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Safety evaluation of signalized intersections with left-turn waiting area in China

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ABSTRACT

In recent years the metropolitans in China have seen the surging installations of the left-turn waiting area (LWA) at the signalized intersections. The design allows the left-turning vehicles to enter the intersection at the onset of the through green phase (of the same approach) and wait for the exclusive left-turn signal at the LWA. The LWA layout can effectively reduce the probability of stranded and queue overflow of the left-turn vehicles, but no study is conducted yet to assess the safety performance of the signalized intersections with LWA. The paper adopts the traffic conflict technique (represented by post-encroachment time), compares the discrepancy of conflict types between intersections with LWA and without, and develops the severity models to identify the contributing factors for the left-turn conflicts. Results demonstrate that the left-turn volume, driving outside the LWA, running red light, the presence of secondary conflicts, and the rear-end conflicts significantly increase the severities of traffic conflicts at the LWA. The findings serve to provide recommendations to revise the current design standard of the LWA (GB5768-2009) and consequently improve the safety operations of signalized intersections with LWA in China.

1. Introduction

In the recent decades the rapid economic development in China has lead to serious traffic congestions at the urban intersections. The traffic phenomenon can be partially contributed to the escalating traffic conflicts between the left-turn and through movements at the signalized intersections. Traffic engineers in China have been actively seeking innovative techniques to increase the number of vehicles passing through the intersections per unit time, one of which is to designate a waiting area inside an intersection for the left-turning vehicles (Fig. 1).

This area is called "left-turn waiting area" (LWA), which is located beyond the stop bar and generally considered as the extension of the exclusive left-turn lane. Typically, it consists of two parallel, slightly curved white dash lines on both sides, an additional stop bar in the front, and a left-turn arrow marking inside the dwelling area, according to the national design standard for "Road Traffic Markings" (GB5768-2009) in China. The traffic operation of the left-turn movement at the LWA requires a lagging left-turn phase immediately following the initiation of the through indication at the same approach; the queuing vehicles in the exclusive left-turn lane are released into the LWA when the through vehicles have the rights-of-way and the leading vehicle will stop right behind the stop bar (in the front) until the LWA is fully occupied. The waiting vehicles will accomplish the left-turn movement when the lagging left-turn phase turns on. Considering its unique design layout and traffic operation, it has gradually attracted the attentions and thus the implementations at the signalized intersections in most of the capital cities in China since its introduction in 1999.

The comprehensive review has revealed that the majority of the historical studies are devoted to evaluating the capacity of the intersections equipped with the LWA. For example, Ni et al. (2006) and Xu (2009) utilized the "stop line" method and shockwave theory to discuss the effects of LWA on the approach and overall capacity at the signalized intersections. Intuitively, it appears that the installation of LWA can improve the traffic efficiency of the signalized intersections, because it can store several left-turn vehicles in advance and allow them to enter intersections ahead of their release time in every signal cycle. A number of researches (Wei et al., 2008; Li, 2009a,b; Li et al., 2011; Chen, 2012; Yang et al., 2012a) had verified that the LWA could increase the capacity of the left-turn movement through simulating different traffic conditions and the capacity gains enlarged with the mounting size of the left-turn waiting areas. Yang et al. (2012b, 2012c) conducted a cross-sectional analysis to compare the start-up lost time and

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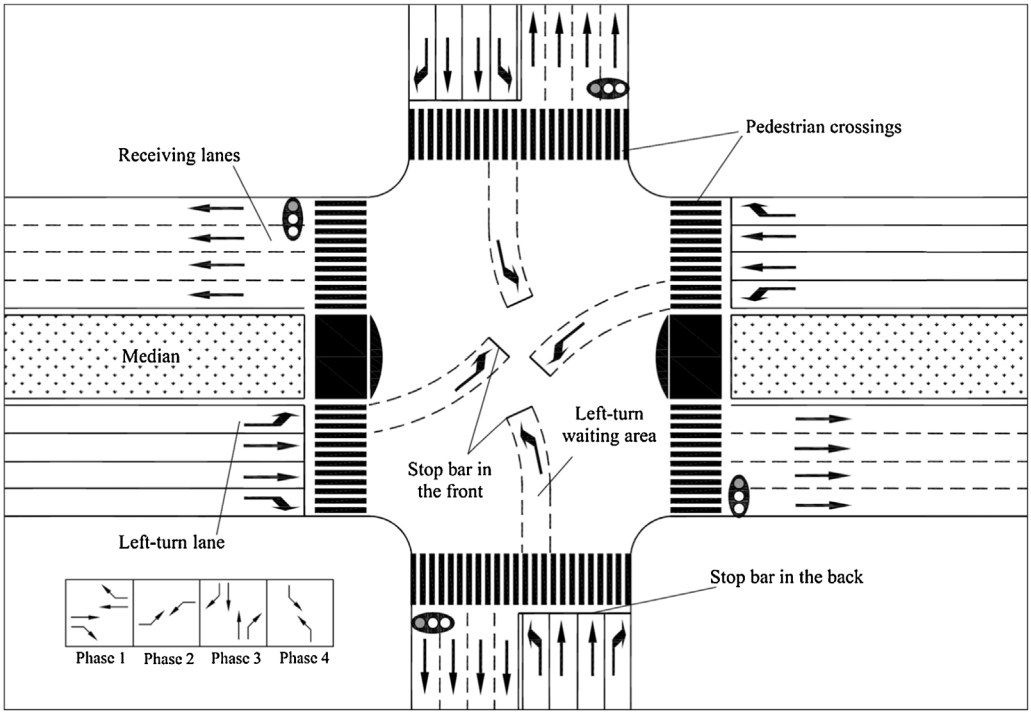

Fig. 1. Typical design layout of a signalized intersection with left-turn waiting area.

saturation headways of left-turn passenger cars at the LWA with single and dual left-turn lanes and found that the use of LWAs enhanced the capacity of exclusive left-turn lanes but did not considerably affect the saturation headways of left-turn passenger cars behind the stop bar. Zhou and Zhuang (2012) evaluated the traffic performance at the signalized intersections with the shared lane and LWA and found that the utilization of LWA significantly improved the discharge rate of the through lane without compromising the efficiency of left-turning flows, thus reducing the average vehicle control delay. Previous studies seemingly point to the conclusion that LWAs can always improve the traffic capacity of the signalized intersection. Jin (2006) provided a different viewpoint that the left-turn traffic capacity actually remained unchanged regardless of the installation of LWA or not, given that the left-turn vehicles could not cross the conflict point (between the left-turn and opposite through movements) until the opposite through cleared. Nonetheless, the LWA could effectively reduce the probability of the overflow of left-turn vehicles at the exclusive left-turning lanes.

After the LWA is installed at the existing intersections, the lagging left-turn phase needs to be properly designed to ensure the normal operation for the left-turn vehicles. Particularly, the time interval between the left-turn phase and through phase should be prolonged to avoid the possible conflicts between the left-turners and the opposite through movement (Jin, 2006; Ni et al., 2006). Also, studies (e.g., Li, 2009a,b; Wang et al., 2009; Guan, 2011) have been conducted to calculate the minimum green time and maximum red time of the left-turn phase at the intersections with the LWA. Furthermore, considering that the left-turn vehicles needed to stop twice to cross the intersection with LWA, Ni et al. (2006) found that the number of stops for the left-turn vehicles increased significantly after installing the LWA and that LWA with a greater storage capacity had a larger frequency of stops. Guan (2011) modified the conventional stop-rate model and made it applicable for the intersections with the LWA. It is also reported that the increasing stop-and-go conditions can cause more fuel consumptions and exhaust emissions of the motorized vehicles at intersections of such (Gao, 2009).

In order to develop warrants as to when and where to install the LWA, various studies (e.g., Zhai, 2005; Ji et al., 2006; Ding and Zhai, 2007; Li, 2009a,b; Wang et al., 2009; Luo, 2010; Guan, 2011) stipulated the conditions applicable for the LWAs in terms of geometric layout, signal timings, and traffic volume. For a specific design, Xu (2009) built a mathematical model to identify the optimal location for the stop bar (in the front) for the LWA.

In summary, the appraisal on the past studies has demonstrated that the overwhelming majority of the researches focus on the operations, traffic capacity analysis, and warrants of installing a LWA at the signalized intersections. Consensus is reached that the LWA can generally improve the intersection capacity and the critical conditions are identified to install the LWA.

However, there is a great lack of systematic studies to specifically explore the safety impacts of the LWA. The traffic design of the LWA allows the left-turners to move closer to the opposite through movement, which may pose potential safety risks for both movements. From the operation perspective, a number of conflict types were identified and linked to the left-turn movement in the field observations (Fig. 2). Although all the intersections of interest had the protected lagging left-turn phase, the opposite through volume was typically heavy and vehicles still got into the intersections at the end of the green indication. This phenomenon caused the left-turn and opposite through vehicles conflict for both scenarios (e.g., vehicles F and H in Fig. 2). Left-turn diverging conflicts took place at the onset of the through green, when left-turn vehicles started to enter the LWA until its full capacity and then the following vehicles continued to leave the stop bar (in the back) and occupy both sides of LWA (e.g., vehicles B and C). Consequently, the merging conflicts occurred at the receiving lanes where different streams of left-turn vehicles began to merge (e.g., vehicles E, F, and G). Rear-end conflicts occurred between the proceeding and the following left-turn vehicles for both scenarios (e.g., vehicles F and D) and also between the vehicles waiting outside LWA and the through vehicles of the

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