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Original Research Paper

Left-turn phasing selection considering vehicle to vehicle and vehicle to pedestrian conflicts

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HIGHLIGHTS

- Evaluated pedestrians' impact on traffic conflicts in permissive left-turn phasing.
- V-V conflicts increased with pedestrian presence.
- Higher opposing-through traffic caused less V-P conflicts in total conflicts.
- Pedestrian presence warranted left-turn protection at lower left-turn volume.

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ABSTRACT

Left-turning vehicle movement at signalized intersections with permissive left-turn phases creates safety concerns due to the higher chance of conflict with opposing-through vehicles and pedestrians. In this research, a simulation-based study was conducted to evaluate pedestrians' impact on traffic conflicts between left-turning vehicles and opposing-through vehicles (V-V conflicts) as well as traffic conflicts between left-turning vehicles and pedestrians (V-P conflicts) in the permissive left-turn phasing scenario. Intersections with different opposing-through volumes, left-turn volumes, number of opposing-through lanes, and pedestrian volumes were modeled in VISSIM, a traffic micro-simulator. The surrogate safety assessment model (SSAM) was used to estimate the number of V-V and V-P conflicts. The effect of pedestrian presence on V-V and V-P conflicts was evaluated using simulation scenarios with and without pedestrian presence. Simulation results revealed that pedestrian presence increased both V-V and V-P conflicts. As pedestrian presence increased the total number of traffic conflicts, permissive left-turn phasing processed fewer left-turn vehicles to maintain the same level of intersection safety with pedestrian presence compared to the no-pedestrian scenario. Since current left-turn phasing decision guidelines do not consider the impacts of pedestrian presence, this research quantified pedestrian-influenced and pedestrian-involved left-turn traffic conflicts to determine appropriate left-turn signal phasing decisions to ensure safe and efficient crossing of pedestrians and vehicles at signalized intersections. This simulation-based study's findings

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can be beneficial in the decision making of left-turn phasing selection as the before-after intersection safety performance analysis by collecting field data often resources intensive.

1. Introduction

Intersections are the most crash-prone locations in the surface transportation system due to the inherent nature of conflicting movements of heterogeneous traffic (e.g., different types of vehicles, pedestrians, bikes). Intersections are signalized to allow orderly movement of conflicting traffics to minimize the risk of crashes and improve operational efficiency. However, it is challenging to develop a signal timing plan that will simultaneously maximize operational efficiency and reduce traffic conflicts at an intersection (Majhi and Senathipathi, 2021). In the U.S., forty-five percent of traffic crashes at intersections were related to left-turning vehicles, where left-turning vehicles represent only 10%–15% of intersection traffic volume (Maze et al., 1994; Stamatiadis et al., 2015). Furthermore, left-turning vehicles usually have to encounter more delays during conducting turning movement at an intersection. To address the safety and operational efficiency issues related to left-turning vehicle movements, traffic engineers use different signal phasing strategies: permissive only, protected only, and a combination of protected-permissive for left-turning movements. In permissive left-turn phasing, two opposing-through traffics are provided green concurrently, where left-turn movements must yield to opposing through traffics and pedestrians, and complete the movements depending on the gap availability (Stamatiadis et al., 2016). At a signalized intersection, left-turn movements using permissive left-turn phasing are challenging as they require drivers' judgment of a sufficient gap to avoid collisions with opposing-through traffic (Stamatiadis et al., 2016), though permissive left-turn phasing is the operationally efficient option. On the contrary, the protected left-turn phasing is the safest option with lower operational efficiency (FHWA, 2009; Shebeeb, 1995). Protected left-turn phasing is preferred at high-volume, high-speed (Gibby et al., 1992), and highly urbanized intersections (Chen et al., 2013). Protected-permissive left-turn phasing provides a balance between operational efficiency and safety. Typical factors considered in selecting appropriate left-turn phasing are left-turn volume, cross-product of opposing-through volume and left-turn volume, the number of left-turn lanes, and historical crash record at an intersection. Seventeen state Departments of Transportation (DOTs) consider crash history in selecting appropriate left-turn phasing (Stamatiadis et al., 2016). Several studies on the justification of left-turn phasing selection conducted an empirical before-after study to investigate the reduction of the left-turn traffic involved crashes. As before and after studies are time-consuming, there is a need for alternative methods so that decision-makers can evaluate the effectiveness of modified left-turn phasing without post-improvement data collection (Tarko et al., 2009). Microsimulation traffic tool shave been used to model and analyze traffic conflicts at signalized intersections. Estimation of traffic conflicts is used as the surrogate measure for crash risk estimation. Traffic conflict is defined as a potential crash situation, where two or more road users (i.e., vehicles, pedestrians) approach each other very close in terms of space and time, and a collision is imminent if direction and speed are unchanged by one or more road users (Tiwari et al., 1998). In a micro simulation environment, vehicle and pedestrian trajectories are developed considering different intersection geometry, signal timing and phasing strategies, and vehicle and pedestrian volumes. The generated trajectories are then used to determine the number of traffic conflicts. This study aims to investigate the effect of pedestrian movements on resulting vehicle to vehicle (V-V) and vehicle to pedestrian (V-P) conflicts at a signalized intersection using permissive left-turn phasing. The findings of this research will help traffic engineers to select appropriate left-turn phasing by considering pedestrian presence at signalized intersections.

2. Literature review

Agent and Deen (1978) made the first systematic effort to evaluate the performance of permissive, protected, and protected-permissive left-turn phasing. The authors developed left-turn phasing warrants based on four criteria: traffic crash experience, delay, volumes, and traffic conflicts before and after the installation of protected left-turn phasing for performance evaluation. Left-turning vehicle-involved traffic crashes and conflicts were reduced significantly with protected left-turn phasing. In the subsequent studies (Agent, 1979, 1985; Agent et al., 1995), Agent proposed guidelines for the selection of protected and protected-permissive left-turn phasing. Yu et al. (2008) recommended that the protected-permissive left-turn phasing should be selected when the cross-product value is equal to or less than 133,000 for one opposing-through lane and 93,000 for two opposing-through lanes. Asante et al. (1993) developed three graphs on left turn volume versus opposing-through vehicle speed to guide the selection of permissive only and some form of protected left-turn phasing for one, two, and three opposing-through lanes. Koonce and Rodogerdts (2008) recommended protected left-turn phasing when one of the following scenarios is satisfied 2 or more left-turn lanes, 4 or more opposing-through lanes, cross-product of opposing-through traffic, and left-turn traffic exceeds 50,000 for one opposing-through lane and 100,000 for 2 or 3 opposing-through lanes during peak hour, opposing-through traffic speed limit exceeds 45 mph, and left-turn delay exceeds 35 s per vehicle during peak hour. Kell and Fullerton (1982) recommended considering traffic volume, left-turn delay, and crash counts in left-turn phasing selection. In addition to opposing-through volume and left-turn volume, Al-Kaisy et al. (2001) identified cross-street traffic volume as an important factor in left-turn signalization decision making, as cross street traffic influences green time split. Zhang et al. (2005) also reported the importance of cross-street traffic volume on the left-turn phasing selection. Stamatiadis et al. (1997) used left-turn volumes, crash rates, product of opposing-through volumes and left-turn volumes data for 217 intersections in Kentucky to examine the effect of left-turn phasing type on the safety and operational efficiencies at signalized intersections. Jolovic et al. (2016) designed 338 different phasing sequences by changing the number of rings and phases. The objective was to test the Traffic Engineering Handbook (TEH) warrant recommendations for left-turn phasing selection. Left-turn involved V-V conflicts were used by Stamatiadis et al. (2016) to recommend left-turn phasing. This study developed two figures on left-turn phasing selection for one and three opposing-through lanes.

Some studies focused on understanding the influence of pedestrian presence on left-turn signal phasing (Pratt et al., 2013; Qi and Yuan, 2012; VDOT, 2015), but did not consider pedestrian-involved and pedestrian-influenced traffic conflicts in left-turn phasing selection. In our study, pedestrian presence in various simulation scenarios with permissive left-turn phasing was estimated to determine the impact of pedestrian volume on the left-turn vehicle involved V-V and V-P conflicts and left-turn phasing decision. Estimation of traffic conflicts as surrogate measures of traffic crashes was validated by several studies such as Stamatiadis et al. (2016), Caliendo and Guida (2012), Sacchi et al. (2013), and FHWA (2008). Past studies calibrated VISSIM simulation models by focusing on headway, flow, speed, and traffic volume parameters to evaluate traffic conflicts using SSAM. Arafat et al. (2021) developed a simulation model of a four-leg intersection in VISSIM using traffic volume, directional vehicle distribution, and signal timing parameters. Priority rules were used to simulate conflicting movements. The authors adjusted drivers' gap acceptance behavior with the minimum headway and minimum gap time parameters, where the associated data were collected using video recording. Arafat et al. (2020) used vehicle speed and parameters in Wiedemann 99 car-following model to calibrate four signalized intersections and validated saturation headway and saturation flow rate obtained from simulation with field measurement. Lu et al. (2016) used automated video processing techniques to obtain vehicle trajectory data and measured car-following parameters (i.e., desired speed, desired acceleration, and safe following distance) directly to calibrate the VISSIM model. The calibrated model outperformed the default-setting model while validating the model in terms of saturation headway. Fan et al. (2013) adjusted two parameters of Wiedemann 99 car following model, standstill distance and headway time to match simulated travel time with field travel time to do conflict analysis using SSAM. Virdi et al. (2019) calibrated their models with traffic volume and validated using travel time and queue length to determine traffic conflicts using SSAM. Kim et al. (2005) used non-parametric statistical techniques (i.e., Wilcoxson rank-sum test, Moses test, and Kolmogorov-Smirnov test) to examine the closeness of simulated travel time distribution with field observations. Using this technique, the authors reported obtaining statistically valid simulation results, where simple metrics (e.g., mean absolute error) could lead to misleading calibration results. Lidbe et al. (2017) compared three meta-heuristic techniques, genetic algorithm, simulated annealing, and tabu search for their effectiveness to calibrate microsimulation models. The metaheuristic process was reported to possess a better ability to adjust model calibration parameters effectively by automating a time-consuming calibration process. Tabu search was reported to perform better in terms of calibrating microsimulation models compared to genetic algorithm and simulated annealing techniques.

Modeling pedestrian behaviors is VISSIM is a challenging task. Pedestrian behaviors and interactions with different components of roadway networks are usually underrepresented in VISSIM simulation models. The simulation model outputs in VISSIM are highly sensitive to pedestrian-related parameter selection (e.g., priority rule configurations, pedestrian gap acceptance criterion, and crosswalk width) and could significantly influence simulation results (Suh et al., 2013). Crosswalk width could influence pedestrian throughput rate and pedestrian delay. In addition, there is variability in the real world in the pedestrian arrival and departure process at an intersection, pedestrian gap acceptability, and pedestrian-vehicle interaction, which are insufficiently represented in VISSIM simulation models (Suh et al., 2013).

3. Methods

3.1. *Simulation model calibration*

The research team used PTV VISSIM 2020, a traffic microsimulation tool, to model the traffic simulation scenarios (PTV Group, 2020a). A calibrated simulation model of the Patteson Drive and University Ave intersection in Morgantown, WV, was developed with field data related to intersection geometry, signal timing, traffic volume, directional vehicle distribution, and vehicle composition. Travel time and queue length were used to validate the simulation model. Field travel time data was collected for eight travel time segments, and queue length was measured for four approaches. Sample sizes of the validation parameters (i.e., travel time and queue length) were determined using the guidelines recommended in Chapter 3 of the ITE Transportation Planning Handbook (Anderson Bomar, 2009). For an error rate of 10%, 11 travel time samples for each travel time segment and 13 queue length samples for each approach were required to achieve a 95% confidence interval. Simulation parameters (e.g., speed distribution, headway) in VISSIM were modified to achieve simulation travel time and field travel time within ±10% for all segments as well as simulation queue length and field queue length within ±10% in all approaches. The standstill distance

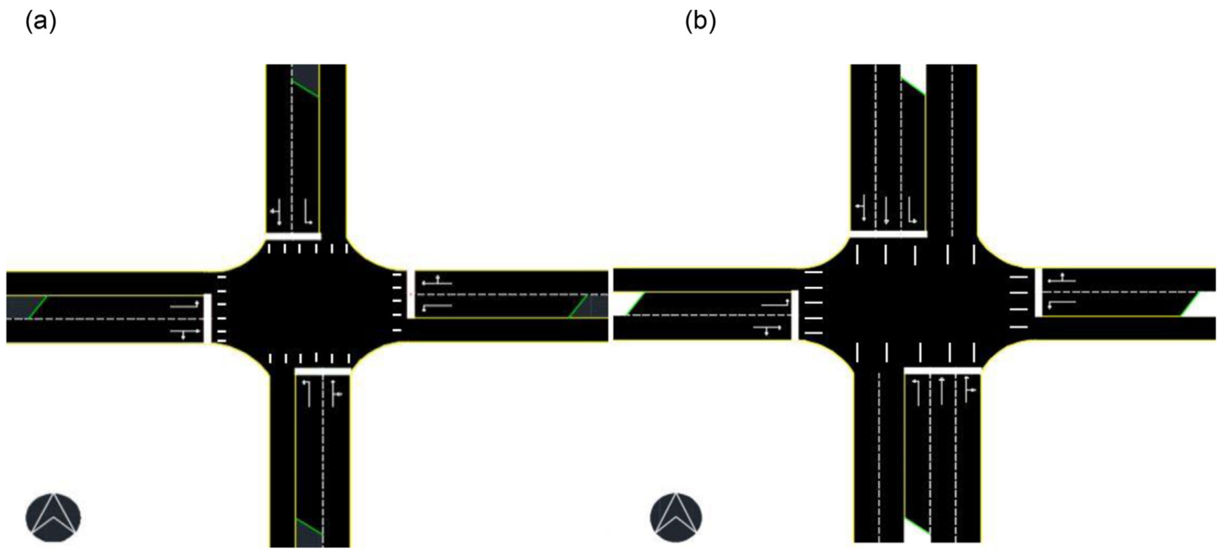

Fig. 1 – Intersection configurations used in this research. (a) One opposing-through lane (north-south). (b) Two opposing-through lanes (north-south).

parameter of Wiedemann 99 car following model was 1.2 m after calibration from the default value of 1.5 m, where the headway time parameter was 1.0 s after calibration from the default value of 0.9 s. A normally distributed vehicle speed profile of 25–35 mph was used for all vehicles.

3.2. *Developing experiment simulation scenarios*

Calibrated VISSIM intersection models developed for this research were typical 4-way intersections. The north-south (N-S) street was the major street, and the east-west (E-W) street was the minor street. A simple 2-phase signal timing plan with permissive left-turn movements was used for the signal operation.

Traffic and signal timing parameters (i.e., cycle length, percent green time for the major street, number of opposing-through lanes, and hourly opposing-through vehicle volume, left-turn volume, and pedestrian volume) were selected for the development of simulation scenarios. The simulation scenarios have been divided into two main sub-sets for one opposing-through lane (Fig. 1(a))and two opposing-through lanes (Fig. 1(b)) in the N-S major street. Fig. 2 provides a high-level illustration of the research steps followed in this study.

Table 1 summarizes the left-turn and opposing-through traffic volume and lane configurations used for developing simulation scenarios to evaluate the effect of pedestrian presence on left-turn involved V-V and V-P conflicts. To determine the impact of pedestrian presence on the V-V and V-P conflicts, a pedestrian volume of 250 per hour was assumed, which was equally distributed on all four crosswalks and eight pedestrian movement directions (i.e., two movement directions on each crosswalk). The pedestrian volume of 250 per hour has been considered as medium pedestrian activity level based on pedestrian activity data of 317 signalized intersections in the study by Zaidel et al. (1987). To facilitate the interactions between pedestrians and vehicles, priority rules were used. Pedestrians were assumed to have a walking speed distribution of 3.5–4.5 ft/s (1.07–1.37 m/s) (Montufar et al., 2007). Each simulation scenario was configured in two ways (i.e., with pedestrian presence and without pedestrian presence) to estimate the effect of pedestrian presence on V-V conflicts. Overall, both one opposing-through lane and two opposing-through lanes had 26 simulation scenarios.

Wiedemann's car-following model was used in the VISSIM simulation models (PTV Group, 2020b). All simulation scenarios were run ten times with different seed numbers using PTV VISSIM 2020 to estimate average output values (i.e., number of V-V or V-P conflicts). The traffic composition consisted of passenger cars only (i.e., 0% heavy vehicles). A normally distributed speed profile (with 25 mph to 35 mph range) was used for all vehicles. The traffic signal cycle length used was 90 s, and 70% of the green time was allocated for the major street (north-south). A yellow interval of 3 s and a red clearance interval of 1 s were provided for both major and minor streets.

The green time split, yellow time, and all red time were adopted from field observations at the study intersection.

Vehicle and pedestrian movement trajectory files were generated by simulating the developed scenarios in VISSIM to determine V-V and V-P conflicts. Trajectory files were imported to SSAM 3 to determine the number of traffic conflicts (FHWA, 2008). During V-V conflict analysis, the threshold values for maximum time to collision (TTC) and maximum post encroachment time (PET) used were 1.5 s and 5 s, respectively (Lee et al., 2013). TTC indicates the time until a collision between vehicles might occur if the vehicles maintain their courses and speeds, while PET indicates the difference between the times a vehicle enters a conflict point until another vehicle arrives at that point. SSAM model differentiates V-V conflicts based on the encounter angle between two vehicles. In this study, trajectories of two vehicles that interacted at angles greater than 85° were considered as crossing traffic conflicts, angles smaller than 30° as rear-end traffic conflicts, and angles between 30° and 85° as lane-change traffic conflicts as recommended in Stamatiadis et al. (2016). In

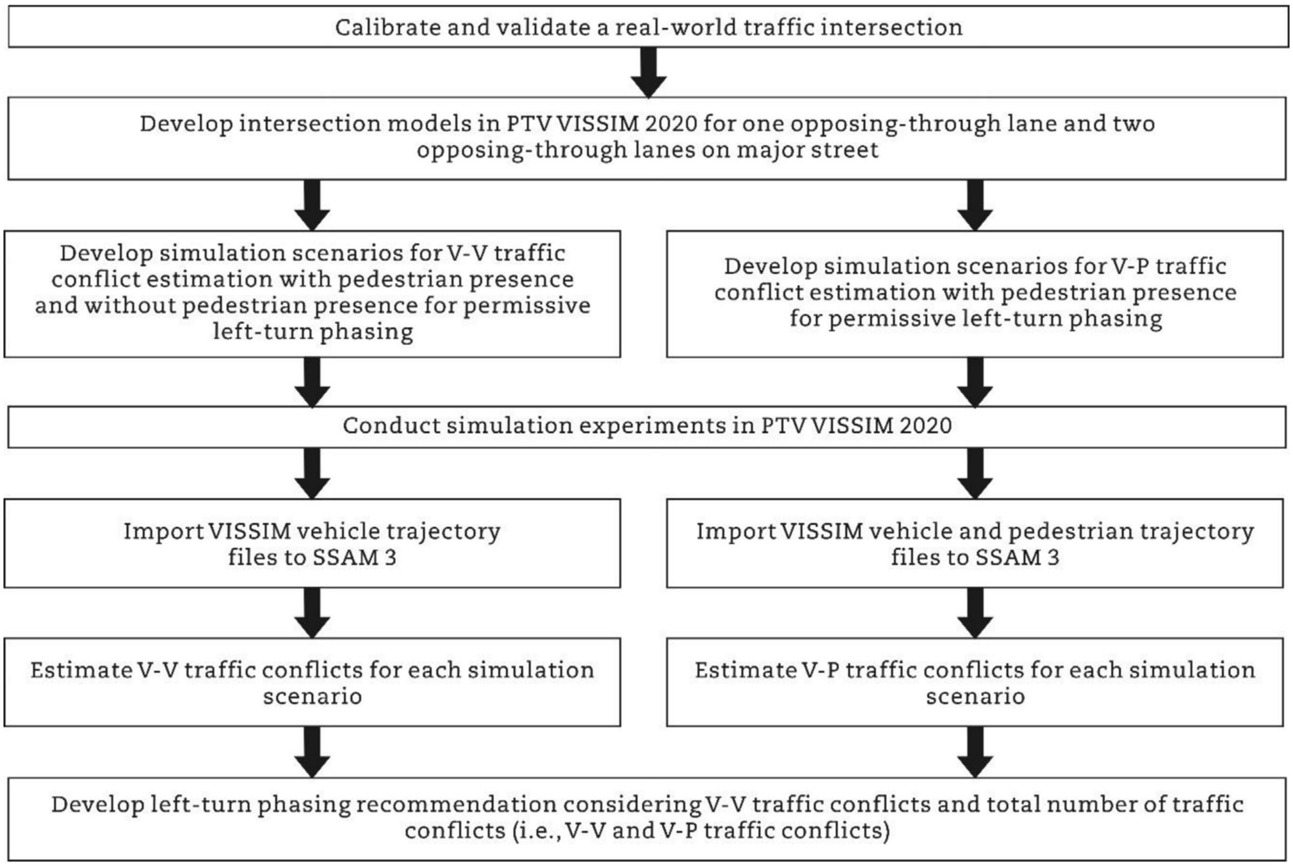

Fig. 2 – Flow chart of the research plan.

Table 1 – Simulation input parameters for V-V and V-P conflict estimation.

Number of opposing-through lane	Opposing-through volume (vehs/h)	Pedestrian volume (peds/h)	Left-turn volume (vehs/h)
1	500	250	50, 100, 150, 200, 250, 300, 350, 400
	750		50, 100, 150, 200, 250
2	750	250	50, 100, 150, 200, 250, 300, 350
	1000		50, 100, 150, 200, 250, 300

this research, only V-V crossing conflicts were determined (primary conflict type between left-turning traffic with opposing-through traffic), as lane-change and rear-end traffic conflicts were not typically occurred between left-turn and opposing-through movements. For V-P conflict analysis, the threshold values for maximum TTC and maximum PET used were 2.7 s and 8 s, respectively (Wu, 2017).

4. Results and analysis

This section presents the analysis of the simulation results to identify the impacts of pedestrian presence in the left-turning vehicle involved traffic conflicts considering different left-turn volumes, number of opposing-through lanes, and opposing-through traffic volume (as discussed in the last section). Table 2 presents the simulated V-V and V-P conflicts for different combinations of left-turn volume, opposing-through lanes, and opposing-through volume.

4.1. *V-V conflict estimation*

A positive exponential relationship was observed between left-turn traffic volume and the number of V-V conflicts with and without pedestrian presence irrespective of opposing-through volume and number of opposing-through lanes. Goodness-of-fit index, R^2 values of each non-linear regression equation was greater than 0.79, which indicates a strong correlation in terms of higher V-V conflicts with the increase in left-turn traffic volume. Fig. 3 shows the exponential positive relationship between left-turn traffic volume and V-V conflicts for a different combination of opposing-through volume and number of the opposing-through lane. For the V-V conflict estimation, the thresholds of maximum time to collision (TTC) and post encroachment time (PET) were 1.5 and 5 s, respectively. Thus, a V-V conflict was estimated when the trajectories of the left-turn vehicle and opposing-through vehicle were less than 1.5 s from a collision point with the assumption of both vehicles maintaining their trajectories

Table 2 – V-V and V-P conflicts estimation for different number of the opposing-through lane, opposing-though volume, and left-turn volume.

Opposing-through lane and opposing-through volume	Left-turn volume (vehs/h)	V-V conflicts per hour with pedestrian presence	V-V conflicts per hour without the pedestrian presence	V-V conflicts per hour due to the pedestrian presence	Percentage increase in V-V conflicts due to pedestrian presence	V-P conflict per hour	Total traffic conflict per hour	Contribution of V-P conflicts in total traffic conflicts (%)
One opposing-through lane and 500 vehs/h opposing-through volume	50	1.39	0.81	0.58	71.93	9.7	11.09	87
	100	1.99	1.21	0.78	64.37	9.9	11.89	83
	150	2.83	1.80	1.03	57.13	10.4	13.23	79
	200	4.04	2.69	1.35	50.22	12.1	16.14	75
	250	5.76	4.01	1.75	43.61	12.4	18.16	68
	300	8.21	5.98	2.23	37.29	12.4	20.61	60
	350	11.72	8.93	2.79	31.25	14.6	26.32	55
	400	16.71	13.32	3.39	25.47	15.6	32.31	48
One opposing-through lane and 750 vehs/h opposing-through volume	50	4.48	3.81	0.67	17.67	9.3	13.78	68
	100	6.66	5.57	1.08	19.45	10.6	17.26	61
	150	9.88	8.15	1.73	21.25	12	21.88	55
	200	14.67	11.92	2.75	23.08	12.9	27.57	47
	250	21.77	17.42	4.35	24.94	13.7	35.47	39
Two opposing-through lanes and 750 vehs/h opposing-through volume	50	1.56	1.47	0.09	6.46	9.5	11.06	86
	100	2.20	2.01	0.18	9.16	10.5	12.70	83
	150	3.09	2.76	0.33	11.92	10.8	13.89	77
	200	4.34	3.78	0.56	14.75	10.9	15.24	72
	250	6.10	5.18	0.91	17.66	11.3	17.40	65
	300	8.56	7.10	1.46	20.64	11.8	20.36	58
	350	12.03	9.73	2.30	23.69	12.3	24.33	51
Two opposing-through lanes and 1000 vehs/h opposing-through volume	50	2.95	2.72	0.23	8.44	8.6	11.55	75
	100	4.25	3.84	0.41	10.63	10.00	14.25	70
	150	6.12	5.42	0.70	12.87	10.6	16.72	63
	200	8.81	7.65	1.16	15.15	11.5	20.31	57
	250	12.70	10.81	1.89	17.47	11.6	24.30	48
	300	18.29	15.26	3.03	19.85	11.9	30.19	39

and speeds. In terms of PET, a V-V conflict occurred when the first road user (i.e., a left-turn vehicle or an opposing-through vehicle) crossed a conflict point, and the second road user (i.e., an opposing-through vehicle or a left-turn vehicle) arrived at the same conflict in less than 5 s.

4.1.1. *Effect of opposing-through volume and number of the opposing-through lane on V-V conflicts*

A comparison between the estimates of the number of V-V conflicts with and without the pedestrian presence for different opposing-through lane volumes and opposing-through lane scenarios is presented in Table 2. In all opposing-through lane volumes and the number of opposing-through lane scenarios, V-V conflicts are consistently higher with pedestrian presence compared to without pedestrian scenarios.

- In one opposing-through lane and 500 vehs/h opposing-through volume scenarios, the number of V-V conflicts increased from 0.81 to 13.32 per hour due to an increase in left-turn volume from 50 vehs/h to 400 vehs/h without the pedestrian presence. In this same scenario, with the pedestrian presence, the V-V conflict increased from 1.39 to 16.71 per hour due to the increase in left-turn volume from 50 to 400 vehs/h (Table 2). It indicates that V-V conflicts increased by at least 25% in the pedestrian presence (Table 2, sixth column) in one opposing-through lane with 500 vehs/h opposing-through volume scenarios.
- In one opposing-through lane and 750 vehs/h opposing-through volume scenarios, the number of V-V conflicts increased from 4.48 to 21.77 per hour with pedestrian presence due to an increase in left-turn volume from 50 vehs/h to 250 vehs/h, and V-V conflicts increased from 3.81 to 17.42 per hour without the pedestrian presence (Table 2). In this scenario, V-V conflicts were at least 18% higher in pedestrian presence than in the no-pedestrian scenario (Table 2, sixth column).
- The above simulation results indicate that when the opposing-through vehicle volume increased from 500 to 750 vehs/h, the chance of left-turning vehicle involved V-V conflicts increased as left-turning vehicles had to find gaps in a higher number of opposing-through traffic. Left-turn movements also became more difficult with pedestrian presence, as V-V conflicts increased in pedestrian presence. A similar pattern was observed for two opposing-through lane scenarios presented in Table 2.

4.1.2. *Effect of left-turn volume on V-V conflicts*

Irrespective of opposing-through volume and the number of opposing-through lanes, V-V conflicts increased with higher left-turn volume with and without pedestrian presence. However, the effect of left-turn volume on V-V conflicts due to pedestrian presence depends largely on corresponding opposing-through volume. With higher opposing-through volume, the same number of V-V conflicts were created

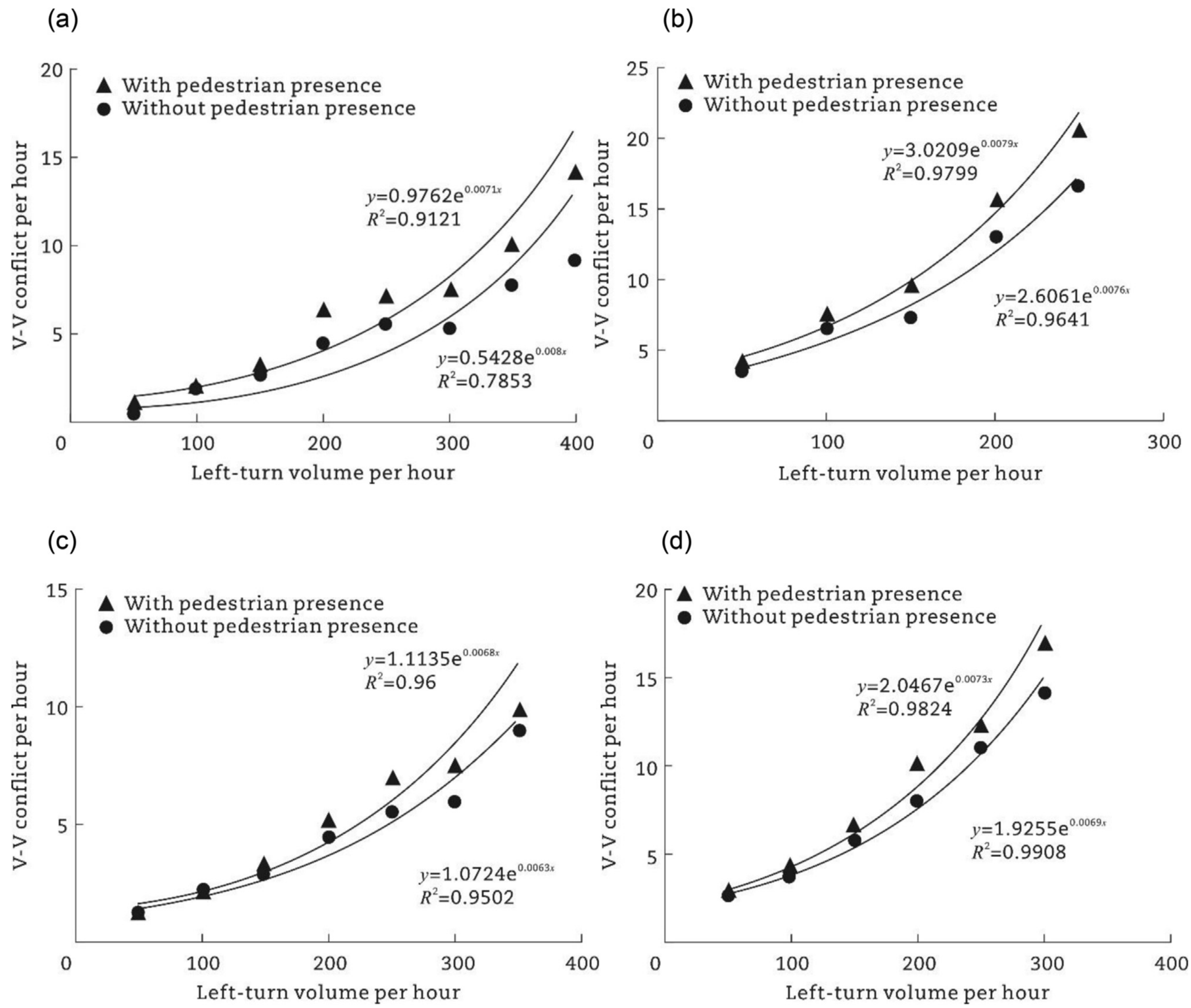

Fig. 3 – Effect of left-turn volume on V-V conflicts. (a) One opposing-through lane and 500 vehs/h opposing-through volume. (b) One opposing-through lane and 750 vehs/h opposing-through volume. (c) Two opposing-through lanes and 750 vehs/h opposing-through volume. (d) Two opposing-through lanes and 1000 vehs/h opposing-through volume.

with fewer left-turning vehicles, as higher opposing-through traffic volume provided a smaller number of gaps for left-turn movements and created more V-V conflicts. Approximately every 145 left-turning vehicles created one V-V conflict for 500 vehs/h opposing-through volume in one opposing-through lane due to pedestrian presence. When the opposing-through volume increased to 750 vehs/h in one opposing-through lane, every 92 left-turning volume (approximately 37% less left-turn volume compared to 500 vehs/h opposing-through volume) produced one V-V conflict due to the pedestrian presence (Fig. 4). A similar pattern was observed for two opposing-through lane scenarios (Fig. 5).

4.1.3. *Effect of pedestrian volume on V-V conflicts*

Fig. 6 summarizes the influence of pedestrian presence on V-V conflict counts. For one opposing-through lane with 500 vehs/h opposing-through volume, 364 vehs/h left-turn volume resulted in 10 V-V conflicts, where 327 vehs/h left-turn volume resulted in the same number of V-V conflicts in pedestrian presence. Pedestrian presence in the crosswalks caused a lower number of left-turning vehicles to create the same number of V-V conflicts in permissive left-turn phasing.

In the simulation scenarios presented earlier, a pedestrian volume of 250 per hour was used in the V-V conflict estimation. Fig. 7 illustrates the effect of the change in pedestrian volume on the left-turn vehicle involved V-V conflicts. A left-turn volume of 100 vehs/h, the opposing-through volume of 1000 vehs/h in two opposing-through lanes was selected for this analysis. The higher pedestrian volume produced a higher number of V-V conflicts and showed a positive relationship. With higher pedestrian volume, left-turning vehicles encountered more difficulty in finding a gap considering opposing-through vehicles and a higher number of pedestrian movements simultaneously.

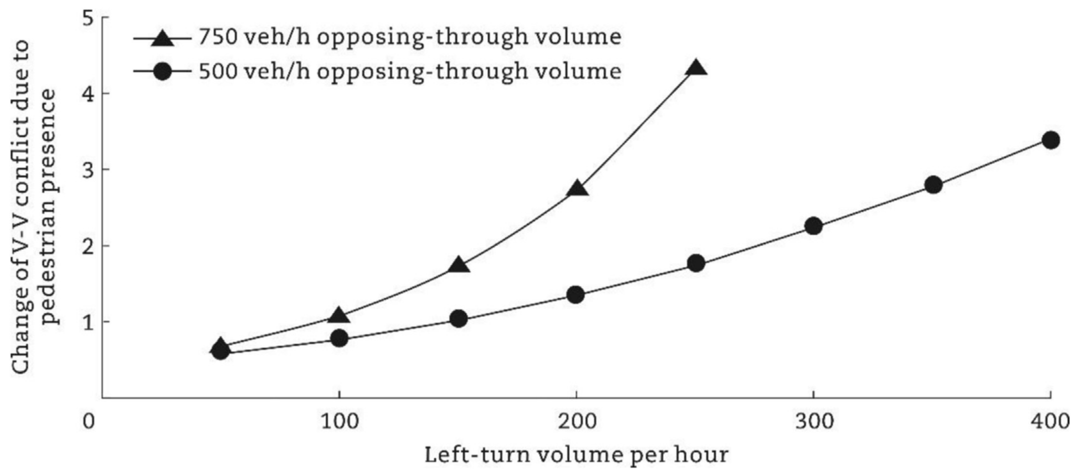

Fig. 4 – Effect of left-turn volume on V-V conflicts for one opposing-through lane due to the pedestrian presence.

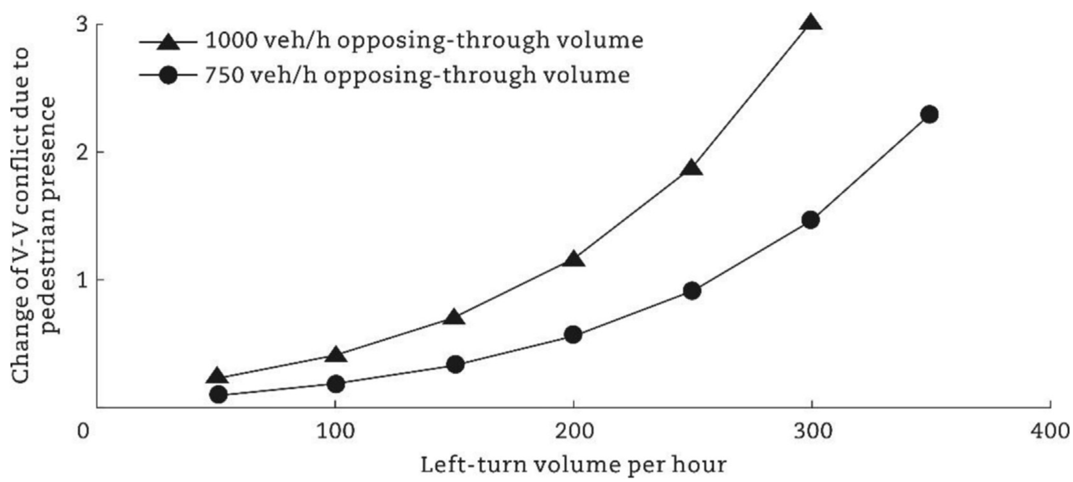

Fig. 5 – Effect of left-turn volume on V-V conflicts for two opposing-through lanes due to the pedestrian presence.

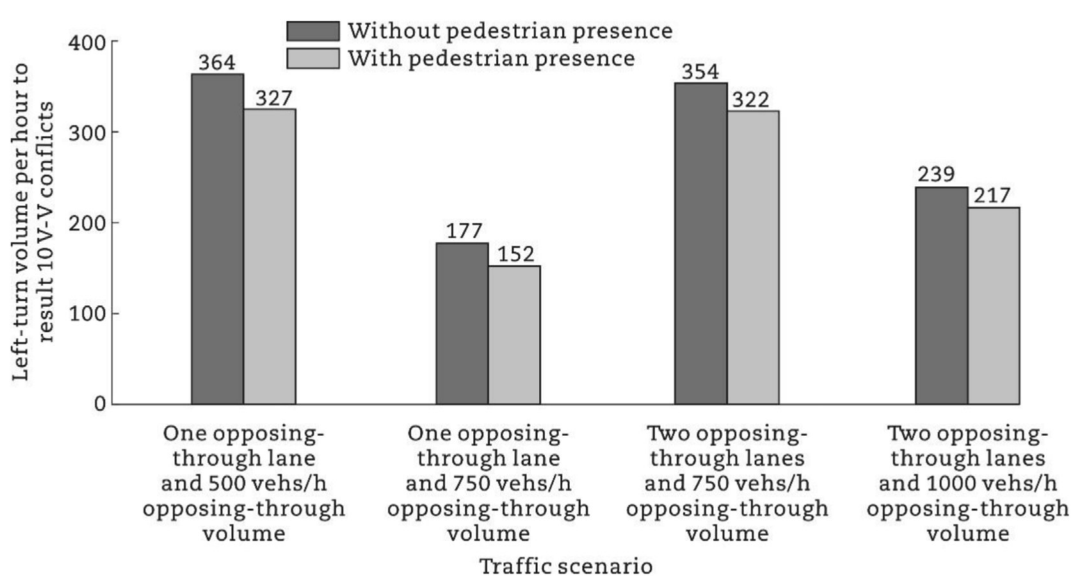

Fig. 6 – Influence of pedestrian presence on the V-V conflicts.

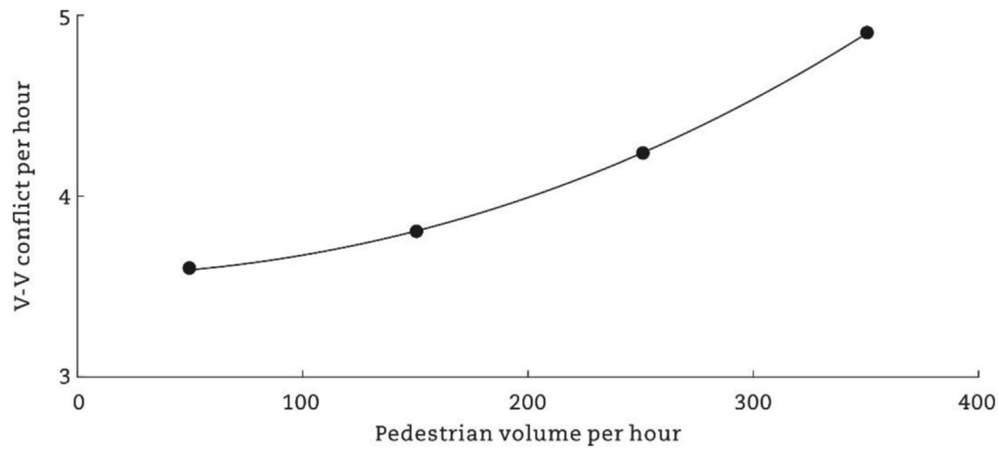

Fig. 7 – Effect of pedestrian volume on V-V conflicts.

4.2. V-P conflict estimation

As injury severity of pedestrians in pedestrian-vehicle crashes was much higher than vehicle occupants' injury severity, consideration of vehicle-pedestrian (V-P) conflicts in left-turn phasing decisions is important. This section presents V-P conflict estimation considering the different levels of pedestrian activities at signalized intersections.

In this research, two pedestrian volume levels (63 pedestrians per hour and 250 pedestrians per hour) were considered (Bonneson et al., 2012). Based on V-P conflict estimation, the left-turn vehicle involved V-P conflicts increased with higher pedestrian volume irrespective of opposing-through volume, left-turn volume, and the number of opposing-through lanes. For example, in 500 vehs/h opposing-through traffic volume, 100 left-turn volume, and one opposing-through lane scenario, V-P conflicts increased from 3.6 conflicts per hour to 9.9 conflicts per hour for the increasing pedestrian volume from 63 pedestrians per hour to 250 pedestrians per hour. For the V-P conflict estimation, the thresholds of maximum time to collision (TTC) and post encroachment time (PET) were 2.7 and 8 s, respectively. Thus, a V-P conflict was estimated when the trajectories of the left-turn vehicle and pedestrian were less than 2.7 s from a collision point with the assumption of vehicle and pedestrian maintaining their trajectories and speeds. In terms of PET, a V-P conflict occurred when the first road user (i.e., a left-turn vehicle or a pedestrian) crossed a conflict point, and the second road user (i.e., a pedestrian or a left-turn vehicle) arrived at the same conflict in less than 8 s.

Besides, the left-turn vehicle-involved V-P conflicts increased with higher left-turn volume irrespective of pedestrian volume, number of opposing-through lanes, and opposing-through volume. Higher left-turn volume in permissive left-turn phasing increased the traffic conflict risk. The potential reason could be that the left-turn vehicles needed to find an acceptable gap between both opposing through vehicles and pedestrians on the crosswalk. The higher left-turn volume required vehicles to complete left-turning maneuvers with shorter gaps, and led to a higher number of traffic conflicts.

Table 2 presents the estimation of V-P conflicts, V-V conflicts, and total traffic conflicts for scenarios with 250 pedestrians per hour. The results showed that V-P conflicts contributed less to the total number of traffic conflicts at higher opposing-through lane volumes. For example, in two opposing-through lanes and 750 vehs/h opposing-through volume, V-P conflicts were 83% of overall intersection traffic conflicts for a left-turn volume of 100 vehs/h. When opposing-through traffic volume was increased (i.e., 1000 vehs/h), V-P conflicts represented 70% in total traffic conflicts (Fig. 8). At a higher opposing-through volume, the chance of traffic conflict between left-turning vehicles and opposing-through vehicles was higher compared to traffic conflict between left-turning vehicles and pedestrians, and at a lower opposing-through volume, left-turning vehicles got more gaps in opposing-through traffic, and the chance of encountering pedestrians on the cross walks was higher. A similar traffic conflict pattern was observed for one opposing-through lane scenarios (Table 2).

The left-turn vehicle involved V-P conflicts creates safety risks and reduces the left-turn vehicle processing capacity in a permissive left-turn phasing. For example, in two opposing-through lanes, 1000 vehs/h opposing-through volume, and 250 pedestrians per hour scenario, 272 left-turning vehicles resulted in 15 V-V conflicts without taking V-P conflicts into account (Fig. 9). In contrast, if V-P conflicts were taken into consideration, 118 left-turning vehicles generated the same number of traffic conflicts (i.e., V-V and V-P conflicts) (Fig. 9). This indicates that an intersection can serve approximately 57% less left-turning vehicles with pedestrian presence in a permissive left-turn phasing to maintain the same level of safety (assuming V-V and V-P conflicts have the same level of crash severity).

5. Discussion and conclusion

Safe and efficient movement of heterogeneous traffic (e.g., vehicular traffic, pedestrian, bicycle) at signalized intersections have been a major challenge for traffic engineers to balance safety and operational performance. This study investigated the effects of pedestrian presence on permissive left-turn phasing performance by estimating pedestrian-influenced V-V and pedestrian-involved V-P conflicts by

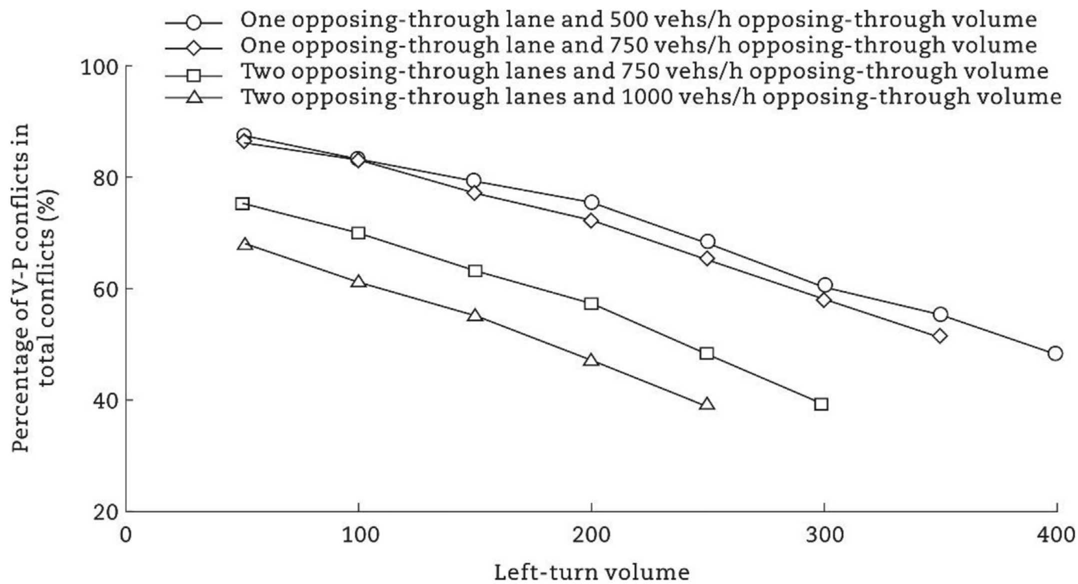

Fig. 8 – Change in percentage of V-P conflicts in total traffic conflicts with left-turn volume for different opposing-through lane and opposing-through traffic scenarios.

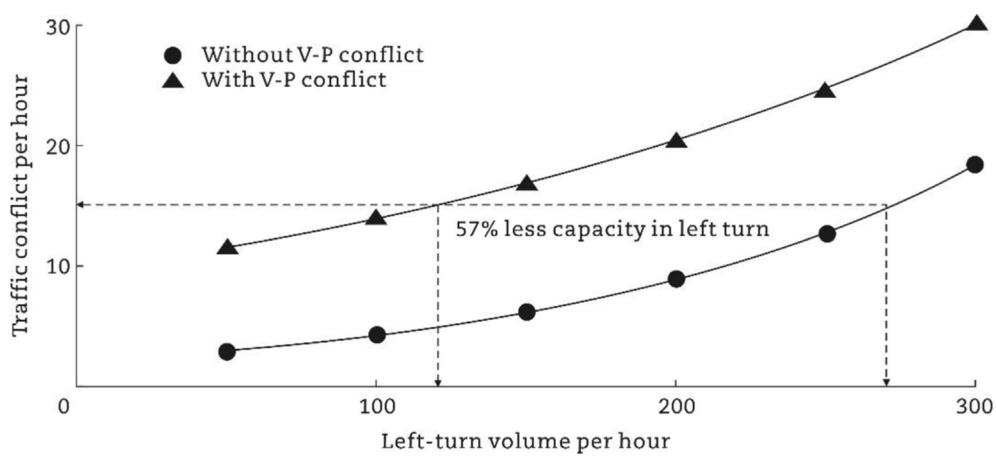

Fig. 9 – Effect of V-P conflicts on the total number of traffic conflicts (two opposing-through lanes, 1000 opposing-through volume and 250 pedestrian volume per hour).

conducting simulation-based research. The left-turn phasing selection strategies recommended in past studies have not explicitly included the impact of pedestrian presence on V-V and V-P conflicts. This study quantified the safety impact of pedestrian presence at a signalized intersection with permissive left-turn phasing to ensure the safe movement of vehicles and pedestrians. In permissive left-turn phasing, two opposing-through traffics were provided green concurrently, where left-turn movements yielded to opposing through traffics and pedestrians, and completed the movements depending on the gap availability. As presented in Table 2, pedestrian presence increased left-turning vehicle involved V-V conflicts with a permissive left-turn phasing. As left-turning vehicles need to yield to both opposing-through vehicles and pedestrians in permissive left-turn phasing, crash risks with both opposing-through vehicles and pedestrians increased. A similar observation was reported in Bonneson et al. (2012) and Stamatiadis et al. (2016). A higher volume of pedestrians increased the difficulties of left-turning maneuvers in permissive left-turn phasing (Qi and Guoguo, 2017), as left-turning vehicles need to identify gaps in opposing-through traffic and pedestrians on the crosswalks.

Based on the current study's findings, the number of left-turning vehicle-involved V-P conflicts in permissive left-turn phasing was substantial. The left-turn vehicle involved V-P conflict decreased with the increase of opposing-through traffic. The V-P conflicts had less influence on the total number of traffic conflicts in higher opposing-through volume scenarios. Left-turning vehicles with longer wait times to find a gap in higher opposing-through traffic allowed the majority of the pedestrians to cross the intersection, which reduced V-P conflicts. This finding is consistent with Lord et al. (1998).

Moreover, drivers' visual searches are usually focused more on the right side than the left side (Lord et al., 1998), which also could increase the occurrence of the left-turn vehicle involved conflicts in the real world. Overall, pedestrian presence reduces the left-turn vehicle processing capacity in permissive left-turn phasing. Thus, it is recommended to reduce the left-turn volume threshold in left-turn phasing warrants in providing some form of left-turn protection (i.e., protected-permissive or protected left-turn phasing) to maintain the same level of intersection safety with pedestrian presence compared to the no-pedestrian scenario.

Agent and Deen (1978) recommended providing some form of protection in left-turn phasing for the number of conflicts ten or more. Based on the study's findings, 250 pedestrians per hour resulted in more than ten total traffic conflicts in all left-turn volume scenarios. Thus, intersection with medium pedestrian activity requires some form of protected left-turn phasing (i.e., protected or protected-permissive) to reduce pedestrian-related safety risk at intersections irrespective of left-turn traffic volume.

This study evaluated permissive left-turn phasing by developing simulation scenarios considering some combinations of opposing-through volume, left-turn volume, number of opposing-through lanes, and pedestrian volume and did not consider the effect of cross-street traffic volume. Additional combinations of simulation scenarios with diverse intersection geometric features, traffic composition, pedestrian volume, and signal timing, including cross-street traffic volume, could be used to develop a comprehensive guide for left-turn phasing decision making. Also, to improve the reliability of simulation-based results, validation of the simulated traffic conflict estimates with real-world traffic conflict counts should be investigated in future research.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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