CRITICAL GAP ESTIMATION AND ITS IMPLICATION ON CAPACITY AND SAFETY OF HIGH-SPEED UN-SIGNALISED T-INTERSECTION UNDER HETEROGENEOUS TRAFFIC CONDITIONS

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Resume
In India, priority rules at un-signalized intersections are often ignored by drivers. The present paper reports the applicability of deterministic and probabilistic methods for estimating the critical gaps at high-speed un-signalized T-intersections. The critical gap is estimated for different vehicle types and crossing movements. The study quantifies the implication of critical gap values on the capacity and safety values at un-signalized T-intersections. The results point to conclusion that the value obtained for the critical gap using deterministic methods is lower than that estimated by the probabilistic method. The gap values estimated using the Binary Logit Regression method are similar to those computed using the equation reported in Indo-HCM (2017). It was concluded that a lower value of the critical gap yields a higher capacity value and a higher value of risk probability.

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1 Introduction and background

Drivers' gap acceptance behavior significantly affects the traffic operation and the safety of un-signalized intersections. While manoeuvering through the intersection, the driver accepts or rejects the available gap. The characteristics of the approaching or conflicting vehicle, traffic volume, intersection characteristics (type of control, intersection characteristics) and the characteristics of the offending vehicle (subject vehicle performing crossing manoeuvers) affect the driver's decision to accept or reject an available gap [1]. Further, heterogeneity due to drivers' demographics, like age, gender, experience and driving behavior results in the dynamic nature of accepted gaps. Poor acceptance of gaps is a major reason for crashes at un-signalized intersections [2]. The magnitude of the accepted gap governs the risk while manoeuvering through the intersection. For instance, a driver accepting larger gaps is at lower risk than drivers accepting smaller gaps.

The critical gap, the derived value of a gap, is the most used indicator to estimate the safety and capacity at un-signalized intersections. The critical gap is defined as "the minimum gap that all the drivers in the traffic stream are assumed to accept at similar locations" [3]. "Generally, it is assumed that the driver's critical gap is greater than the largest gap rejected and shorter than the accepted gap for that driver." Generally, the drivers accept all the gaps greater than the critical gap and reject gaps lesser than the critical gap. This definition holds if the drivers in the traffic stream are homogeneous. However, considering heterogeneity in drivers due to perception-reaction time, risk-taking behavior and demographics, a certain proportion of drivers accept a gap smaller than the critical one. It implies that the value of the critical gap could be used as a measure in addition to accepted gaps to gauge the prevailing levels of safety at un-signalized intersections.

The critical gap value varies from driver to driver, among the intersection, as per the traffic movements and traffic situations. Incorrect estimates of the critical gap value led to inappropriate design of the road components. Different methods were developed in the past for estimating values of the critical gaps at

intersections\. Broadly, the methods for critical gap estimation can be categorized into (a) deterministic methods and (b) probabilistic methods. These methods are developed for homogeneous and lane-disciplined based traffic conditions.

Raff's method was developed in the early '50s to analyze the lag data and it can be used for small traffic volumes [4]. The result is highly dependent on the conflicting traffic volume [5-6]. The modified method of the previous method was the lag method, which requires sufficient lag data for each interval of time, which is not easily available and needs longer observation periods. Raff's method rejects the major valuable data and does not consider the gap data. This results in the over-representation of aggressive behavior of the driver and it is the major drawback of this method [6-8]. In 1968, the Ashworth method was developed to overcome the negative aspects of Raff's method. The Ashworth method illustrated the empirical distribution function considering the mean and standard deviation of the accepted gap. This method disregarded the biased results by using the probability distribution curve. This method assumes that the gap is exponentially distributed and that the critical gap is normally distributed. In this method, the value of the critical gap is highly dependent on the major street traffic volume, which is the major limitation [6].

A method that represents the critical gap, based on a histogram by using the total number of the gap acceptances and rejections is known as the Greenshields Method. The same extent of acceptances and rejections is obtained for the critical gap value estimation. The critical gap value is acquired as the mean value of acceptance and rejection. This method considers only a smaller quantity of samples leading to misinterpretation of the results and this is the major limitation of this method [9-11].

Similar to the lag method, a harder's method is developed, which considers only the value of the accepted gap and average floating value rather than lag. This method assumes that the gap value lies within the interval of 1 to 21 seconds. It overestimates the critical gap value when only the gap data is considered, but the result improvises when the lag value is also included [6-8]. The critical gap shows the properties of the cumulative distribution function and the value fluctuates, which is the major drawback of this method [11].

A logit model can be characterized using the binary logit model as a utility function, which is an alteration in the safety and reduction in delay time. This model generally deals with the gap acceptance behavior of the driver and it obtains the optimum value of critical gap as per past research studies [12]. Seigloch method requires the vehicle count of the major street under continuous queuing. The value of the critical gap estimated using this method is stochastic. However, it is not suitable for estimating the values for different turning movements and under saturated traffic conditions. Hence, its practical application is impossible.

The most predominant method used for estimating the critical gap values over the last two decades is the Maximum likelihood method [3-4, 6, 13]. This method assumes that the driver behavior is homogeneous and consistent. This method estimates the value based on probability of lying between the accepted and rejected gap. However, this method is unsuitable for heterogeneous traffic conditions and overestimates the value of a cautious driver [8]. A simple alternative method, the Probability Equilibrium Method (PEM), was established, which does not include any complex calculation. The concept is based on the probability equilibrium of accepted and rejected gaps by the cumulative distribution function. The advantage of this method is that it applies to a smaller sample size [14-15]. An advanced method is the Acceptance curve, based on empirical and theoretical considerations [11]. The disadvantage of this method is that for fewer gap data intervals, it will not provide S- a shaped curvilinear curve. The values will float, resulting in an inaccurate estimation of the critical gap [16]. A Probit method is based on fitting a weighted linear regression line to gap data after dividing the time interval [16]. It is unreliable and gives biased results compared to other methods [4]. Another method is Hewitt, which is an iteration method to estimate the value of a critical gap, however there is a doubt on its applicability for heterogeneous traffic conditions.

A Clearing Time Approach method is similar to Raff's method and estimates the value based on the cumulative distribution curve of accepted gap (F_a) and Clearing time (F_r). The clearing time is defined as the time interval required by the vehicle to cross the conflict area of the intersection. However, the limitation of this method is that the critical gap is a function of the accepted and rejected gap [8]. An Occupancy Time Method is an improved version of the clearing time approach method [17]. It includes the cumulative distribution of accepted gap and occupancy time, based on the traffic condition. An advantage of this method is that it is applicable for heterogeneous, as well as homogeneous traffic conditions. All the existing methods used to estimate the critical gap are described briefly above. A summary of the methods, their advantage, limitation, data requirements and applicability can be found in detail in [18-19].

The literature review reveals that various methods were developed for estimating critical gap values. The applicability of various methods and their comparative appraisal is widely studied for homogeneous traffic conditions. Few studies have estimated the critical gap values for un-signalized intersections [8, 11, 20]. However, very few studies in the past have estimated the critical gaps for the high-speed un-signalized intersections under mixed traffic conditions. The critical gap value influences the capacity and safety at un-signalized

intersections. Therefore, the variation in the critical gap value ought to influence the capacity and safety at un-signalized intersections. However, to the best of the authors' knowledge, the implication of a critical gap on capacity and safety at un-signalized intersections is not well reported. With the following inspiration, the purpose of the present study is framed as below.

(a) To estimate the critical gap values by vehicle type and crossing movement at the high-speed un-signalized intersections.
(b) To analyze the implication of the critical gap value on capacity and safety of the high-speed un-signalized intersections.

2 Critical gap estimation methods

In the present study, four methods, i.e., Raff's, Ashworth, Occupancy Time and Binary Logit, are adopted to estimate the critical gap for the high-speed un-signalized intersections. Raff's, Ashworth's and Occupancy time methods fall under deterministic methods, whereas the Binary Logit method is considered as a probabilistic method. The methods are discussed next.

2.1 Raff's method

Raff's method was introduced in 1950 for estimating the value of the critical gap [21]. Due to its simple application, several authors have used the Raff method to estimate the critical gap for homogenous and heterogeneous traffic conditions. The cumulative sum of the accepted and the rejected gap equals 1 [22]. However, the limitation of this method is that it does not consider the lag data. Lag is the time interval between the arrival of a yielding vehicle and the way of the next priority stream vehicle. Therefore, the Raff's method was modified, also known as Modified Raff's method. The mathematical representation of this method is:

$$F_a(t) + F_r(t) = 1. \tag{1}$$

As per this method, the value of the critical gap is the gap for which the accepted gap is larger than the critical gap and gaps shorter than the critical gap are rejected gaps. In Equation (1), F_a and F_r are the cumulative probabilities of the accepted and the rejected gaps. The intersecting point of the cumulative distribution curve of the accepted and rejected gaps is a critical gap.

2.2 Ashworth method

In 1968, the Ashworth method was developed to estimate the critical gap by using the mean and standard deviation values of the accepted gap. These result in the elimination of the unfair results obtained by the probability distribution curve. The gap follows the exponential distribution and the critical gap value follows the normal distribution obtained by this method. As per NRC (National Research Council, 1966), the estimation of the critical gap can be done using the following equation,

$$t_c = \mu - p\sigma_a^2, \tag{2}$$

where μ is the mean accepted gap, σ_a is the standard deviation, p is the traffic volume in vehicles per second and t_c is the critical gap value. The main limitation of this method is that the value obtained for the critical gap is highly correlated with the major street traffic volume [6].

2.3 Occupancy time method

Under the prevailing mixed traffic condition, priority rules at unsignalised intersections are violated in India. The drivers perceive equal priority from major and minor approaches, resulting in high risk at intersections. The driver's aggressive behavior during the turning from minor to major is observed due to accepting smaller gaps and rolling over to the major traffic stream. The available gap gets altered due to this type of aggressive behavior of the driver while manoeuvering. Therefore, the occupancy time method is proposed and advocated to estimate the critical gap in this kind of aggressive crossing behavior [16].

The occupancy time method is the modified form of the clearing time approach method [8]. It is generally defined as the „total time required by a vehicle executing the priority movement to occupy the conflict area". The occupancy time is influenced by driver behavior, intersection geometry, type of subject vehicle and opposing vehicular traffic [1, 6, 23].

The Occupancy Time Method states that "*for a low priority movement to clear the intersection area through the gap in conflicting flow, the following inequality must be satisfied*" [1]:

$$P(t_a > t) \geq P(ot \leq t)), \tag{3}$$

where, P is the probability of an event, t_a is the accepted gap, t is the time gap and *ot* is the occupancy time.

Based on the above equation, the critical gap is the intersection point of intersection of the cumulative frequency curves of accepted gaps (1 - F_a) and occupancy time (F_{ot}). Moreover, the speed of the conflicting vehicle significantly affects the gap size and critical gap. However, this method does not explicitly account for the effect of speed on the critical gap value and, therefore, forms a major limitation.

2.4 Binary logit regression method

The decision for the available gap (to accept or reject) varies among the drivers and is random and discrete. Therefore, choice of the modelling methods can be extended to model drivers' decisions and estimate the critical gap value. The deterministic term of observed utility is a function of different variables that influence the gap acceptance behavior at an uncontrolled intersection. The utility function is defined in the mathematical form below:

$$V_i = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n\,, \tag{4}$$

where V_i is the deterministic component of the utility of selecting a particular substitute. α is constant, x_1, x_2 ….. x_n are independent variables and β_1, β_2……β_n are the weighted coefficients.

If the model is developed for rejected gaps, then the probability of rejection using the binary logit model can be calculated as:

$$P = \frac{\exp(V_i)}{1 + \exp(V_i)}. \tag{5}$$

The gap corresponding to a 50% probability of acceptance or rejection is termed a critical gap. As per different studies, the researchers concluded that the value obtained from this method is the smallest [12]. It is reported that better results may be obtained if only the gap data is used. However, the method would provide underestimated critical gap value if the lag data is considered, as well [6]. Moreover, the method enables to study of the effect of waiting time on the critical gap [24]. In the present study, the decision to a gap, i.e., accepted or rejected, was modelled as a function of the gap size, the waiting time of the following vehicle and the speed of the conflicting vehicle. The critical gap was estimated for two types of crossing movements (major to the minor street and minor to the major street) and for four classified vehicle types to represent the heterogeneous traffic conditions.

3 Data

As per the MORTH (2020) [25] statistics on road accidents in India, 20.7% of intersection-related crashes are contributed by uncontrolled intersections. Further, uncontrolled T-intersections contributed to 35% of the intersection-related fatalities among all the intersection types. Therefore, un-signalized T-intersections were the main focus of the analysis. The traffic data for three un-signalized T-intersections were collected using videography on rural highways with similar geometry. The snapshots of the selected study locations are shown in Figure 1. The intersections are sufficiently away from the upstream and downstream of the other intersections, ensuring that the traffic flow is unaffected by the nearby intersections. In addition to that, during the data collection, each intersection approach was free from adjacent encroachments. The geometric and traffic details of the selected study intersections are summarized in Table 1. Traffic video for the subject study intersections was collected by

Figure 1 *Snapshot of study sections and position of the camera*

Figure 2 *Methodology for the extraction of (a) gap (b) occupancy time*

placing a high-definition camera (frame rate of 33 frames per second) near a high-rise building to serve as a vantage point. The traffic video was collected to capture the natural driving behavior. The data was collected on a weekday in November and December under fair weather conditions for 12 hours (9:00 AM to 9:00 PM). All the physical dimensions of the intersections were measured manually during the free-flow traffic conditions with the aid of the traffic police. The videos were recorded such that at least 200 m on major roads and 100 m on minor roads are visible. The camera location for collecting the traffic data is illustrated in Figure 1.

The selected intersections are represented as L1, L2 and L3, respectively. The three traffic movements are classified as M1, M2 and M3, where M1 represents the traffic from the major stream manoeuvering to minor stream and M2 is the traffic movement from minor stream to major stream; both M1 and M2 are the right-turning movements and are critical at un-signalized intersections. The major and minor streams are categorized and defined as per the Indian Highway Capacity Manual [26]. M3 is the approach comprised of the major through traffic. Figure 1 represents the snapshots of the study section.

3.1 Data extraction

In countries like India, the left-turning movement at the intersection is free. Therefore, the gap in acceptance for the right turning movement from major and minor approaches, which are the critical movements at the intersection. Hence, data for the right-turning movements are only extracted and analyzed. In the absence of a trustworthy automatic traffic data extractor, the gap, occupancy and speed data were extracted manually by repeatedly playing the video file in the laboratory. Figure 2 illustrates the conceptual diagram for extracting gap and occupancy time data. The gap and occupancy time was measured in 1/100th of a second.

3.1.1 Extracting the gap size and driver‘s decision

The gap is referred to as the time headway between the two consecutive vehicles in the major and minor traffic stream, as shown in Figure 2(a) [8]. The gap data (size and decision) was extracted from the recorded video. The data extraction resulted in 868 gaps for the major right turn and 622 for the minor right turn (including both accepted and rejected gaps) for the subject study locations. Both accepted and rejected gaps by vehicle type and crossing movements were extracted for all three locations.

3.1.2 Extracting the occupancy time

Occupancy time is defined as the „time occupied by the vehicle in the conflicting area until the driver accepts the gap for manoeuvering through the intersection“ [27]. Figure 2b shows the conflict area of the intersection where the two traffic streams interact.

3.1.3 Extracting the speed of the conflicting vehicle

For each location, depending upon the visual clarity and appropriateness of the data requirements, trap lengths of 37, 46 and 50 m were marked on the approach to calculate the speed of conflicting vehicles. The speed of the conflicting vehicle is calculated by noting the time difference a vehicle takes to clear the trap length of the respective length. The speed is then calculated by dividing the length of the intersection by the time taken to clear the trap.

3.1.4 Extracting the waiting time of offending vehicle

The waiting time of the vehicle is extracted by noting the time until the right-turning vehicle accepts

the gap and merges into the traffic stream. If the driver approaches the intersection and accepts the first gap, then in such cases, the waiting time of the right-turning driver is recorded as zero.

4 Results and discussion

4.1 Preliminary analysis

The traffic composition at all three intersections was classified under six categories, which are motorized two-wheelers (M2W), motorized three-wheelers (M3W), four-wheelers (Cars), light commercial vehicles (LCV), buses and trucks. A summary of classified traffic configuration is illustrated in Table 2.

M2W dominates the traffic composition at the study intersections with a share of 50-63 %, followed by 4W (17-30 %) and 3W (5-17 %). For L-3, the proportion of heavy vehicles (including LCVs, buses and trucks) is 14.8 %, whereas the same for L-1 and L-2 was 4.05 % and 6.01 %. Table 2 summarizes the descriptive statistics of gap and occupancy time data.

The accepted gap and occupancy time vary significantly by crossing movement and vehicle type (Table 3). For instance, drivers of M2W and M3W accept the smaller gaps compared to the drivers of cars and heavy vehicles, which can be attributed to the easy manoeuverability of motorized two-wheeler and three-wheeler. This implies that drivers of 2W and 3W tend to roll over and accept smaller gaps, highlighting aggressive driving behavior. The variation in the values of occupancy time corroborates the observation (lower value of occupancy time for 2W and 3W compared to 4W and HV). A smaller value of occupancy time also highlights aggressive driving behavior [1].

A lower value of accepted gap can be noted for drivers performing right turning movement from major to minor stream. On the contrary, drivers accept larger gaps when performing right turning movement from a minor to a major approach. At high speed, un-signalized T-intersections, the vehicle along the major approach travels at a higher speed. Therefore, the drivers of the minor approach exhibit safe and cautious gap-acceptance behavior. The safe driving behavior can also be seen from the higher values of occupancy time for the minor approach compared to the major approach. The variation in the magnitude of accepted gaps and occupancy time, by type of vehicle and crossing movement, significantly influences the critical gap value. Therefore, in the present study, the critical gap is estimated by the type of vehicles and the right-turning movements. The estimation of the critical gap using different methods is explained in further sections.

4.2 Critical gap estimation

4.2.1 Raff's method

Raff's method is one of the oldest methods for estimating the value of the critical gap. As per Raff's method, the critical gap is the point of intersection of the cumulative percentile curves of accepted gaps F (a) and rejected gaps 1-F(r), as shown in Figure 3. Here, the critical gap for L1 is shown as an example. From Figure 3, 2.72 s represents the critical gap for L1. The critical gap is estimated by the type of vehicle and right-turning movement for each location. The results are summarized in Table 4.

4.2.2 Ashworth method

This method is very simple and effortless to apply. The three different types of input are required to estimate the critical gap. This section calculates the critical gap for all three locations for the vehicle type by following the procedure explained earlier. The extracted accepted gap was used to evaluate the mean and standard deviation for different vehicle types for each location. The critical gap is estimated by type of the vehicle and the right-turning movements for each location and the results are summarized in Table 4.

Table 2 *Descriptive statistics of the gap and occupancy time by crossing movement and vehicle type*

Vehicle Type	Accepted Gap (s)				Occupancy Time (s)	
	Major Right Turn		Minor Right Turn		Major Right Turn	Minor Right Turn
	N	Mean (SD)	N	Mean (SD)	Mean (SD)	Mean (SD)
M2W	326	3.52(1.70)	214	3.45(1.56)	5.09(1.74)	5.45(2.02)
M3W	233	3.49(1.36)	194	3.61(1.42)	5.06(1.70)	5.22(1.93)
Cars	234	3.87(1.34)	159	4.12(1.47)	5.92(2.74)	5.62(1.92)
HV	75	4.76(1.51)	55	5.03(1.40)	6.87(2.42)	7.12(2.52)

Note: N: Number of samples; SD: Standard deviation; M2W: motorized two-wheelers; M3W: motorized three-wheelers; HV: Heavy vehicles (LCV, buses and trucks combined)

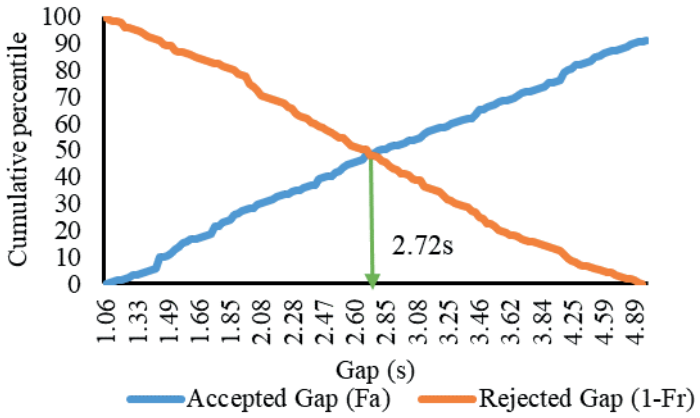

Figure 3 *Critical gap for location 1 by the Raff's method*

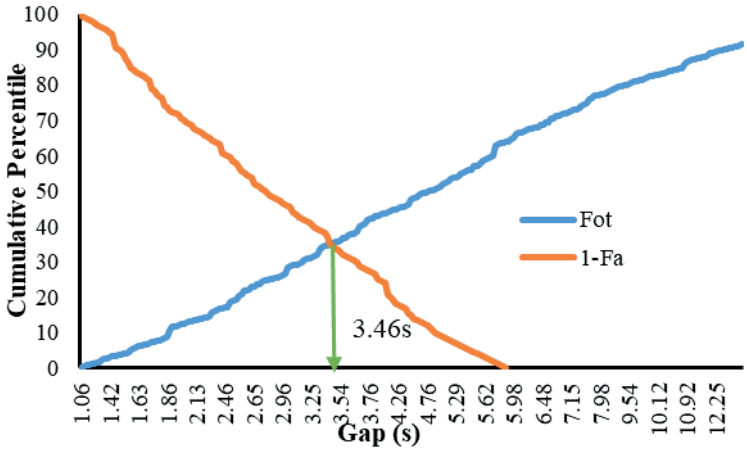

Figure 4 *Critical gap for location 1 by occupancy time method*

Table 3 *Binary logit model by vehicle type and crossing movement*

Major Right Turning Movement				
Variable	Vehicle Type			
	2W	3W	4W	HV
Constant (SE)	3.820 (0.736)	2.879 (0.828)	-1.066 (0.765)	4.366 (0.452)
G (SE)	-1.125 (0.150)	-1.623 (0.266)	-1.230 (0.206)	-0.324 (0.315)
WT (SE)	-0.216 (0.131)	-0.542 (0.217)	-0.580 (0.148)	-0.201 (0.209)
CS (SE)	0.012 (0.015)	0.010 (0.016)	0.086 (0.020)	0.41 (0.031)
Log-likelihood function	-295.153	-225.771	-234.434	-81.826
Cox and Snell R squared	0.336	0.323	0.304	0.152
Nagelkerke R squared	0.455	0.431	0.405	0.205
Minor Right Turning Movement				
Variable	Vehicle Type			
	2W	3W	4W	HV
Constant (SE)	4.255 (0.835)	4.446 (0.947)	-0.212 (0.046)	6.242 (.156)
G (SE)	-0.726 (0.154)	-1.433 (0.287)	-0.528 (0.160)	-0.280 (0.310)
WT (SE)	-0.194 (0.109)	-0.324 (0.214)	-0.0390 (0.118)	-0.359 (0.251)
CS (SE)	0.013 (0.017)	0.030 (0.017)	0.085 (0.023)	0.081 (0.040)
Log-likelihood function	218.346	186.525	174.398	155.956
Cox and Snell R squared	0.275	0.311	0.241	0.215
Nagelkerke R squared	0.37	0.415	0.321	0.289

Note: G: Gap Size (s); WT: Waiting Time (s); CS: Speed of Conflicting vehicle; SE: Standard error. All variables are significant at 95% CI

4.2.3 Occupancy time method

An occupancy time method (OTM) effectively estimates critical gaps under mixed traffic conditions [1]. This method incorporates aggressive driving behavior for estimating critical gaps. According to the occupancy time, the critical gap is the intersecting point of the cumulative frequency curves of accepted gaps ($1\text{-}F_a$) and occupancy time (F_{ot}), as shown in Figure 4.

Here, 3.46 s represents the critical gap value for L-1 (location-1). The critical gap is estimated by the type of a vehicle and the right-turning movements for each location. The results are summarized in Table 4.

4.2.4 Critical gap estimation using the Binary Logit Regression Method (BLRM)

In the present study, the drivers' decision for gap i.e. to accept or reject an available gap, was modelled as a function of the gap size, waiting time of the offending vehicle and the speed of the conflicting vehicle using the binary logit regression. The model summary is shown in Table 3.

For all the models developed in the present study, a negative coefficient can be noted for the gap size. It implies that as the gap size increases, the probability of rejection decreases, or the probability of acceptance increases. Similarly, a positive sign for the speed of the conflicting vehicle can be noted. This highlights that as the speed of the conflicting vehicle increases, the probability of rejecting a gap increases. Consistent observations can be noted for both crossing movements and different vehicle types.

A negative coefficient can be noted for the waiting time. This implies that the probability of rejection decreases as the waiting time increases. This highlights that as the waiting time increases, the drivers become impatient and force themselves into the traffic stream by accepting and rolling over smaller gaps to manoeuver through the intersection. Consistent observations can be noted for both crossing movements and different vehicle types. The present study is the first to report the effect of the waiting time of offending vehicles on the gap-acceptance phenomenon under the mixed traffic conditions.

The critical gap is estimated by calculating the gap corresponding to the 50% probability of acceptance or rejection. The estimated value of the critical gap by vehicle type and crossing movement is summarized in Table 4.

4.2.5 Critical gap estimation using Indo-HCM

The average critical gap is evaluated using the base critical gap, which depends on the geometry of the section, the proportion of large vehicles and an adjustment factor depending on the movement and vehicle type as per Indo-HCM -2017 and then based on the Equation (6) the critical gap is estimated.

$$t_{cx} = t_{cb} + f_{lv} * \ln(P_{lv}). \quad (6)$$

The critical gap is estimated by vehicle type and crossing movement for each location and the results are summarized in Table 4.

Table 4, illustrates that the critical gap varies significantly by type of a vehicle and the right-turning movements. For instance, lower critical gap values can be noted for M2Ws (1.18 sec) and M3Ws (1.62 s) compared to cars (2.08 s) and HVs (2.54 s). This implies that drivers of different vehicle types, i.e. M2Ws and M3Ws exhibit aggressive driving behavior (accept and rollover smaller gaps) compared to cars and HV. The results of the critical gap corroborate the observations deduced from Table 4 for different categories of vehicles and the right turning movements. The lower value of the critical gap also highlights that drivers of M2Ws and M3Ws are at a higher risk than drivers of cars and HVs. Consistent observation can be noted for the critical gap estimated using different methods.

Further, the lower critical gap values can be noted when drivers from a major approach take a right turn to merge into the minor stream (Refer to Table 4). This highlights that drivers from the major approach exhibit aggressive crossing behavior (accepting smaller gaps and lower occupancy time) as the priority rules at unsignallised intersection are not followed. On the contrary, drivers of the minor stream reveal cautious gap-acceptance behavior. This can be attributed to the fact that at high-speed un-signalized T-intersections, the vehicle along the major approach travels at a higher speed. Therefore, the drivers of the minor approach exhibit safe and cautious gap-acceptance behavior. This can be witnessed from the values of occupancy time and the accepted gap. Consistent observation can be deduced using different methods of critical gap estimation. It can also be observed that the critical gap varied between the subject study locations for a given vehicle type and crossing movement. The variation in the critical gap can be attributed to variation in traffic volume, speed of the vehicles and driving behavior characteristics.

From Table 4, it is evident that the critical gap estimated using different methods varies significantly. For instance, the lower value of the critical gap for different vehicle types and crossing movements was estimated using Ashworth's method compared to other methods. However, larger values of the critical gap are estimated using the BLRM. It is important to note that the values of the critical gap, estimated using deterministic methods (Raff's method, Ashworth method and Occupancy time method) are lower than the critical gap estimated using the probabilistic method (BLRM). The critical gap estimated using the BLRM is in close agreement with the values estimated using the Indo-

Table 4 *Critical gap by vehicle type and crossing movements*

Major Right Turning						
Location	Vehicle Type	Raff's Method	Ashworth Method	Occupancy Time method	Indo-HCM	BLRM
L1	M2W	1.60	1.56	1.64	2.78	2.24
	M3W	1.86	1.75	2.56	3.07	3.18
	Cars	2.52	2.25	3.52	3.50	3.59
	HV	2.96	2.54	4.36	4.28	3.92
	Average	2.23	2.02	3.02	3.40	3.23
L2	M2W	1.82	1.62	2.20	2.53	2.76
	M3W	2.08	1.81	2.26	2.72	3.12
	Cars	2.37	2.37	2.59	3.28	3.62
	HV	2.76	2.83	3.45	3.96	4.18
	Average	2.25	2.15	2.62	3.12	3.42
L3	M2W	2.18	2.09	2.18	2.88	2.84
	M3W	2.42	2.26	2.52	3.32	3.26
	Cars	2.87	2.54	3.16	3.65	3.48
	HV	3.53	3.39	3.48	4.04	3.62
	Average	2.75	2.57	2.83	3.47	3.30
Minor Right Turning						
Location	Vehicle Type	Raff's Method	Ashworth Method	Occupancy Time method	Indo-HCM	BLRM
L1	M2W	1.96	1.18	2.06	2.56	2.54
	M3W	2.23	2.02	2.85	3.44	3.38
	Cars	3.58	2.24	3.85	3.62	3.94
	HV	3.05	2.68	4.07	4.05	4.18
	Average	2.71	2.03	3.21	3.42	3.51
L2	M2W	1.90	1.26	1.45	2.32	2.45
	M3W	2.14	1.65	2.86	3.46	3.82
	Cars	2.42	2.08	3.25	3.85	3.96
	HV	2.86	2.57	3.84	4.16	4.28
	Average	2.33	1.89	2.85	3.45	3.63
L3	M2W	2.25	1.44	2.08	3.14	2.48
	M3W	2.68	1.62	2.16	3.58	3.26
	Cars	2.96	2.25	3.54	4.06	3.88
	HV	3.17	2.89	4.29	4.22	4.15
	Average	2.77	2.05	3.02	3.75	3.44

Note: All values in seconds (s)

HCM [25]. It is important to mention that the critical gap estimated using the BLRM explicitly considers different factors such as gap size, waiting time of the offending vehicle and speed of the conflicting vehicle on the drivers' decision and hence, the critical gap. Therefore, the critical gap estimated using the probabilistic method could be deemed robust and consistent [17]. The impact of varying critical gap values on capacity and safety is discussed next.

4.3 The implication of critical gap to capacity

The critical gap is the most popularly used to estimate the capacity of the un-signalized intersection and further identify the section's level of service (LOS). The intersection's capacity enables planners and engineers to comprehend the prevailing LOS. The capacity of un-signalized intersections depends on the value of critical gap and follow-up time, conflicting volume and road geometric features. The capacity for un-signalized intersection is as:

$$C_x = a * V_{cx} \frac{e^{-Vcx(tcx-b)}/3600}{1-e^{-Vcx \cdot tfx}/3600}, \quad (7)$$

where, C_x is Capacity of movement (in PCU/h); V_{cx} is conflicting volume corresponding to the movement in PCU/hr, t_{cx} is the critical gap in seconds (s), t_{fx} is follow-up time in seconds (s); a and b are the adjustment factors based on intersection geometry.

Table 5 *Capacity in PCU/h using different methods of critical gap estimation*

Location	Raff's Method	Ashworth Method	OTM	Indo-HCM	BLRM
Major Right Turn					
L-1	1866	2213	1053	815	903
L-2	1809	1955	1340	928	754
L-3	1106	1293	1033	612	702
Minor Right Turn					
L-1	1000	1680	708	618	582
L-2	1250	1824	835	545	483
L-3	747	1429	605	337	429

Note: All values in PCU/h

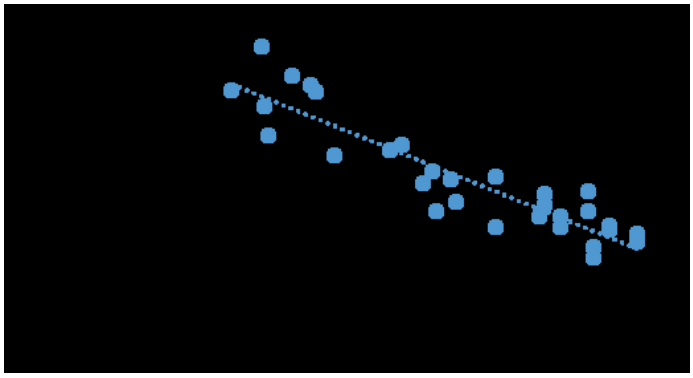

Figure 5 *Variation in capacity with the critical gap*

Un-signalized intersections are characterized by frequent merging, diverging and crossing operations. The presence of heterogeneity and non-lane-based aggressive traffic complicates the traffic operations. Crossing operations are the most critical at un-signalized intersections compared to other legal movements [27]. A crossing operation involves turning for merging into a major stream or diverging into a minor stream. Therefore, the present section estimates capacity values only for the right-turning operations. Table 5 summarizes the capacity values estimated using different methods of critical gap estimation by crossing movement.

From Table 5, a significant variation in capacity values obtained using different methods of the critical gap, is evident. Higher capacity values can be noted for critical gap values estimated using Ashworth's method (1293-2213 PCU/h). The capacity value obtained from the deterministic method is quite high (605-2213 PCU/h). However, the critical gap estimated using the BLRM yields a lower capacity value (429-582 PCU/h) for the minor right turn than (702-903 PCU/h) for major right turn. Further, for different crossing movements, smaller capacity values can be noted for the minor approach compared to the major approach. Further, a significant variation in capacity between the subject study locations can be noted. The variation in capacity values by crossing movement, study locations and different methods can be attributed to variation in critical gap values. To probe further, the variation in capacity with the critical gap is analyzed using a scatter plot, as shown in Figure 5. Here, the results obtained using different methods are merged.

A negative correlation between capacity and the critical gap is estimated in Figure 5. The lower value of the critical gap yields the higher value of the capacity. It is observed that with a lower critical gap, the majority of the drivers accept lower gap values. As a result, higher capacity values can be noted.

4.4 The implication of the critical gap on safety

The decision to cross the intersection is measured using the gap (i.e. accepted or rejected). In general, the drivers often reject the smaller gap and accept the larger gap. Thus, a driver accepting a larger gap endures lesser risk than a driver accepting a smaller one in the traffic stream. This implies that risk (R) is an inverse function of the magnitude of the accepted gap. Therefore, mathematically risk can be represented as:

$$Risk(R) = \frac{1}{Accepted\ gap(s)}. \tag{8}$$

Based on the above equation, a smaller value of the accepted gap indicates the higher risk and vice-versa. The concept of Probability of Critical Crossing Conflicts (PCCC) is used as an indicator of operational risk at un-signalized intersections [27]. The PCCC is derived by

modelling the post encroachment time (PET) data using the extreme value theory (EVT). In the present study, Probability of Risk (POR), an indicator of operational risk based on accepted gaps, is derived. The computation of POR is explained next.

The Generalized Pareto (GP) and Generalised Extreme Value (GEV) are the two most popular extreme value distributions used by researchers to model the variation of different traffic conflict indicators. Past studies have reported that the best-fitted distribution to model the variation in the risk is the generalized extreme value (GEV) distribution [28-36].The safety of an un-signalized intersection has been evaluated using the EVT. The technique has shown potential for use in safety-related studies and is now widely used in conflict and crash-related studies. Recently, researchers have demonstrated the applicability of EVT theory in estimating the number of crashes [30-32]. Therefore, the GEV distribution is used to derive the POR in the present study.

Consider X1, X2, X3,…Xm as independent random variables (in the present case, the value of risk) with a similar probability distribution, where Yn = max (X1, X2, X3,…., Xm). When n→∞, the Yn will converge to a GEV distribution [27], as shown:

$$f(x) = \frac{1}{\sigma}\exp\left(-(1+kz)^{-\frac{1}{k}}(1+kz)^{-\frac{1}{k}}\right)^{-1-\frac{1}{k}} \quad k \neq 0, \tag{9}$$

where, $z = (x - \mu)/\sigma$, μ is the location parameter, σ is the scale parameter and k is the shape parameter.

The POR is defined as an area under the probability density function of GEV distribution between the thresholds of gap representing serious conflicts. The POR can be computed using the following

$$Probability\ of\ risk\,(POR) = \int_{LL}^{ULL} f(x)dx\,, \tag{10}$$

where, $f(x)$ is the probability density function of GEV distribution, *LL* and *UL* represent the Lower and Upper limits of risk, representing the critical conflicts, respectively.

Recently, the critical gap could characterize the risk of crossing conflicts. Based on the critical gap value, the risk of crossing conflict was characterized as serious and non-serious conflicts [36]. Therefore, the critical gap value was used in the present study to evaluate the POR of the un-signalized T-intersections.

Considering the critical gap as a threshold to define serious conflict, the Equation (11) to estimate POR can be rewritten as:

$$Probability\ of\ risk\,(POR) = \int_{\min imum\ risk}^{risk\ at\ critical\ gap} f(x)dx\,. \tag{11}$$

A higher value of POR indicates that most of the crossing manoeuvers are serious and hence, the safety is poorer. The value of POR can facilitate monitoring of the level of operational risk at un-signalized intersections. Intersections with a higher POR value are riskier and unsafe than intersections with a lower POR value. The probability of risk (POR), obtained using different critical gap estimation methods, is summarized in Table 6 by location and type of crossing movement.

When different methods are compared to each other, the POR values revealed a wide variation. A higher value of POR was observed for the Ashworth method, whereas lower values of POR can be noted for BLRM and Indo-HCM methods. The difference in POR can be recognized by the critical gap value. The POR estimated for Indo-HCM and BLRM method is similar and statistically insignificant, attributed to the similar critical gap values (Refer to Table 5). Further, it can be noted that the POR varied between different crossing movements. A lower value of the probability of risk can be noted when drivers of the minor approach accept the gap to merge into the major approach. At high speed, un-signalized T-intersections, the vehicle along the major approach travels at a higher speed. Therefore, the drivers of the minor approach exhibit safe and cautious gap-acceptance behavior. On the contrary, drivers of the major stream accept and roll over smaller gaps and, thus, endure higher risk.

The variation in POR with the critical gap was analyzed using a scatter plot, as shown in Figure 6. A negative correlation between the probability of risk and the critical gap value is evident. For location 3, from Tables 5 and 6 lowering the value (2.77 sec) of the critical gap results in a higher (62%) probability of risk for location 3. Therefore, intersections with a higher

Table 6 *Probability of Risk using different critical gap estimation methods*

		Major Right Turn			
Location	Raff's Method	Ashworth Method	OTM	Indo-HCM	BLRM
L-1	0.70	0.77	0.42	0.36	0.36
L-2	0.66	0.72	0.52	0.26	0.26
L-3	0.56	0.65	0.54	0.37	0.37
		Minor Right Turn			
L-1	0.41	0.64	0.28	0.22	0.22
L-2	0.73	0.88	0.53	0.30	0.30
L-3	0.62	0.88	0.52	0.37	0.37

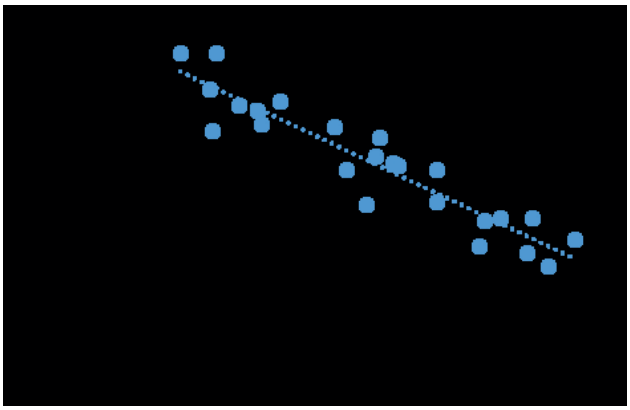

Figure 6 *Variation in the probability of risk with critical gap*

critical gap (3.44 sec) have a risk of (37 %) and are safer than intersections with a lower critical gap value. Overall, it can be concluded that the magnitude of the accepted gap and the value of the critical gap jointly influence the safety of un-signalized T-intersections.

5 Conclusions and way forward

At un-signalized T- intersections in India, a significant number of crashes and fatalities are recorded as compared to other types of intersections. Crossing conflict is one of the severe types compared to other types at un-signalized intersections. Driver's gap acceptance behavior influences traffic operations and safety at un-signalized intersections. A driver accepts or rejects the available gap for crossing movement through the intersection. The present paper explores and compares different methods of the critical gap for the high-speed un-signalized T-intersection under heterogeneous traffic conditions. The study also explores the implication of the critical gap value on the capacity and safety at an un-signalized T-intersection. The traffic data is collected for three high-speed un-signalized T-intersections and the critical gap for the study area is estimated using deterministic (Raff's, Ashworth's, and Occupancy Time Method) and probabilistic methods (Binary Logit Regression method) The comparative analysis of the estimation of the critical gap is illustrated. Some of the important conclusions, drawn from the present study, are discussed below:

1. The critical gap varies significantly by vehicle type. A lower value of the critical gap was noted for motorized two-wheelers (1.18 s) and motorized three-wheelers (1.62 s) compared to cars (2.08 s) and heavy vehicles (2.54 s). This implies that motorized two-wheelers and motorized three-wheelers manoeuver through the intersection by accepting the smaller gaps in the traffic stream, thereby enduring higher risks.
2. The critical gap values vary significantly by crossing movement. A higher value of the critical gap was noted when drivers from the minor approach performed the right-turning operation to merge into the major approach than the drivers performing the right-turning operations from the major approach. This can be attributed to the fact that at high-speed un-signalized T-intersections, the vehicle along the major approach travels at a higher speed. Therefore, the drivers of the minor approach exhibit safe and cautious gap-acceptance behavior.
3. The critical gap estimated using different methods varies significantly. For a given vehicle type and crossing movement, a lower value (1.56 s) of the critical gap (from Table 5) was derived using Ashworth's method, whereas a relatively higher value (2.24 s) of the critical gap was derived using the Binary Logit Regression method. Consistent observations were noted for different vehicle types and crossing movements.
4. For various vehicle types and crossing movement, a lower value of the critical gap is derived using the deterministic methods (Raff's method, Ashworth's method and Occupancy Time method) compared to the critical gap derived using the probabilistic method (Binary Logit Regression method). Moreover, the gap values estimated using the Binary Logit Regression method are similar to those computed using equation reported in Indo-HCM (2017).
5. The value of the critical gap significantly influences the capacity and safety of un-signalized intersections. A higher capacity value (2213 PCU/h) was noted for smaller critical gap values (2.02 s). On the other hand, a higher probability of risk (POR) (77 %) was observed for smaller critical gap values.

The estimated critical gaps do not capture the effect of the age, gender of the driver, passenger occupancy, other physical activities, variation in climate and traffic encroachments on the gap acceptance behavior. The effect of the factors mentioned above on the critical gap can be studied. The selected study areas are on high-speed un-signalized T-intersections. Therefore, the transferability of different critical gap estimation methods to un-signalized intersections in an urban area can be studied. The probability of risk can be evaluated by the vehicle type and varying traffic volume

levels. The derived POR values can be modelled as a function of traffic flow and intersection geometry-related characteristics. The severity of the crossing conflict could be quantified by correlating the size of the accepted gap and the speed of the conflicting vehicle. Further, drivers' dilemmas at un-signalized intersections can be modelled and the implication of the length of the dilemma on safety can be quantified. The study can be extended to analyze the variation in the gap acceptance based on the traffic volume by collecting more data on the sites and at different time durations.

Data availability

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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