Simulation on Two Types of Improved Displaced Left-Turn Intersections Based on VISSIM

Yingcheng Zheng, Qianqian Shao, Yunfeng Zhang, and Siqi Zhang

Abstract Displaced left-turn (DLT) intersections, which solve the conflict between left-turn traffic and opposing-through traffic are currently the most efficient innovative intersection design. There are no *T*-shaped DLT intersections in use due to few researches have proposed the implementation of DLT design at *T* intersections. This paper proposes an improved design method for DLT intersections suitable for two types of intersections, which considering the demand of pedestrian and non-motorized vehicles crossing the street, the phase scheme of the improved DLT, the length of the storage section of the left-turn vehicle and lane-changing length is designed. The operational performance of two types of the improved DLT intersection is validated using the VISSIM simulation. Besides, a sensitivity analysis is demonstrated to compare two types of DLT with conventional intersections under different left-turn ratios. The results demonstrate the effectiveness of the proposed method and provide a basis for the design of DLT intersections geometric layout and signal timings.

Keywords Traffic engineering · Displaced left-turn · Signal design · Geometric layout · Simulation evaluation

1 Introduction

Congestion at intersections continues to worsen in numerous cities throughout the world. As the demand for transportation has gradually increased, urban traffic has become increasingly congested. However, while demands on the transportation system continue to grow, the conventional treatment of intersections through the provision of left-turn bays with protected left-turn phases may not be sufficient to avoid long delays. Consequently, various unconventional intersection designs and control strategies have been proposed by researchers to help enhance the efficiencies of intersections.

Y. Zheng · Q. Shao (✉) · Y. Zhang · S. Zhang
School of Transportation Engineering, Shenyang Jianzhu University, Shenyang, China
e-mail: mr_Crowley@163.com

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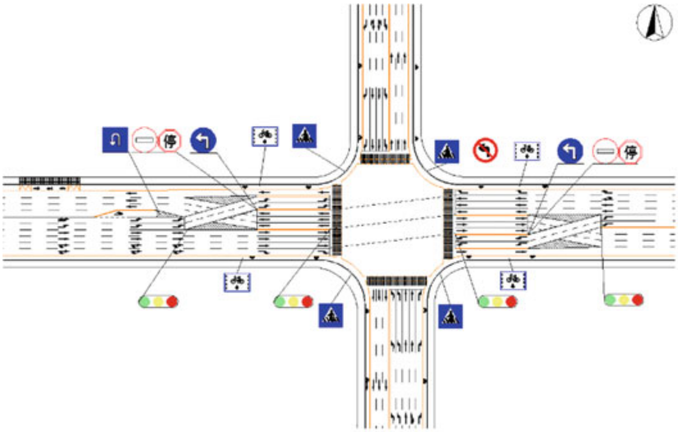
Among these innovative intersection designs, the displaced left-turn (DLT) intersection is quickly becoming prevalent worldwide [1–3]. Wu et al. [4] analyzed the influence of the DLT design on the trajectory of left-turning vehicles, and established a left-turn vehicle capacity calculation model and a left-turn vehicle delay calculation model at the DLT intersections, which demonstrated the effectiveness of the DLT. Yang et al. [5] conducted a comprehensive analysis of the delay of the entire DLT intersection, identified potential queue overflow locations, and developed a set of DLT design geometry planning stage models. Chang et al. [6] in order to further improve the traffic capacity of DLT intersections, the signal coordination relationship between the main intersection and sub-intersection was analyzed, and a signal timing optimization model with general adaptability was proposed. You et al. [7] proposed a model for a full continuous flow intersection (CFI), which is a type of the DLT intersection, with the objective of cycle length minimization to obtain signal timings based on the analysis and formulation of the queue length. Sun et al. [8] further proposed a simplified continuous flow intersection (called CFI-Lite) design, which uses the existing upstream intersection, instead of newly constructed sub-intersection, to allocate left-turn traffic to DLT lane.

The current studies suggest that determining optimal control strategies and suitable geometric layout for unconventional intersection designs remain a significant challenge in practice. In this paper, the design of intersection that combines the type of DLT intersection selection, the length of the DLT lane, and signal timings is presented. This paper innovatively applied the DLT intersection design to different types of intersections, including *T*-intersections and cross intersections, and further hopes to provide a basis for the design of DLT intersections geometric layout and signal timings.

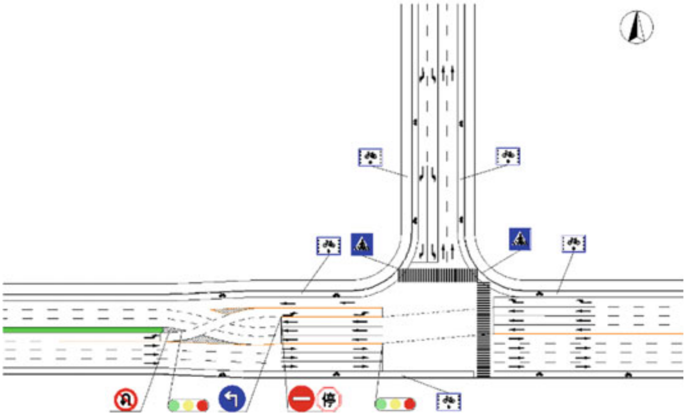
2 Improved Layout Design of the DLT

Displaced left-turn intersections as a new type of intersection, also referred as continuous flow intersections (CFI) and parallel flow intersection (PFI). As shown in Fig. 1, the improved DLT requires the relocation of the left-turn movement to the other side of the opposing roadway. Drivers who need to turn left at the main intersection should pass the opposite lane first turn left at the intersection upstream of the main intersection. Subsequently, left-turning traffic and through traffic on a roadway proceed simultaneously, without conflict, at the primary intersection [9]. Especially, the right-turning traffic can also leave the intersection without conflict under the unconventional layout of the improved DLT intersection.

The DLT intersection effectively circumvents the conflict between left-turning traffic and through traffic of opposite. Through the coordination of several road sections and intersection signal lights, through volume and left-turning volume are continuously passed through the intersection, reducing the number of phases and vehicle delays.



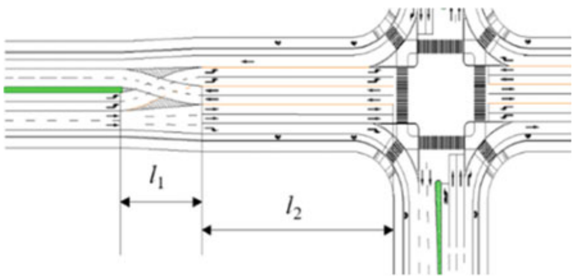
(a) Improved layout of across intersection



(b) Improved layout of T-intersection

Fig. 1 Improved layout of DLT at different types of intersections. **a** Improved layout of across intersection, **b** improved layout of T-intersection

Fig. 2 Lane-changing length of left-turn vehicle



As shown in Fig. 2, for the length of lanes at the left-turn crossover needs to be limited to meet the normal traffic flow of the intersection. For the DLT intersection, the left-turning vehicle enters the shifted left-turn lane from the stop line of the road section to change lanes, and the road section l_1 must meet the vehicle turning needs and safety distance, as constraint (1) illustrated. Constraint (2) requires that the length of the DLT lane should be long enough to accommodate the queuing length of left-turn vehicles.

$$l_1 \geq 2\sqrt{r^2 - [r - (w_1 + 0.5w_c)]^2} \tag{1}$$

$$l_2 \geq \frac{3600L_{el}}{mnS_{el}} \tag{2}$$

where l_1 is the length of lane-changing, as in Fig. 2; r is the minimum turning radius of vehicle; w_1 is the width of a lane; w_2 is the width of double amber lines; l_2 is the length of the storage section of DLT, as in Fig. 2; L_{el} is the length of all left-turn vehicles in line; m is the number of left-turn lanes; n is the number of signal cycles at intersections within one hour; S_{el} is the saturated flow rate of left-turn lanes.

3 Improved Design for DLT Intersection

The optimization objective is determined to minimize the total vehicle delay at the intersection. The objective function is as follows:

$$\min P = \left(d^{sub} + \sum_{i=1}^{n} d_i^{main}\right) \Big/ \left(q^{sub} + \sum_{i=1}^{n} q_i^{main}\right) \tag{3}$$

where d^{sub} is the vehicle delay of sub-intersection; d_i^{main} is the vehicle delay of phase i of main intersection; q^{sub} is volume of sub-intersection;q_i^{main} is volume of phase i of main intersection.

Constraints (4)–(6) are general signal constraints for all types of intersections. For the DLT intersection design, in order to reduce the number of stops for vehicles that have left the intersection, ensure that the vehicles that left the intersection in the previous phase pass through leg l_1 smoothly before allowing a left-turning vehicle to change lanes. At the same time, the duration of green of the sub-intersection needs to consider the length of section l_2 and the volume of left-turn traffic. Constraints (7)–(9) show the special requirements of main signal and pre-signal at DLT intersection.

$$C = L + \sum_{i=1}^{3} g_i^{main} \tag{4}$$

$$g_i^{\text{main}} \le g_i^{\max} \tag{5}$$

$$g_i^{\text{main}} \ge g_i^{\min} \tag{6}$$

$$g^{\text{sub}} - g_1^{\text{main}} \ge \frac{l_2}{v_{sl}} + t_1^{\text{main}} \tag{7}$$

$$g_2^{\text{main}} \ge \frac{3600 Q_{\text{el}}}{nmS_{\text{el}}} \tag{8}$$

$$g^{\text{sub}} - g_2^{\text{main}} \ge \frac{l_1 + l_2}{v_{\text{es}}} + t_2^{\text{main}} \tag{9}$$

where C is the cycle length; g_1^{main} is the duration of green for the left-turn phase of the main intersection without the sub-intersection; g_2^{main} is the duration of green for the through phase of the main intersection without the sub-intersection. There is no g_2^{main} and the phase corresponding to g_2^{main} if the type of intersection is T-shaped; g_3^{main} is the duration of green for left-turn and through phase of the main intersection with the sub-intersection; L is the loss time of signal cycle; $g_i^{\min}$ is the minimum duration of green for each phase; $g_i^{\max}$ is the maximum duration of green for each phase; g^{sub} is the duration of green of the sub-intersection; t_1^{main} is the time that the traffic flow corresponding to g_1^{main} leaves the intersection; v_1^{main} is the average speed of the traffic flow corresponding to g_1^{main}; t_2^{main} is the time that the traffic flow corresponding to g_2^{main} leaves the intersection; v_2^{main} is the average speed of the traffic flow corresponding to g_2^{main}.

4 Simulation and Analysis

4.1 Simulation Data

In order to verify the effectiveness of the proposed method, the existing two types of intersections in Lanzhou as an example.[1] The data acquisition time is from 17:30 to 18:30 in the evening peak of ordinary working days. The traffic demand for the test is summarized in Tables 1 and 2.

[1]The traffic data for this research work was obtained from the actual intersection of Xijin West Road, Anning District, Lanzhou City, China.

Table 1 Traffic demand of cross intersection

Across intersections	East import (pcu/h)	West import (pcu/h)	South import (pcu/h)	North import (pcu/h)
Left	370	336	760	178
Through	1379	1816	625	327
Right	100	554	616	256
Total imports	1849	2706	2001	761
Total intersections	7314			

Table 2 Traffic demand of *T* intersection

T intersections	East import (pcu/h)	West import (pcu/h)	South import (pcu/h)
Right	688	None	252
Through	1148	1475	None
Right	None	488	251
Total imports	1836	1963	503
Total intersections	4302		

4.2 Traffic Simulation—VISSIM

In this section, the performance of two types of the improved DLT intersections are evaluated through simulation tests. The intersection where DLT is set and the current situation is executed in VISSIM 6.0. The phase diagram scheme of intersection entered in VISSIM is shown in Fig. 3. The green light duration of each phase of the cross-shaped main intersection and sub-intersection of the improved cross-shaped DLT is 0–38 s, 41–68 s, 71–104 s, and 48–69 s, respectively. The green light duration of each phase of the *T*-shaped main intersection and sub-intersection of the improved

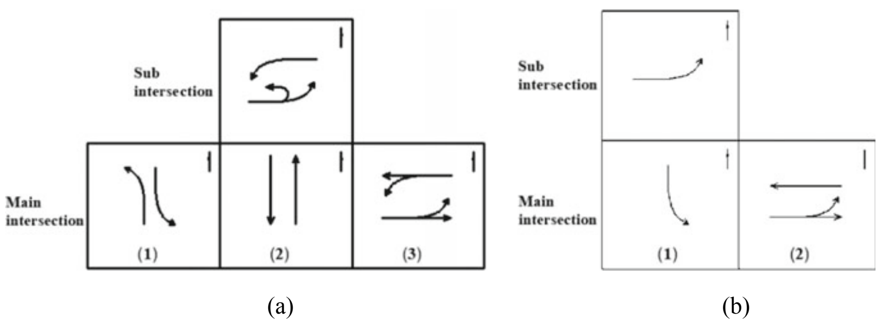


Fig. 3 Phase diagram scheme of intersection. **a** Scheme of cross DLT, **b** scheme of *T*-shaped DLT

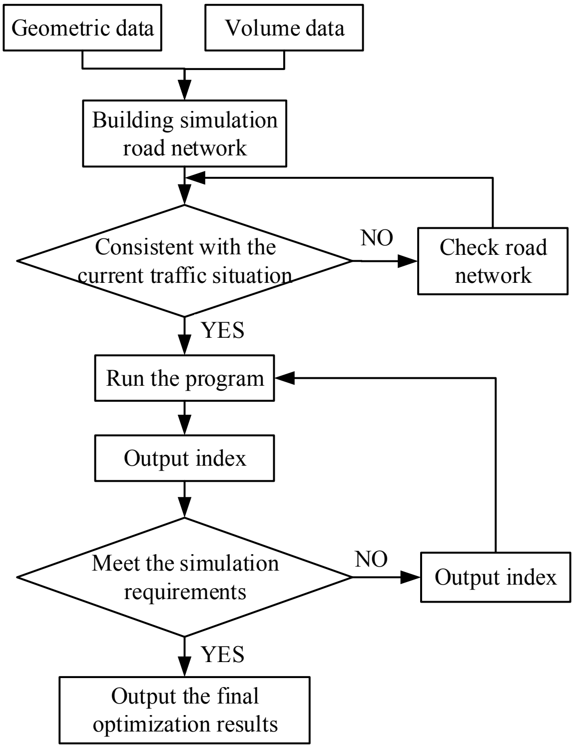


Fig. 4 VISSIM simulation process

cross-shaped DLT is 0–18 s, 21–57 s, and 7–18 s, respectively. All signals use 3 s amber.

The default driver behavior parameters in VISSIM are used in the simulation of the two types of the improved DLT intersections, and considering that software simulation requires a certain amount of traffic loading time to ensure the accuracy of the collected data, the starting time of the simulation data collection is set to 100 s, and the simulation is run 10 times. The simulation steps of VISSIM are shown in Fig. 4. The geometric layout of the intersections is shown in Fig. 1, where l_2 is set to 50 m.

4.3 Simulation Results

The performance evaluation results are illustrated in Table 3. Results from analyses show that the DLT intersections outperform the conventional design in terms of improving the intersection capacity.

Table 3 Comparison of simulation results

Simulation index	Cross intersection	Cross DLT	Optimization rate (%)	T intersection	T-shaped DLT	Optimization rate (%)
Average stop delay (s)	41.3	26.9	34.87	17.9	9.9	44.69
Average vehicle delay (s)	33.4	20.6	38.32	25.6	17.5	31.64
Maximum queue length (m)	22.3	13.9	37.67	107.7	66.4	38.35
Stops	14.4	7.8	45.83	5.2	4.8	7.69

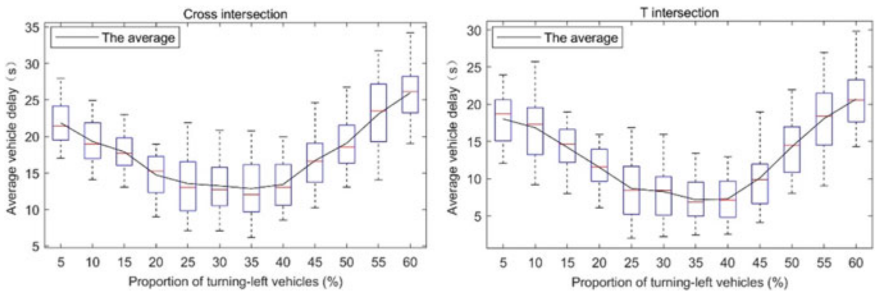


Fig. 5 Influence of left-turn ratio on delay of vehicles at intersections

Figure 5 displays the result of the sensitivity test, when the proportion of left-turn volume reaches 30–40%, the benefits of optimized design in reducing vehicle delays begin to manifest.

The indicators of the two types of intersections after setting up as DLT intersections have been greatly improved compared with the current situation, which validates that the improved DLT design method proposed in this paper is also suitable for T intersections.

5 Conclusion

It is developed, in this paper, an improved setting method for displaced left-turn (DLT) intersections suitable for two types of intersections. The contribution of this paper is comprehensively considered that there are many T intersections in the actual situation. Meanwhile, aiming at improving the general applicability of unconventional intersection design to different types of intersections. Established a VISSIM simulation model based on the actual intersection as a prototype, and the situation before and after the intersection was set as DLT intersection was simulated. The results show that the design of DLT intersection can directly and effectively reduce vehicle delays in the straight direction and enhance the traffic efficiency of the entire intersection.

However, it should be noted that DLT intersections may result in reduce driving comfort and safety and increase air pollution. Moreover, it leads to more complex intersections and requires the driver to have a strong ability to cope with unfamiliar driving environment. Therefore, future work will be introducing the evaluation of the safety performance of the intersection to ensure the DLT operation effect, while ensuring the operation efficiency of DLT intersection, the safety of the intersection will be improved to a greater extent.

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