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Safety Evaluation of Unconventional Outside Left-Turn Lane Using Automated Traffic Conflict Techniques

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Abstract: The objective of this study is to evaluate the safety impacts of unconventional outside left-turn lane at signalized intersections. New designed unconventional outside left-turn lane are increasingly used at signalized intersections in urban areas in China. The unconventional outside left-turn lane design allows an exclusive left-turn lane to be located to the right of through lanes to improve the efficiency and increase the capacity of left-turn movements. However, the design also raises some concerns regarding potential negative safety impacts. The evaluation is conducted using an automated video-based traffic conflict technique. The traffic conflicts approach provides better understanding of collision contributing factors and the failure mechanism that leads to road collisions. Traffic conflicts are automatically detected and time to collision (TTC) is calculated based on the analysis of the vehicles' positions in space and time. Video data is collected from a signalized intersection in Nanjing, China, where both traditional inside and unconventional outside left-turn lanes are installed on two intersection approaches. The other two approaches have only inside left-turn lanes. The study compared frequency and severity of conflict for left-turning vehicles as well as the percentage of vehicles involved in conflicts from the inside and outside left-turn lanes. The results show that the intersection approaches with outside left-turn lanes had considerably more conflicts compared to approaches without outside left-turn lanes. As well, the approaches with outside left-turn lanes had significantly higher conflict severity than the approaches without outside left-turn lanes. As such, it is recommended that the trade-off between the improved mobility and negative safety impact of outside left-turn lanes be carefully considered before recommending their installation.

Keywords: safety analysis; traffic conflicts; computer vision; outside left-turn lanes

1. Introduction

China has seen significant increase in private vehicle ownership over the past two decades which has resulted in high levels of traffic congestion. In many large cities in China, transportation engineers are being challenged by the ever-increasing traffic demand and the corresponding congestion at at-grade signalized intersections. One of the most important factors that impact the performance of at-grade signalized intersections is the presence of heavy left-turn movements (Tabernerero and Sayed 2006). Therefore, several measures to improve the performance of intersections with heavy left-turn movements have been investigated, some of which have been unconventional schemes. Traditional measures to improve the performance of intersections with heavy left-turn movements include signal timing optimization, adding exclusive left-turn lanes, and signal coordination. However, in many cities, these traditional measures have been exhausted and are no longer able to alleviate congestion at signalized intersections (Hummer 1998). Other solutions such as grade separation are costly and aesthetically unpleasing (Goldblatt et al. 1994). As such, the use of unconventional intersection designs has been advocated as a solution to improve traffic operations at at-grade signalized intersections (Autey and Sayed 2013; El Esawey and Sayed 2013). Several unconventional measures for treating left-turns have been developed including the Median U-turn, the Crossover Displaced Left-Turn (XDL), and the Upstream Signalized Crossover (USC) schemes (Liu et al. 2007; El Esawey and Sayed 2013). In China, a new design, the unconventional outside left-turn lane, has been progressively used at signalized intersections in many urban areas. The unconventional outside left-turn lane design allows an exclusive left-turn lane to be located to the right of through lanes, which improves the efficiency of left-turn vehicles (Figure 1). Protected left-turn phases are also provided to accommodate the left-turn movements at these signalized intersections.

The unconventional outside left-turn lane design is often used on major urban arterials in several Chinese cities under the following conditions: (a) when there is a bus station located within the upstream function area of a signalized intersection and a large number of buses need to make left turns at the intersection; (b) when a major right-side street is located close to an intersection and a high number of vehicles from the driveway need to make left turns at the intersection; and (c) when an urban interchange ramp terminal is located within the upstream functional area of a signalized intersection and a large number of vehicles from the ramp terminal need to make left turns at the intersection.

There are two main advantages associated with the outside left-turn lane: (a) it provides larger left-turn radius for left-turn movements of heavy vehicles and buses, and (b) left-turning vehicles coming from upstream driveways or bus stations do not have to make lane changes to the most inside lane to make left turns. As such, it is supposed to simplify driving tasks and to reduce conflict points on approaches to signalized intersections. However, the use of unconventional outside left-turn lane has also raised some safety issues. There are two main shortcomings: (a) vehicles in through traffic may mistakenly enter the outside left-turn lane and will cause safety problems at signalized intersections when they are trying to merge back to through traffic; and (b) the presence of two left-turn traffic streams at one approach may result in high number of conflicts inside the signalized intersection.

Therefore, there is an important need to conduct a safety evaluation for this unconventional design. Traditionally, safety evaluations were mainly based on collision data. However, reliable collision data may not always be available in many jurisdictions. This is particularly true for China, where the reliability and availability of crash data are often problematic. Additionally, an adequate number of collisions are required to occur and be recorded over an adequately long period in order to conduct a sound safety evaluation. The use of

traffic conflicts for safety evaluation has been gaining acceptance as a surrogate for collision data analysis (Amundsen and Hydén 1977; Sayed and Zein 1999; Tarko et al. 2009). The traffic conflicts approach provides better understanding of collision contributing factors and the failure mechanism that leads to road collisions. As well, traffic conflicts are more frequent than road collisions and are of marginal social cost.

The objective of this study is to evaluate the safety impacts of unconventional outside left-turn lane at signalized intersections. The evaluation was conducted using a video-based automated traffic conflict technique. Video data were collected from a signalized intersection in Nanjing, China, where both traditional inside and unconventional outside left-turn lanes are present. The study compared the severity and frequency of conflict for left-turning vehicles from inside and outside left-turn lanes.

2. Previous Work

2.1 Unconventional outside left-turn lane

Although the use of outside left-turn lanes has been recently increasing in larger cities in China, little information and documentation of their use are available about this unconventional design. A review of the literatures regarding the outside left-turn lane design found only a few studies related to the operation evaluation and drivers' selection of the unconventional outside left-turn lanes. No studies were found evaluating the safety of outside left-turn lanes. A recent study by Liu et al. (Liu et al. 2011) compared the left-turning speed and saturation flow rate from the outside left-turn lane and the inside left-turn lane. It was reported that the outside left-turn lane provided a significantly higher speed of passenger cars and heavy vehicles than that of the inside left-turn lane. However, the higher speeds did not result in higher left-turn lane capacity. It was

found that the left-turn saturation flow rate of the outside left-turn lane was slightly lower, but generally comparable to that of the inside left-turn lane.

In a subsequent study conducted by Liu et al. (Liu et al. 2013), the factors affecting driver's selection of the outside left-turn lanes at the signalized intersections were identified using a binary logit model. The results showed that the likelihood of drivers choosing the outside left-turn lane would increase with an increase in traffic volume on the major road and the queue length in the inside left-turn lane; while it would decrease with an increase in the distance from the upstream driveway to the signalized intersection. Furthermore, heavy vehicle drivers and those from the upstream driveway were more likely to select the outside left-turn lanes. Liu et al. (Liu et al. 2013) also developed a procedure to determine if outside left-turn lanes were needed given traffic conditions and geometric characteristics of a signalized intersection.

2.2 Conflict analysis

The traffic conflict technique (TCT) is probably the most developed surrogate safety assessment method. The objective of TCT is to identify the frequency and severity of near misses which enables the assessment of the safety performance of a road facility without waiting for collisions to occur. The traffic conflict technique was first developed by Perkins and Harris (Perkins and Harris 1968). The definition of traffic conflicts has since been revised with an accepted definition proposed by Amundsen and Hydén (Amundsen and Hydén 1977) as “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged”.

Various conflict indicators have been developed to measure the severity of a traffic conflict by quantifying the spatial and temporal proximity of road users involved in the interaction (Brown 1994; Tarko et al. 2009). The main advantage of conflict indicators is their ability to capture the severity of an interaction in an objective and quantitative way (Autey et al.

2012). A commonly used traffic conflict indicator is the time-to-collision (TTC) defined as “...the time that remains until a collision between two vehicles would have occurred if the collision course and speed difference are maintained” (Hayward 1972).

The traffic conflict technique involves the observation, recording, and evaluation of the frequency and severity of traffic conflicts at a location. The observation was traditionally conducted manually by a team of trained observers. However, manual conflict observation has been challenged by several issues, such as cost of training observers and reliability and consistency of the result (Sayed et al. 1994). Recently, video-based automated conflicts analysis was advocated as an alternative conflicts data collection procedure (Saunier et al. 2010). The automated approach provides a more practical and efficient way to capture, store and analyze elements of the traffic information. It provides a guideline for the objective measurements of conflicts indicators (Laureshyn et al. 2009; Sayed et al. 2012). As well, it overcomes the shortcomings of field-based methods which are unreliable, time consuming and costly. Furthermore, video data represents a permanent record of the traffic events analyzed and can be reviewed and validated. The application of video-based automated conflict analysis was demonstrated to be very useful in conducting various safety analysis such as before-after safety evaluation (Autey et al. 2012; Tageldin et al. 2014), bicycle related data collection and safety diagnosis (Zaki et al. 2013; Sayed et al. 2013), and pedestrian related safety analysis (Ismail et al. 2010; Zaki et al. 2013).

3. Study Location

Video data were collected from a signalized intersection in Nanjing, China. Nanjing is the capital city of the Jiangsu province in the south area of China. The number of motor vehicles in Nanjing reached two million by the end of 2014. The selected signalized intersection was located on

Jiangdong Road with Aoti Street. Jiangdong Road is a north-south eight-lane divided highway serving as a major corridor in the west area of Nanjing city. The average annual daily traffic on Jiangdong Road exceeded 30,000 vehicles per day in the year 2009 (Liu et al. 2013). Aoti Street is a west-east minor street. Both traditional inside and unconventional outside left-turn lanes are installed at the southbound and northbound approaches of the signalized intersection, while only the traditional inside left-turn lanes are installed at the westbound and eastbound approaches of the signalized intersection (see Figure 1). Protected left-turn phases are also provided to accommodate the left-turn movements at the signalized intersections. The unconventional left-turn lanes were installed at the intersection in 2005 with the aim of improving the mobility of left-turn traffic flow. Figure 1 also shows the six left turn lanes numbered as well as examples of potential conflicts. Field observation showed that the left-turn movements at the southbound and westbound approaches lead to four main types of traffic conflicts related to the outside left-turn lanes. The rear-end conflicts take place at both of the outside and inside left-turn lanes (Figure 1 (a)). The left-turn movements from the outside and inside left-turn lanes at the same approach can result in sideswipe conflicts and merging conflicts (Figure 1 (b) and (c)). The left-turn movements from the outside and inside left-turn lanes at the opposite approaches can lead to head-on conflicts (Figure 1 (d)).

Video recording of the location was done for 2.5 hours on May 12, 2011. The video frame rate is 30 frames/sec. The camera was placed on top of a roadside building to achieve adequate viewing height. Field data collection was conducted during a weekday morning peak period under sunny weather. The aim is to eliminate the impact of weather factor, such as rainy, and fog and haze, on the traffic flow.

4. Computer Video Analysis

The computer video analysis system used in the study was developed at the University of British Columbia (Saunier and Sayed 2006; Saunier et al. 2010), which includes two modules as shown in Figure 2. The computer video analysis system can automatically detect, classify, and track road users and interpret their movements. The main steps of the analysis are summarized below.

Camera calibration: The outcome of the camera calibration is a mapping between the three dimensional real world and the two dimensional image space (Figure 3). Details of the mixed-feature camera calibration approach can be found in Ismail et al. (Ismail et al. 2013). The accuracy of the estimated parameters was tested by use of a set of line segments of true length estimated from the orthographic image. This set of observations was not used in the calibration. The calibration error is represented by the discrepancy between the calculated and the annotated segment lengths normalized by the length of each segment. The accuracy of the final estimates was satisfactory, and no further error in safety analysis was attributed to inaccurate estimated camera parameters.

Features tracking: In this step distinguishable features such as points or lines on the moving objects are tracked (Figure 4 (a)). The automated video analysis relies on computer algorithms to differentiate between features of road users and features that are part of the environment. Features that remain stationary are assumed to belong to the environment and are discarded and not tracked. Features on moving objects are identified and tracked using an implementation of Kanade-Lucas-Tomasi (KLT) feature tracker algorithm (Saunier and Sayed 2006). The KLT algorithm has the advantages of consistently tracking objects under different temporal and light conditions.

Features grouping: Moving objects may have multiple features. Feature grouping is carried out using cues such as spatial proximity and common motion of features to decide common features of each unique road-user. Features with motion vectors differing by more than a

specified threshold are assumed to not belong to the same road-user object and are not grouped, regardless of their spatial proximity. Figure 4 (b) shows moving objects generated by grouping of features. The tracking accuracy for road users was validated by Saunier and Sayed (Saunier and Sayed 2006) and Ismail et al. (Ismail et al. 2010) with accuracy between 90% and 94.4% on different sets of sequences. This accuracy is considered reliable and has little impact on the accuracy of the calculation of conflict indicators.

Objects classification: The object trajectories hold features that reveal the structure of the traffic movements and provide important clues to the characteristics of the road users. Basically, the road user classification method is based on three indicators, namely, movement patterns, maximum speed, and road user size. The cyclist has a special movement pattern which is governed by its pedaling process compared to vehicles, leading to significant periodic variations in the speed profile. Vehicle movement patterns are primarily composed of linear segments corresponding to different speeds chosen throughout the trajectories. This oscillatory behavior associated with cyclist while lacking in vehicles, provides a classification basis through recognizing the class of the road-user (Zaki and Sayed 2013). Subsequently, the maximum speed and road-user size are used as complimentary cues to enhance the classification result. The road user classification has been investigated by Zaki and Sayed (Zaki and Sayed 2013) with accuracy above 90%. Figure 4 (c) shows different objects of vehicle (yellow box) and bike (white box).

Event generation: The generation of interactions between objects can be performed based on the trajectories extracted from the computer vision module. The trajectory of a moving object is matched to individual prototypes (See Figure 4 (d) for illustrative prototypes) from the full set of prototypes using a Longest Common Sub Sequence (LCSS) algorithm (Saunier et al. 2010).

LCSS Algorithm: Let τ be a finite set of road user tracks $\{T_i \mid i \in 1, \dots, N(\tau)\}$, with $N(\cdot)$ is a measure on a finite set that returns the number of the set elements. Let each road user track T_i be composed of a set of coordinate tuples such that $T_i = \{t_{ik} \mid k \in 1, \dots, N(T_i)\}$ and each coordinate tuple t_{ik} be defined as $t_{ik} = (x_{ik}, y_{ik})$. Two points t_{ik} and t_{jl} to be matched if $\max\{|x_{ik} - x_{jl}|, |y_{ik} - y_{jl}|\} < \varepsilon$, where ε is some spatial proximity bound called matching distance. The LCSS of two road user tracks T_i and T_j , $LCSS_\varepsilon(T_i, T_j)$ of respective lengths m and n , is defined recursively as follows:

- 0 if $m = 0$ or $n = 0$,
- $1 + LCSS_\varepsilon(Head(T_i), Head(T_j))$, if the points t_{in} and t_{jm} match,
- $\max\{LCSS_\varepsilon(Head(T_i), T_j), LCSS_\varepsilon(T_i, Head(T_j))\}$, otherwise

where $Head(T_i) = \{t_{ik} \mid k \in 1, \dots, N(T_i) - 1\}$ and the definition is identical for all tracks other than i .

The LCSS algorithm compares the tracks against a set of templates (prototypes) of expected road-user behavior at the given intersection. The computer vision system described earlier has a built-in procedure to extract a set of common tracks of road-users. However, more often the set of generated prototypes do not provide adequate representative of the road-user tracks. This is primary depending on the footage length used in the prototype generation as well as the distinct tracks found in the footage. An iterative procedure may be implemented to ensure certain behavior coverage. An alternative procedure, would be synthesize prototypes to cover certain behavior that deemed hard to extract from the footage. An algorithm is developed to generate prototypes representing behavior at the designated area. An object will therefore be matched with more than one prototype with a probability weighting determined from the LCSS matching distance. The prototypes provide a set of predicted future positions with associated probabilities of occurrence. Conflicts between road users can then be determined by evaluating if

any of these future positions coincide spatially and temporally with other road users. Figure 4 (e) shows an example of rear-end conflict event between two left-turn vehicles.

Conflict indicator filtering: This step is to analyze the severity of the identified conflict events using conflict indicators. The TTC indicator is used in this study as a measure of conflict severity. The TTC is defined as the time until a collision will occur if the two conflicting vehicles were to continue on the same path at their current speed as shown in Figure 5 (a) and Figure 5 (b). Therefore, TTC is continually calculated between conflicting road users, and thus a set of values is returned for each conflict according to the conflicting vehicles instantaneous speeds. The minimum TTC is then extracted from this set to represent the maximum severity of each interaction (Sayed and Zein 1999). To reduce the noise influence on the TTC calculation, the following steps were conducted. First, a low pass filtering is applied to smooth out the trajectories and eliminate tracking noise. Second, the choice of the minimum TTC was based on averaging over few frames, rather than just selecting a global minimal value. Typically, the most severe value is used to represent the overall severity of a traffic event. In this study, only traffic events with associated minimum TTC of fewer than 4 sec were considered for evaluation. This threshold was suggested by Horst (Horst 1991) to distinguish between safe and uncomfortable situations on the roads and it was supported by Farber (Farber 1991) and Osama et al. (Osama et al. 2015).

A significant portion of the study focuses on validating the quality of the automated event detection. First, video data were manually reviewed by an expert to annotate possible conflicts between the road-users using the definition given in this paper and the US FHWA observer's guide (Parker and Zegeer 1989). While manual conflict analyses suffer from the shortfalls previously described, the length of this video allowed for an extremely vigilant review. Each conflict was described by the manual reviewer in detail so that it could later be compared to the

automatically tracked events. Validation was performed on a subset of 50 events selected from the interactions database and results showed a 95.6% accuracy of the automated TTC index estimation. The scope of the validation was limited to a comparison between an event's minimum TTC and a corresponding manually calculated TTC. Each conflict was also assigned a severity rating by the reviewer. Though this measure was highly subjective, it was deemed to have sufficient merit as the engineer had experience in such reviews. The results demonstrated the accuracy of the automated TTC index estimation.

5. Summary of Findings

5.1 Overview of the whole intersection

5.1.1 Conflicts spatial distribution analysis

The conflict analysis includes identifying conflict frequency, severity and location (conflict points). Five types of conflicts are considered of importance for the safety diagnosis of the intersection: rear-end conflicts, merging conflicts, sideswipe conflicts, head-on conflicts and crossing conflicts¹. Traffic conflicts between vehicles and between vehicles and bikes² at the whole intersection were automatically identified. In total, 5893 cars and 2462 bikes were tracked. The density of traffic conflicts per unit area was also measured. Spatial distribution of the vehicle-vehicle conflicts and vehicle-bike conflicts by heat mapping is shown in Figure 6. Figure 6 (a) shows that vehicle-vehicle conflicts covered the whole intersection but were concentrated along Jiangdong road. This may be caused by the high traffic volume and the presence of two left-turn lanes per approach on Jiangdong road. The highest conflict density is found at the inner intersection caused by the left-turn movements, as well as the southbound exit resulting from the

¹ A crossing conflict refers to conflicts between a through vehicle and a vehicle crossing from street on the left or right.

² All types of bikes are considered in the analysis including motorcycles, e-bikes and bicycles.

high volume of north-south direction. Figure 6 (b) shows that vehicle-bike conflicts take place anywhere at the intersection. An observation from the video reveals that the violation behavior of bikes in red light running, occasional reverse driving, waiting at violating positions, and bikes moving in motor-vehicle lanes result in the vehicle-bike conflicts.

5.1.2 Conflicts frequency analysis

Table 1 shows a breakdown of the frequency (per hour) of vehicle-vehicle conflicts and vehicle-bike conflicts according to each TTC value. It shows that a high percentage of conflicts have TTC values fewer than 2 seconds for both the vehicle-vehicle conflicts and vehicle-bikes conflicts, which is considered as high severity conflicts.

Figure 7 shows the frequency distributions of conflicts at the intersections for both vehicle-vehicle conflicts and vehicle-bike conflicts. Rear-end, merging, sideswipe, head-on, crossing, and total conflicts are displayed separately. The distributions are plotted over a range of TTC values from 0 to 4 sec. The figures show that the frequency of vehicle-vehicle conflicts is higher than that of vehicle-bike conflict for all types of conflicts. The only exception is with the crossing conflict where the conflict frequency curves for vehicle-vehicle conflicts and vehicle-bike conflicts overlap.

5.1.3 Conflicts severity analysis

To further evaluate the conflict severity, the minimum TTC of each event can be mapped to a severity index using equation (1) (Saunier et al. 2010; Autey et al. 2012).

$$SI = \exp\left(-\frac{TTC^2}{2PRT^2}\right) \quad (1)$$

where SI is the severity index and PRT is the perception and braking reaction time, which is assumed to be 2.5 sec (Autey et al. 2012). The severity index is a unit-less measure of severity that ranges from 0 to 1, with 0 being uninterrupted passages.

Table 2 shows a breakdown of the number of vehicle-vehicle conflicts and vehicle-bike conflicts by severity. Figure 8 shows the severity distributions of conflicts at the intersections for both vehicle-vehicle conflicts and vehicle-bike conflicts. Rear-end, merging, sideswipe, head-on, crossing, and total conflicts are displayed separately. The conflicts frequency is plotted over a range of severity values from 0 to 1 sec. The results show that considerable numbers of conflicts have high severity index ($SI < 0.4$) for both vehicle-vehicle conflicts (43%) and vehicle-bike conflicts (40%). Similar as the result of conflict frequency distribution, it is found that the severity index of vehicle-vehicle conflicts is higher than that of vehicle-bike conflicts for all types of conflict except for the crossing conflict which has similar severity between the conflicts of vehicle-vehicle and vehicle-bike.

5.2 Comparison of left-turn conflicts from different left-turn lanes

Due to the small sample size of the vehicle-bike conflicts for left-turn movements (12 events per hour), the following sections focus on vehicle-vehicle conflicts. The conflict frequency between left-turn lanes at southbound (SB) and northbound (NB) approaches is shown in table 3. It should be noticed from table 3 that there is a considerable number of head-on conflicts caused by the outside left-turn lane (L1-L3, L1-L4, and L2-L4, See Figure 1 for Lane annotations). As the head-on conflicts are considered as the most severe conflicts, the result indicates that the outside left-turn lanes can have serious safety impacts on the intersection.

The conflict frequency (per hour) and percentage of vehicles involved in conflicts of each left-turn lane is shown in Figure 9. The percentage of vehicles involved in conflicts of each left-turn lane is calculated using Equation (2).

$$\text{Percentage of vehicles per lane involved in conflicts} = \frac{C_i}{V_i} \times 100 \quad (2)$$

where C_i represents the conflicts frequency (per hour) of left-turn lane i ; V_i represent the hourly traffic volume of left-turn lane i .

As shown in Figure 9, lane 2 (inside left-turn lane) is found to have the highest conflict frequency, followed by lane 1 (outside left-turn lane). Lane 3 (inside left-turn lane) is found to have the highest percentage of vehicles involved in conflicts, followed by lane 4 (outside left-turn lane). However, approximately 35% of the conflicts at lane 2 are caused by the outside left-turn lanes, and over 60% of the conflicts at lane 3 are caused by the outside left-turn lanes as shown in table 4. The results suggest that the outside left-turn lane not only contributed to conflicts within the lane itself, but also contributed to conflicts with the other left-turn lanes. The results also show that the inside left-turn lanes at the eastbound (EB) and westbound (WB) approaches where only inside left-turn lanes were installed have the smallest conflict rate compared to other left-turn lanes at southbound and northbound approaches.

5.3 Comparison of left-turn conflicts from different approaches

To further illustrate the safety impacts of outside left-turn lane, the conflicts frequency and rate between the four approaches were compared. As shown in Figure 10, the conflict frequency at SB approach is maximum with a very high value of 98 conflicts per hour compared to other approaches. This is caused by the high left-turn traffic volume from southbound approach. However, NB approach is found to have the highest percentage of vehicles involved in conflicts with the value of 75%. The low left-turn traffic volume from northbound approach contributes to the high percentage of vehicles involved in conflicts. The lower conflicts frequency and percentage of vehicle involved are found at EB approach and at WB approach. In addition, the outside left-turn lane provides plenty of merging conflicts and sideswipe conflicts with the inside left-turn lane at SB approach and NB approach.

To further clarify the comparison, the left-turn conflicts at approaches with both outside and inside left-turn lanes and at approaches with only inside left-turn lanes are aggregated and compared. As shown in Figure 11, both the conflict frequency and percentage of vehicles involved in conflicts at SB and NB approaches are significantly higher than that at EB and WB approaches. The results indicate that approaches with outside left-turn lanes have considerably more conflicts than approaches with only inside left-turn lanes at signalized intersections.

The frequency of conflicts, normalized to exposure, is plotted over a range of severity values as shown in Figure 12. The results reveal a higher severity index at the approaches with outside left-turn lanes. A statistical *t*-test was applied to identify if the difference between severity indices at SB and NB approaches and at EB and WB approaches is statistically significant. Result of the *t*-test shows that the severity index of conflicts related to outside left-turn lanes is significantly higher than that related to inside left-turn lanes with a 90% level of confidence (0.03 & 0.011, $p = 0.064$).

The spatial distribution heat maps for the traffic conflicts from different left-turn lanes are shown in Figure 13. The outside left-turn lane approaches have higher conflict density compared to the non-outside left-turn lane approaches. Specifically, the conflict density for L1 and L2 are higher compared to other left-turn lanes. As mentioned above, the high conflict density for L2 includes conflicts between L2 and other outside left-turn lanes. Although conflict density for L4 is low, most of the conflicts are head-on conflicts. It should also be noted that conflict density for L5 and L6 are significantly lower than the other left-turn lanes. These results confirm that outside left-turn lanes contribute to higher conflict frequency and severity at signalized intersections.

6. Conclusion

The research presented in this paper evaluated the safety effects of an unconventional outside left-turn lane design at signalized intersection. The evaluation was conducted using an automated video-based traffic conflict technique. Several observations can be drawn from the above-mentioned analysis. First, although the outside left-turn lane provided a higher speed of left-turn vehicles (Liu et al. 2011), it leads to negative safety impacts on signalized intersections. The results of the analysis showed that the approaches with outside left-turn lanes had considerable conflicts compared to approaches without outside left-turn lanes. Second, the approaches with outside left-turn lanes had significantly higher severity than approaches without outside left-turn lanes. Third, the outside left-turn lane not only contributed to conflicts within the lane itself, but also contributed to conflicts with the other left-turn lanes. As well, the outside left-turn lane leads to plenty of head-on, merging, and sideswipe conflicts.

The findings of this study provide new insight into the unconventional outside left-turn lanes. The results show that outside left-turn lanes increase the frequency and severity of traffic conflicts inside the signalized intersections. However, it should be noted that the left-turning vehicles do not need to make lane changes to the most inside lane to make left turns. As such, it is expected that the outside left-turn lanes could reduce the conflicts at the upstream areas of the intersection. It is recommended that the trade-off between the benefits at upstream and negative safety impact at the intersection caused by the outside left-turn lanes be carefully considered before recommending their installation. Several limitations need to be considered however in future studies. First, the results of the present study are based on a short observational periods, further study should be conducted using a long time video data. Second, a before-after study should further strengthen the results presented in the study. Third, due to some drivers not being familiar with the new design, some violation behaviors such as aggressive lane changing and driving in wrong direction were observed. The violation and driving behavior analysis was an

extending of the current research. Fourth, a safety diagnose of the outside left-turn lanes should be conducted that extends to the upstream areas of signalized intersections. Further studies should also be conducted to examine the travel speed at the outside and inside left-turn lanes.

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TABLES

Table 1 Vehicle to vehicle and vehicle to bike conflict frequency per hour

Conflicts	Vehicle to vehicle	Vehicle to bike
TTC range	# Event	# Event
0-1s	123	17
1-2s	169	20
2-3s	142	13
3-4s	89	10
Total	523	60

Draft

Table 2 Vehicle to vehicle and vehicle to bike conflict severity distribution per hour

Conflicts	Vehicle to vehicle	Vehicle to bike
SI range	# Event	# Event
0-0.2	126	14
0.2-0.4	101	9
0.4-0.6	86	11
0.6-0.8	87	9
0.8-1.0	123	17
Total	523	60

Draft

Table 3 Conflict frequency per hour between different left-turn lanes

Lane No.	L1	L2	L3	L4
L1	16	15	13	4
L2	15	29	4	2
L3	13	4	5	1
L4	4	2	1	0

Draft

Table 4 Conflict frequency at left-turn lanes and proportion of conflicts related to outside left-turn lane

Lane No.	Frequency	Proportion of conflicts related to outside left-turn lane
L1	48	100%
L2	50	35.3%
L3	23	62.5%
L4	7	100%
L5	11	0
L6	3	0

Draft

FIGURE CAPTIONS

Figure 1 Layout of the analyzed intersection and possible conflicts types for left-turn movements

Figure 2 Video analysis block diagram

Figure 3 Camera calibration results

Figure 4 Demonstration of the video analysis process

Figure 5 TTC and speed of objects for vehicle to vehicle and vehicle to bike conflicts

Figure 6 Spatial distribution heat maps for different types of conflicts at the intersection

Figure 7 Different types of conflicts frequency distribution

Figure 8 Conflicts severity distribution varied different types

Figure 9 Conflict frequency and percentage of vehicles involved in conflicts of different left-turn lanes

Figure 10 Conflicts frequency and percentage of vehicles involved in conflicts at four approaches

Figure 11 Conflicts frequency and percentage of vehicles involved in conflicts at different approaches

Figure 12 Conflicts severity distribution for different approaches

Figure 13 Spatial distribution heat maps for left-turn conflicts from different left-turn lanes

Figure 1 Layout of the analyzed intersection and possible conflicts types for left-turn movements
152x131mm (300 x 300 DPI)

Figure 2 Video analysis block diagram

37x8mm (300 x 300 DPI)

Figure 3 Camera calibration results
179x154mm (300 x 300 DPI)

Figure 4 Demonstration of the video analysis process
266x343mm (300 x 300 DPI)

Figure 5 TTC and speed of objects for vehicle to vehicle and vehicle to bike conflicts
194x203mm (300 x 300 DPI)

Figure 6 Spatial distribution heat maps for different types of conflicts at the intersection
81x32mm (300 x 300 DPI)

Figure 7 Different types of conflicts frequency distribution
181x172mm (300 x 300 DPI)

Figure 8 Conflicts severity distribution varied different types
181x170mm (300 x 300 DPI)

Figure 9 Conflict frequency and percentage of vehicles involved in conflicts of different left-turn lanes
100x59mm (300 x 300 DPI)

Figure 10 Conflicts frequency and percentage of vehicles involved in conflicts at four approaches
100x59mm (300 x 300 DPI)

Figure 11 Conflicts frequency and percentage of vehicles involved in conflicts at different approaches
100x59mm (300 x 300 DPI)

Figure 12 Conflicts severity distribution for different approaches
100x59mm (300 x 300 DPI)

Figure 13 Spatial distribution heat maps for left-turn conflicts from different left-turn lanes
239x294mm (300 x 300 DPI)