7.67 \approx 8$
Step 4: $n < N_g = 10$ (test of constraints)

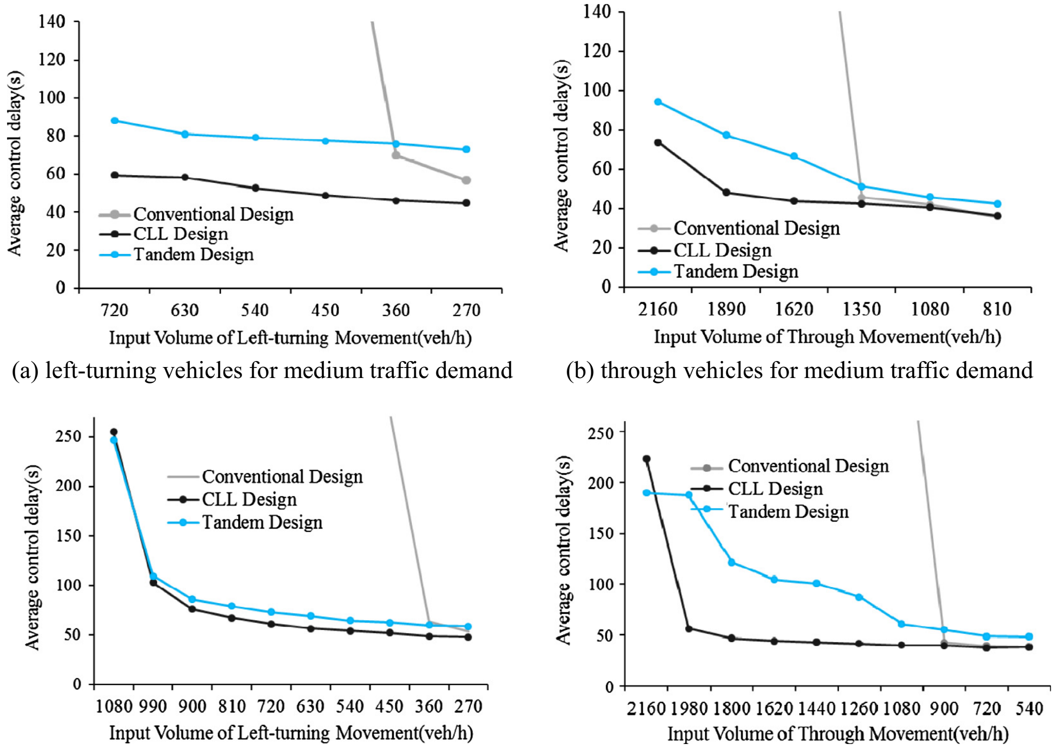
7. Comparison with tandem design

Simulation analyses were conducted to compare the delay experienced by the left-turn and through movement at the signalized intersections with the conventional left-turn lane, the CLL and the tandem design. Three simulation models that took into consideration three different left-turn treatments were developed using the VISSIM simulation package. The lane configurations and signal timing settings for CLL design are as same as those in Table 3, while the method proposed by Xuan et al. (2011) was used for optimizing the tandem design and the results are shown in Table 4. The simulation time was also equal to 45 cycles for each traffic condition considered.

Table 4
Signal timing plan and geometric structure for tandem design.

	N_t[a]	G_L (s)	G_T (s)	g_l[b] (s)	g_t[c] (s)	Cycle length (s)
Medium demand	3	26	49	78	61	150
Heavy demand	3	34	41	97	46	150

[a] N_t = the number of lanes in tandem zone.
[b] g_l = the effective green time for the left-turn movement at the pre-signal.
[c] g_t = the effective green time for the through movement at the pre-signal.



(a) left-turning vehicles for medium traffic demand
(b) through vehicles for medium traffic demand
(c) left-turning vehicles for heavy traffic demand
(d) through vehicles for heavy traffic demand

Fig. 10. Average delay experienced by left-turning vehicles and through vehicles.

The simulated average delay experienced by left-turning and through vehicles for different traffic conditions are plotted in Fig. 10. It was found that both CLL and tandem designs generated less delay for both left-turning and through vehicles than the conventional left-turn lane design did. More specifically, the average delay experienced by left-turning vehicles at conventional left-turn lanes increases dramatically when the left-turn traffic demand exceeds 360 veh/h, indicating that the left-turn traffic flow reaches the oversaturated condition (see Fig. 10(a) and (c)). The excessive left-turn queue also spills onto the adjacent through lanes, leading to increased delay to through traffic (see Fig. 10(b) and (d)). It was also found that the CLL design is generally more effective in reducing delay to both left-turning and through vehicles than the tandem design.

8. Conclusion and discussion

This study evaluated the impacts of an innovative left-turn treatment entitled contraflow left-turn lanes on the capacity of left-turn movement at signalized intersections. An analytical model was developed to estimate the capacity of left-turn movement at the left-turn approach with the CLL design. The capacity model was calibrated and validated using field data collected at six approaches at five signalized intersections in the city of Handan, China. It was found that the use of CLL design improved the capacity of left-turn movements. However, the capacity gains are quite stochastic considering the randomness in the arrivals of left-turning vehicles. A procedure was proposed for optimizing the location of the upstream median opening through which the left-turning vehicles entered the CLL and the green interval of the pre-signal. Analytical delay models were proposed for estimating the delay to left-turning vehicles at intersections with the CLL design. Simulation analyses were also conducted to compare the delay experienced by the left-turning and through vehicles at the signalized intersections with the conventional left-turn lane, the CLL design and the tandem design. The results showed that both CLL and tandem designs outperformed conventional left-turn lane design, and the CLL design generated less delay to both the left-turning and through vehicles as compared with the tandem design.

Even though the CLL design may improve traffic operations at signalized intersections, it also suffers from several limitations. One of the major concerns is related to the potential conflicts between the vehicles trapped in the CLL and opposing through vehicles. This condition may happen due to mechanical failure or when drivers are distracted and fail to realize the initiation of the green signal. Second, the use of pre-signals may increase the number of stops experienced by left-turning vehicles, leading to increased vehicles emissions and fuel consumption. A comprehensive evaluation is needed to evaluation the safety, operational, and environmental impacts of CLL design on signalized intersections. Several issues also need to be addressed before the CLL design is to be implemented more widely, including the drivers' compliance with the CLL design. For example, field observations revealed that some of the opposing vehicles may utilize the median opening to make U-turns, which may block left-turn vehicles and pose safety concerns. Future studies that focus on those issues are warranted.

Acknowledgements

This research was sponsored by the National Natural Science Foundation of China (No. 51322810). The support provided by the NSFC is greatly appreciated.

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