

Safety Assessment at Unsignalized Intersections Using Post-Encroachment Time's Threshold—A Sustainable Solution for Developing Countries



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Abstract India, a country with the highest number of road crashes and resulting injuries/deaths, has several issues associated with crash data for traditional safety analysis. For adequate and faster safety evaluation, traffic conflict technique using several proximal indicators is in practice worldwide. Among all indicators, Post-Encroachment Time (PET) is the most popular one for its easier measurement. However, accurate identification of critical conflicts based on PET threshold is still a gray area. For this purpose, four unsignalized intersections have been selected from the NCR India. This study is focused on identifying critical conflicts on the concept of perception-reaction time for emergency situations and adopted PET threshold of 1 s. This value of emergency perception-reaction is recommended by AASHTO (2001) for hazardous situations. Among various crossing situations, the maximum proportion of critical conflicts is found when through-moving vehicles are Two Wheelers (2W) followed by Light Commercial Vehicles (LCV). The appropriateness of the proposed method is verified by using 5 years' crash data for right-turn right angle and right-turn head-on collisions and finding a statistically significant relationship between these right-turn-related crashes and critical crossing conflicts. This study can be utilized as an effective tool to evaluate the safety at various traffic facilities where the collection of detailed crash data is a serious issue.

Keywords Unsignalized intersection · Proximal safety indicator · Post-encroachment time · Critical conflicts

1 Introduction

Road traffic crash is increasing at a rapid pace across the globe, and presently it is one of the leading causes of death. In developing countries like India, vehicle population and construction of good road networks are increasing rapidly. However,

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the lack of enforcement and policies are unable to deal with increasing traffic and have contributed to the significant increase in traffic crashes. Road crashes have earned India a dubious distinction.

The situation is worst at intersections locations. Within transportation system, an intersection is an operationally complex location where large numbers of conflict points are created, thus rendering it one of the most crash-prone locations. According to the latest ministry report, in India, about 37.8% of motor vehicle crashes occurred at intersections [1]. Most of the severe crashes and fatalities are found to occur more at unsignalized intersections that accounted for around 85% of crashes [1]. This is because, in India, most of the unsignalized intersections are uncontrolled, i.e., no signals or pavement markings are available to control the traffic. Additionally, traffic signs associated with the priority rules such as the stop and yield signs are not provided to a particular movement at these intersections. Even if any movement is prioritized with signs, many drivers do not follow those due to the nonexistence of enforcement. The priorities are basically established by the situations drivers perceive [2, 3]. At many instances, vehicles from all the directions attempt crossing and turning at the same time which increases the probability of crashes. The traffic rule in India is to keep left, and hence the maneuver of left-turning traffic is not a serious issue at intersection locations. On the other hand, the right-turning traffic of major/minor road has to wait for suitable gaps between through-traffic traveling along the major road to cross the road. If high traffic volume exists on the major road, drivers turning right from the major/minor road onto the minor/major road have to wait long for the adequate gaps. Due to that longer waiting time, many right turners lose their patience and demonstrate a tendency to cross over the intersection by accepting smaller gaps which may be dangerous [4]. While right turners are supposed to reduce their speed in order to take a turn, higher speed is observed for both right turnings and through traffic which increases the chances of severe collisions. Accordingly, critical conflict situations occur at frequent intervals between right turners and through traffic, which often lead to unsafe crossing situations and result in probable collisions.

Under such circumstances, drivers get engaged in many unsafe activities such as the sudden application of brakes, abrupt lane changes or not following lane discipline, etc. Therefore, traffic maneuvers at such intersections are highly complex and potentially very unsafe which have a direct influence on the higher crash rate observed at uncontrolled intersections. Due to all of the abovementioned facts, intersection safety becomes a serious public health issue which cannot always be solved merely by providing or making changes in signs and signals. Therefore, it is important to conduct rigorous and reliable safety analysis which will help to reduce the crash rate at uncontrolled intersection locations and enhance the road traffic safety significantly.

Traditionally, road safety evaluation has been performed using different statistical techniques based on historical crash data. There are several drawbacks associated with these types of analysis such as random and rare nature of accidents, underreporting of different types of accidents, improper documentation of accidents types, and their precise locations by the law enforcement officers. These observational errors negatively affect the accuracy and reliability of safety analysis. Over the past few

decades, researchers have identified traffic conflict as the best surrogate measure as it occurs more frequently than crashes and represents the nearness to the collision [5–9]. This indirect safety measure, traffic conflict technique, was originally developed by Perkins and Harris [10]. Traffic conflict analysis using proximal safety indicators has received widespread attention across the globe. The key benefit of these indicators is that they represent the temporal and spatial proximity characteristics of unsafe interaction and near accident [11]. Proximal safety indicators such as time to collision (TTC), time-exposed TTC, time-integrated TTC, deceleration rate (DR), proportion of stopping distance (PSD), etc. have been proposed by various researchers to assess the safety of a traffic facility using traffic conflict technique. However, these indicators are not easily measurable from the video recordings. One indicator which is most commonly used to identify the crossing conflicts between two road users is post-encroachment time (PET). It refers to the time interval between two instances when the first vehicle leaves a conflict point and the second vehicle enters into it. PET has all the essential properties of surrogate safety measure.

Similar to other surrogate measures, PET is estimated from observable non-crash events and indicates the resulting event of conflicts between vehicles, how closely a collision has been avoided. In fact, PET is a less resource-demanding indicator as it does not involve an estimation of vehicular speed and distance from the common conflict point as in the case of TTC [12]. To identify conflict as a critical one, a threshold value of PET is used which indicates that identified critical conflicts can be resulting in collision. However, in previous studies, it is observed that several threshold values of PET ranging from 1 to 6.5 s have been historically used [13–15]. The selection of these threshold values to determine a critical conflict situation has been carried out in several ways, such as using the SSAM's default threshold values, the perception-reaction time, or even arbitrarily. American Association of State Highway and Transportation Officials (AASHTO) Greenbook [16] provides the driver perception-reaction time of 1 s for hazardous situations. Therefore, the present study aims to identify critical conflicts in crossing situation using PET threshold as 1 s. For this purpose, four unsignalized intersections located at National Capital Region (NCR) locations are selected, and critical conflicts are identified. The appropriateness of the proposed method is verified from a relationship between observed critical conflicts and five years' crash data for right-turn right angle and right-turn head-on collisions.

2 Literature Review

Several studies talked about the importance of the threshold values associated with proximal indicators. Chin and Quek [17] mentioned that a PET threshold value of 1.0 was considered as critical. Svensson [18] talked about the importance of threshold identification for the conflict measure to know about the safety problems that are to be investigated. Gettman et al. [19] stated that PET thresholds depend on the type of roads, vehicles as well as involved road users in a particular traffic conflict situation.

An FHWA report [12] first talked about Surrogate Safety Assessment Model (SSAM) to identify conflicts among all vehicular interactions. It proposed default threshold values for two surrogate measures, TTC and PET as 1.5 s and 3 s, respectively. Sonchitruska and Tarko [20] studied crossing conflicts leading to right angle collisions at signalized intersections. They modeled the behavior of PET in their proposed extreme value theory approach and found a promising relationship between conflicts and historical crash data at a PET threshold of 6.5 s. Archer and Young [13] observed that proximal measures of safety through observation or video analysis are useful to assess safety at specific locations by their threshold values so that appropriate countermeasures could be implemented. The maximum threshold value for the PET safety indicator was set to 1.5 s. Caliendo and Guida [14] selected SSAM's default thresholds for TTC and PET, 1.5 s and 5 s, respectively, as reported in FHWA study, 2008 [19]. Shekhar Babu and Vedagiri [20] observed crossing conflicts at an uncontrolled intersection using PET. A threshold value of 2.5 s was considered which is the perception-reaction time for stopping sight distance recommended by Indian Roads Congress. Peesapati et al. [21] determined PET threshold as 1 s from the correlation between conflicts and crashes. Zheng et al. [22] mentioned that the selection of a proper threshold is a big challenge on the use of traffic conflict counts. In brief, it is observed that several threshold values of PET ranging from 1 to 6.5 s have been historically used. The selection of these threshold values to determine a critical conflict situation has been carried out in several ways, such as using the SSAM's default threshold values, the perception-reaction time for a comfortable driving situation or even arbitrarily. Adaptation of any such value can influence all the components of a safety-based study, including evaluation tasks, determination of crash causation, and countermeasure analysis. Additionally, there is no basis to support the practice of a default, predetermined or arbitrary threshold without any proper justification. Contrarily, the present study carried out the safety analyses by a PET threshold of 1 s which is a recommended value by AASHTO for the unexpected driving situation or hazardous situation.

3 Methodology

PET is a quantitative measure to identify the conflict situation. This is calculated as a time difference between the passages of two road users with a common spatial point or area of potential collision [11]. For the present study, critical conflicts are identified based on a threshold value of PET, which can assess the probability of collision. A PET value of 1 s is taken as a threshold to determine the critical conflicts. AASHTO [15] proposed this value as the perception-reaction time of drivers for stopping sight distance at the unexpected situation. It was also mentioned in AASHTO that at any hazardous situation, 90% of drivers' perception-reaction time is 1 s as traffic conflict situation is also defined as an unexpected condition on the road confronted by drivers; in the present study, the PET threshold is considered as 1 s. Any conflict with PET value less than 1 s is identified.

3.1 Site Selection and Data Collection

To evaluate the effectiveness of the new indicator for the assessment of safety performance at unsignalized intersections, study sites have been selected from the National Capital Region (NCR), India. Primarily, several unsignalized intersections are identified considering different geometric configurations and traffic conditions such as (i) they are geometrically alike, (ii) there is high traffic demand at each site to capture large number of conflict data within a limited time period, (iii) motorists travel at their desired speed, (iv) there is no influence of on-street parking and bus stops within the functional area of intersection, and (v) there are very limited pedestrian and cyclists activities. Later, by associating these configurations, intersections are further shortlisted based on their crash history. Accordingly, 5 years (2011–2015) crash data for the selected sites are collected from concerned police stations. From the crash database, for each crash, a variety of information is obtained, e.g., date, time, precise location (distance and direction from the intersection), types of the crash (head-on, read end, right angle, right-turn head-on, sideswipe, etc.), and severity of collision (property damage only to fatality). As the present study focuses on crossing conflicts, only the sites with a higher number of right-turn related crashes (i.e., right-turn right angle and right-turn head-on crashes) are selected. By considering all of these factors, four unsignalized intersections located on four different intercity highways are finally selected for further analyses. Out of these four sites, two are three-legged intersections, whereas other two are four-legged ones. All the intersections are at-grade intersections and have major and minor roads. The details of the intersection locations along with crash data of selected crash types are given in Table 1.

As per objective of the study, the data collection is focused on the conflicts between two cross-traffics approaching from major as well as minor roads. It is already mentioned in the site selection section that selected intersections are located on intercity highways. No distinct peak or off-peak hours are observed for these kinds of highways. Therefore, data are collected using videography technique for a particular daytime (from 10 A.M. to 1 P.M.) on weekdays under good visibility conditions. For this purpose, a high-definition video camera is set up at an elevated point to obtain the clear view of the study location. Using this technique, two types of data are collected from the field, namely, traffic operational data and conflict data. A snapshot of video recording is shown in Fig. 1.

At all the study sites, three types of crossing maneuver are observed between (i) right turners from the major/minor roads and through-moving vehicles on the major roads, (ii) right-turning vehicles from the major road and right turners from the minor road, and (iii) two through-moving vehicles along the minor and major roads particularly for four-legged intersections. Among all traffic movements, crossing maneuvers between right turners from the major/minor roads and through-moving vehicles on the major roads are observed to be more in numbers and therefore included in this study. It is interesting to note that the crash record of similar types, i.e., right-

Table 1 Description of selected intersections

Name of sites	Case	Type of intersection	Traffic movement of major road on the side of the median	Lane width (m)	Number of total right-turn-related crashes (5 years)
Airport-NHAI-AIFF intersection at Dwarka	S-1	3-legged	2-lane 1-way	3.5	12
Faridabad-Gurgaon-Sikenderpur intersection at Gurgaon	S-2	3-legged	2-lane 1-way	3.5	15
Bahadurgarh intersection at Delhi	S-3	4-legged	2-lane 1-way	3.5	9
Dwarka-Kargil intersection	S-4	4-legged	2-lane 1-way	3.5	10



Fig. 1 A snapshot of study site 1 (S-1)

turn related crashes are found to be more at the selected study sites. Different traffic movements which are considered for the estimation of PET and subsequent analyses are shown in Fig. 2.

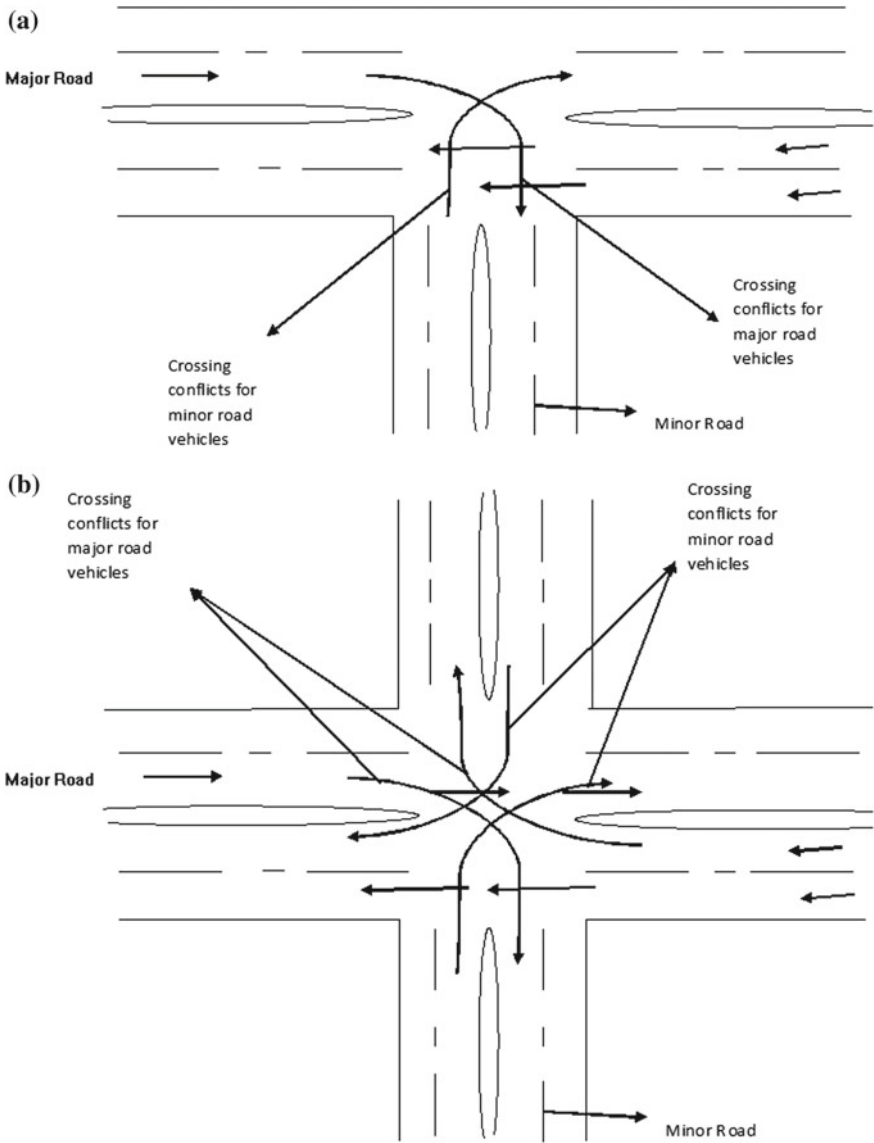


Fig. 2 Crossing conflicts between right turners and through-moving vehicles **a** for three-legged intersections (S-1, S-2), **b** for four-legged intersections (S-3, S-4)

3.2 Data Extraction

Once the field survey is over, several data are extracted from the recorded video as per the requirement of the study. Necessary information such as hourly traffic volume, PET, the number of vehicles involved in the conflict situations along with

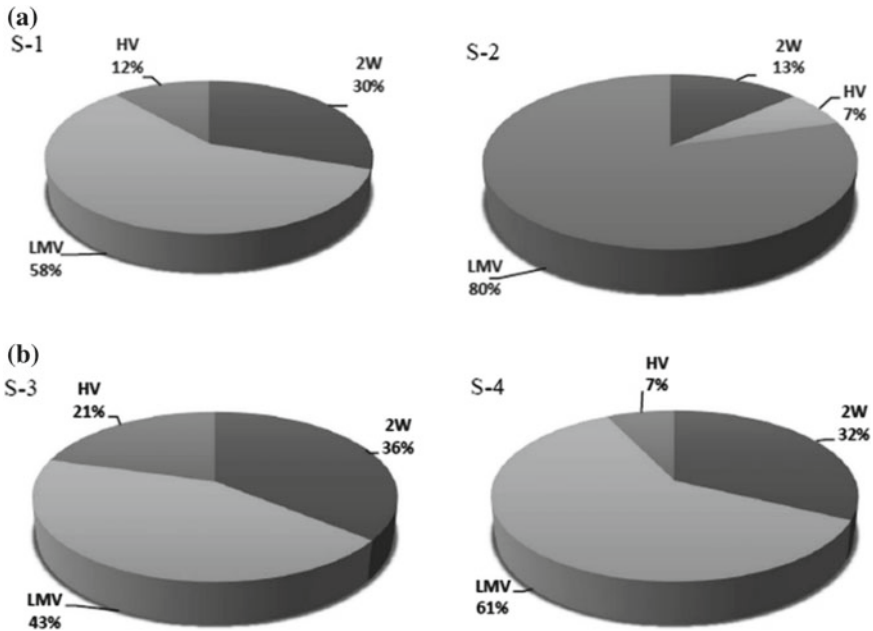


Fig. 3 Composition of vehicles **a** for three-legged intersections (S-1, S-2), **b** for four-legged intersections (S-3, S-4)

their categories, etc. are extracted. In order to have the conflict data, the conflict area of each intersection is divided into an equal number of square grids. The dimension of grids is selected as per the standard size of vehicles (i.e., 2.5 m × 2.5 m). This grid is prepared using Autodesk Maya 3D and then overlaid on the videos using a video editing software, Corel Video Studio Pro X6. Recorded videos are played on a large television screen at a frame rate of 25 frames per second and two time events t_1 and t_2 are noted down to calculate the PET values. t_1 is the time at which a right-turning vehicle exits a particular grid of conflict zone, and t_2 represents the time when the front of through vehicle just enters the respective grid. The difference between these two time events t_2 and t_1 gives the PET value. The hourly traffic volume of the study sites ranged from 1868 to 3778 veh/h. Three different vehicle categories are observed in the study sites, viz., Two Wheelers (2W), Light Motor Vehicle (LMV), and Heavy Vehicle (HV). LMV includes three wheeler, car, big car, and van, whereas HV represents bus, truck, and tractor-trailer. The compositions of total vehicles comprising of both right turners and conflicting through vehicles involved in the observed conflicts are shown in Fig. 3a and b, respectively.

Figure 3a, b shows that, among all the vehicle categories, LMV constitutes dominant share ranging from 43 to 80% of total traffic at all the sites. The percentage of 2W is found to be the second highest followed by HV.

4 Results and Discussion

From the video data, PET values between various right turning and through movements are estimated for all the study sites. Subsequently, the frequency distribution of calculated PET and empirical analysis of these PET values are then carried out.

4.1 Frequency Distribution of Observed PET

The frequency distributions of calculated PET values for the three-legged as well as four-legged intersections are presented in Fig. 4a and b, respectively.

It can be observed from Fig. 4 that at all the study sites the maximum numbers of PET values are distributed from 0.5 to 2 s.

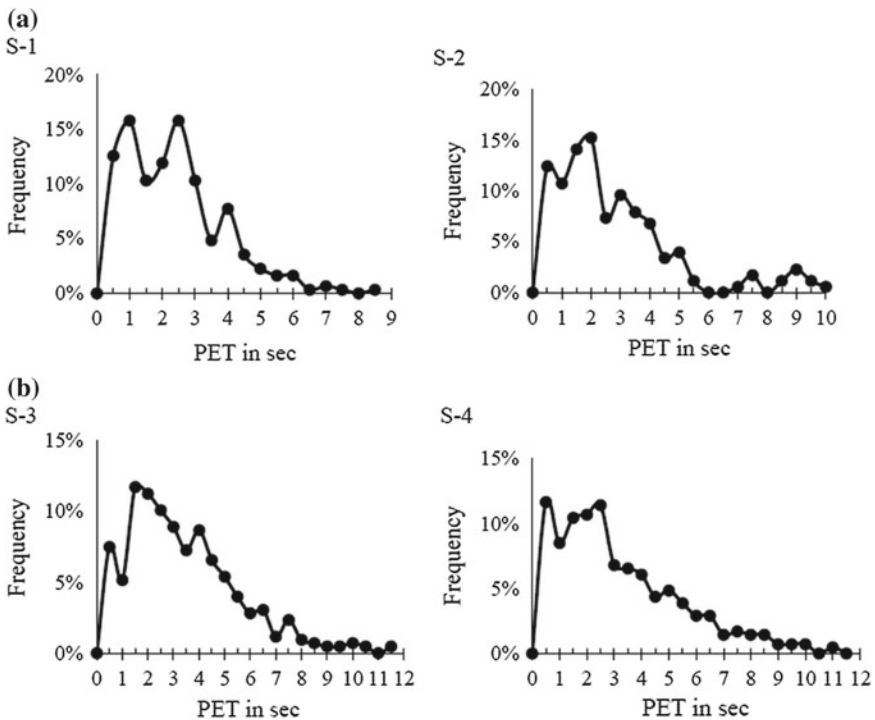


Fig. 4 Distribution of PET **a** for three-legged intersections (S-1, S-2), **b** for four-legged intersections (S-3, S-4)

4.2 Characteristics of PET

An empirical analysis has been carried out to determine the characteristics of PET between right turners and through vehicles. For this purpose, several parameters are estimated, namely, the number of total conflicts as well as critical conflicts observed at each site, the average, minimum, and maximum values of PET, presented in Table 2.

From the recorded data, a total of 1138 conflicts is observed. The minimum PET values are found to be ranging from 0.09 to 0.20 s and for maximum PET values, the range lies between 8.5 and 11 s. The average PET values for all the sites range from 2.08 to 2.87 s, which are very low in numbers. From this observation, it can be stated that non-prioritized vehicles adopted higher risk right-turning maneuvers in front of right-of-way vehicles instead of yielding for through vehicles along the major road. It is observed that four-legged intersections are having a lower value of average PET in comparison with three-legged ones. This observation is due to the greater number of small PET values observed at three-legged sites implying higher risk taken by the right turners. Table 2 shows that the percentage of critical conflicts based on 1 s PET threshold is also found to be more at study sites S-3 and S-4 (four-legged intersections) than S-1 and S-2, which are three-legged intersections. This is because S-3 and S-4 are four-legged intersections and due to the absence of priority rules, drivers of all four legs have equal opportunity to enter the intersection at the same time, either from the major as well as the minor road. This makes the situation critical, and a higher proportion of low PET values are observed than PET threshold. Hence, based on the PET threshold value, it can be inferred that the four-legged intersections are more hazardous locations than three-legged sites. It can also be said that the probability of resulting collisions is also more at these three-legged sites.

Table 2 Characteristics of PET

Study site	S-1	S-2	S-3	S-4
No. of total observed conflicts	263	283	317	301
Minimum PET (s)	0.20	0.16	0.09	0.16
Maximum PET (s)	11	9.0	10	8.5
Average PET (s)	2.74	2.87	2.08	2.42
No. of critical conflicts (i.e., PET values less than 1 s)	58 (22.05%)	61 (21.55%)	80 (25.23%)	76 (25.24%)

4.3 Distributions of Critical Conflicts for Each Through-Moving Vehicle Category with All Right-Turning Traffic

For in-depth information, the effect of each through-moving vehicle category on critical conflicts has been determined. Critical conflicts are further distributed with respect to the observed vehicle categories (i.e., 2W, LMV, and HV) traveling on the major roads. Subsequently, a number of critical conflicts as well as its percentage over the total number of observed conflicts are identified and illustrated for each site in Table 3.

From Table 3, for all the study sites, the percentage of critical conflicts is found to be more for through-moving 2W and LMV compared to HV. It indicates that right-turning vehicles accept smaller gap between the fast-moving through vehicles (2W and LMV), and the conflicts associated with these categories are found to be more critical. Same findings are also observed in the study of Pirdavani et al. [4]. It is thus because 2W is having the smallest size among all the vehicles traveling at the study sites, thus provoking the drivers of other vehicles to take a right turn by disobeying the priority rules. Resultantly, the temporal difference between the end of the encroachment of right turners and the entry of the through-moving 2W at a conflict zone becomes very less, which in turn increases the percentage of critical conflicts. Additionally, at four-legged intersections (S-3 and S-4), the percentage of 2W is observed to be higher than that of the remaining sites (as evident from Fig. 3), which also increases the proportion of critical conflicts at S-3 and S-4. Hence, from the conflict analysis based on PET threshold, it can be ascertained that more critical conflicts are observed when the through-moving vehicles are 2W.

Table 3 Distributions of critical conflicts for each through-moving vehicle category with all right turners

Case	No. of total conflicts	Through-moving vehicle categories					
		2W		LMV		HV	
		No. of critical conflicts	% of critical conflicts (%)	No. of critical conflicts	% of critical conflicts (%)	No. of critical conflicts	% of critical conflicts (%)
S-1	263	41	15.58	32	12.61	5	1.90
S-2	283	45	15.90	36	12.72	2	0.70
S-3	317	52	16.4	47	14.82	9	2.83
S-4	301	56	18.60	51	16.94	6	1.99

4.4 Relationship Between Right-Turn-Related Crashes and Critical Crossing Conflicts

Historically, the validity of the application of proximal indicator is being investigated by checking the correlation between conflicts and actual crash records [23]. The present study primarily used right-turn-related crashes for the final selection of study sites. It is also employed to evaluate the appropriateness of the study attempt. Consequently, a crash–conflict relationship is developed for the selected intersections which represent how observed critical conflicts between right-turning traffic and through-moving vehicles are correlated with the right-turn right angle and right-turn head-on collisions. A nonparametric test is performed to determine whether a statistically significant relationship exists or not between the groups, crash, and critical conflict. As the sample sizes of both the groups are small and they are not normally distributed, therefore, a two-sample Mann–Whitney U test is performed for statistical hypothesis testing. The equations to calculate the test statistics (U values) are, this study used, presented in Eqs. (1) and (2)

$$U_{1(crash)} = n_1n_2 + \frac{n_1(n_1 + 1)}{2} - W_1 \quad (1)$$

$$U_{2(critical\ conflict)} = n_1n_2 + \frac{n_2(n_2 + 1)}{2} - W_2 \quad (2)$$

where n_1, n_2 = sample size, i.e., the number of study locations from where the crash and critical conflict data are collected, W_1, W_2 = the observed sum of ranks for samples of the crashes and critical conflicts. W_1 and W_2 are calculated by combining all the samples from both groups (crash and critical conflict) to one group and then providing ranks to the samples with a numerical number of 1 for the smallest observation. The results of the statistical analysis carried out between the selected crash types and critical conflicts are given in Table 4.

Table 4 Statistical analysis between right-turn-related crash and critical crossing conflict

Parameters	Crash	Critical Conflict
Observation numbers	46	382
Sample size (No. of selected locations)	$n_1 = 4$	$n_2 = 4$
Ranks of samples for four locations	(3, 4, 1, 2)	(7, 8, 5, 6)
Summation of ranks (W)	$W_1 = 10$	$W_2 = 26$
Mann–Whitney U value	$U_1 = 16$	$U_2 = 0$
U_0	0	
p -value	0.0143 (two-tailed)	
R^2	0.68	

Table 4 shows that at $n_1 = 4$ and $n_2 = 4$, the minimum value of U_0 as the test statistics is found for critical conflict, i.e., $U_0 = U_2 = 0$. For a two-tailed test at the 0.05 significance level, p -value for Mann–Whitney U statistic for the small sample is determined, and it is found to be 0.0143 which is less alpha value. Therefore, it can be implied that the relationship between the crash and critical conflicts is statistically significant as given in Table 4. From the test results and goodness of fit, a promising relationship is found between actual crash data and observed critical conflicts. Literature also showed a statistically significant relationship between traffic conflict and crashes by types [14, 21]. This relationship indicates that PET threshold value of 1 s is fit to identify the critical conflict at crossing situation of unsignalized intersections.

5 Conclusions

Traditional safety analysis based on historical crash data has several limitations regarding adequacy and timeliness. Additionally, in developing countries like India, crash data are highly underreported. Only crashes which are severe in nature, i.e., major injuries and fatal crashes, are reported. Apart from these issues, crashes are not reported precisely (types of crashes, location, and other necessary information). Therefore, safety evaluation based on police-reported historical crash data only could lead to erroneous outcomes. By keeping these in mind, the present study utilizes traffic conflict technique to evaluate the safety performance at unsignalized intersections using proximal safety indicator, PET. Employing PET as an indicator provides a useful observation about the safety state of selected study sites. A threshold value of PET is widely used in many studies to distinguish the conflict as serious and non-serious ones. However, historically, PET thresholds have been selected arbitrarily or based on predetermined threshold values. At Indian-unsignalized intersections, priorities are established by the situations drivers perceive, and thus vehicles from all the directions attempt crossing and turning at the same time. Therefore, without proper justification, considering any value as a PET threshold for safety evaluation can be misleading. In this study, the threshold is taken as 1 s, i.e., the reaction time of a driver for unexpected traffic condition based on the assumption that below this time driver could not perceive the situation properly, which may be unsafe and lead to a collision. This value of perception-reaction time for hazardous situations is recommended by AASHTO [15].

The average PET values at these sites are found to be ranging between 2.08 and 2.87 s indicating higher risk-taking crossing behavior of the non-prioritized traffic. The percentage of critical conflicts is observed more at four-legged intersections compared to three-legged ones. This is because, at four-legged intersections, due to the absence of priority rules, drivers of all four legs have equal opportunity to enter the intersection at the same time, either from the major as well as the minor road. The percentage of critical conflicts is found to be more when conflicts occur between all right turners and through-moving vehicle categories of 2W and LMV.

It is thus because 2W is having the smallest size of all the vehicles traveling at the study sites, thus provoking the drivers of other vehicles to take a right turn by disobeying the priority rules. As a result, the temporal difference between the end of the encroachment of right turners and the entry of the through-moving 2W at a conflict zone becomes very less, which in turn increases the percentage of critical conflicts. Moreover, it is observed that at four-legged intersections the percentage of 2W is observed to be higher than that of the remaining sites, which also increases the proportion of critical conflicts. For validation of the proposed method, a statistical analysis is conducted between the observed right-turn-related crashes and critical crossing conflicts identified using PET threshold of 1 s and a statistically significant relationship is observed between them.

Overall, the proposed method is proved to be effective for safety assessment at unsignalized intersections particularly for right-turn related crashes which are the most severe crashes among all crash types [24–26]. This new method is capable of assisting traffic engineers and safety experts proactively with the selection of appropriate traffic calming and management measures to improve the safety at unsignalized intersections. The insights are thus helpful for the safety improvements at unsignalized intersections in an indiscipline traffic environment. The present study can be further extended by collecting conflict data for the whole day. Safety evaluation can also be carried out by considering other types of crashes (e.g., rear end) and using different proximal indicators.

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