



# Gap acceptance behavior of drivers at uncontrolled T-intersections under mixed traffic conditions

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**Abstract** Explicit traffic control measures are absent in uncontrolled intersections which make them susceptible to frequent conflicts and resulting collisions between vehicles. In developing countries like India, drivers at such intersections do not yield to higher priority movements which cause more crashes between vehicles. The objective of this study is to analyze and model the gap acceptance behavior of minor street drivers at uncontrolled T-intersections considering their aggressive nature. Three intersections in the northeast region of India have been selected as the case study area. Preliminary analysis of the data revealed that drivers behave aggressively, not because they have to wait for a long time at the stop line, but because of their lack of respect for traffic rules. Binary logit models are developed for minor road right turning vehicles which show that gap acceptance behavior is influenced by gap duration, clearing time and aggressive nature of drivers. The equations obtained were used to estimate the critical gaps for aggressive and non-aggressive drivers. Critical gaps are also calculated using an existing method called clearing behavior approach. It is also shown that the estimation of critical gap is more realistic if clearing time and aggressive behavior of drivers are considered.

**Keywords** Mixed traffic · Uncontrolled intersection · Gap acceptance · Clearing time · Aggressive behavior · Logit model

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## 1 Introduction

Intersections can be broadly classified into two categories based on traffic control measures—(1) signalized intersections (intersections controlled by traffic signals) and (2) unsignalized intersections; the latter are again classified into (a) uncontrolled intersections, (b) stop sign controlled intersections, (c) yield sign controlled intersection and (d) roundabout. In India, the majority of intersections are uncontrolled. The stop signs are observed at the minor approaches in some intersections. But, in many cases, drivers do not stop or slow down and yield the right of way to the major road traffic. As a result, the major road vehicles are bound to slow down or sometimes even stop to avoid a collision. In these non-standard circumstances, movements at these types of intersections are uncontrolled, so these forms of intersections are also considered as uncontrolled intersections in India.

Gap acceptance is usually considered at junctions where a minor street intersects a major street. If a minor street vehicle has just arrived at the junction, it may clear the intersection while rolling; otherwise, it starts the movement from rest. Drivers intending to perform simple crossing or merging maneuvers are presented with a lag and a series of gaps between vehicles in a conflicting traffic movement. The pattern of arrivals of the major street vehicles creates time gaps of different values. A gap (Fig. 1) between two vehicles is the distance between the rear bumper of the first vehicle and the front bumper of the following vehicle and is usually measured in seconds [1]. Lag (Fig. 2) is defined as the time interval between the arrivals of vehicles at a stop line of minor road and the arrival of the first vehicle at the upstream side of the conflict zone [2]. An important parameter related to gap acceptance behavior is the ‘critical gap’ which is the minimum acceptable gap to a driver

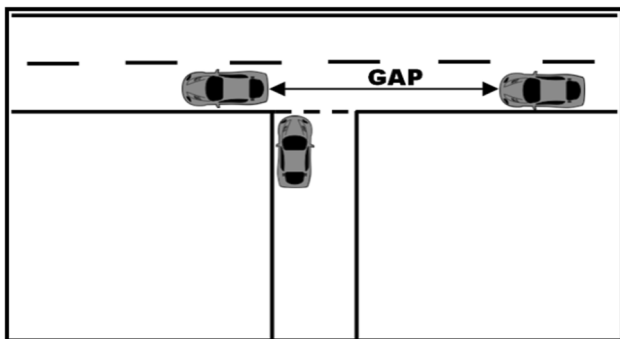


Fig. 1 Schematic diagram of gap

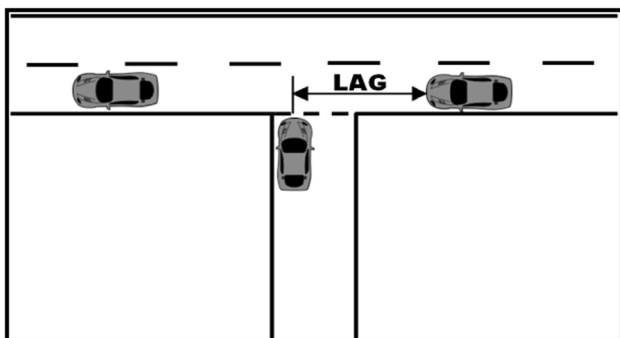


Fig. 2 Schematic diagram of lag

intending to cross a conflicting stream. In this study, the definition used for the critical gap is the gap size that is equally likely to be accepted or rejected by the driver. In other words, the gap duration corresponding to the 50th percentile of the gap acceptance probability distribution is considered as critical gap [3, 4].

Critical gap estimation becomes complex in heterogeneous traffic condition. Traffic characteristics under mixed traffic situation vary widely regarding speed, maneuverability, effective dimensions and response to the presence of other vehicles in the traffic stream. Vehicles such as two-wheelers often squeeze through the minimum possible gap and try to clear the intersection in a zigzag manner. A

single gap in the major traffic stream may be accepted by more than one vehicle moving one after another even though it is not large enough to let more than one vehicle to clear the intersection. As a result, the major road vehicles are sometimes forced to stop to let the minor road vehicles to clear the intersection. The combined effect of all these issues makes it tough to estimate the critical gap. These situations necessitate a re-look into the factors that influence the gap acceptance behavior at uncontrolled intersections where priority rules are often neglected.

This study is focused on developing logistic regression models suitable for uncontrolled intersections in developing countries like India. The response variable is the gap acceptance or rejection of a right turning vehicle from a minor road (left-hand drive rule followed in India), and the independent variables considered are gap duration, type of interval accepted by the minor street vehicle’s driver (gap or lag), forced entry of the minor street vehicles and clearing time (CT). Additionally, the values of the critical gap are estimated using clearing behavior approach [5] and compared with those obtained by logit model.

## 2 Literature review

Several methods have been developed by researchers during the past decades on gap acceptance and most of these methods assumed the drivers to be consistent. Moreover, those studies have been done under homogeneous traffic conditions. Various methodologies that have been developed so far can be broadly classified as shown in Fig. 3. A brief literature review of the past relevant studies is presented in the subsequent paragraphs. The review is grouped into studies focussing on probabilistic approach, and analysis conducted under mixed traffic condition.

The probabilistic approach takes into account the fact that the gap acceptance behavior depends not only on intersection characteristics, vehicular characteristics, opposing flow, type of control, but also on qualitative

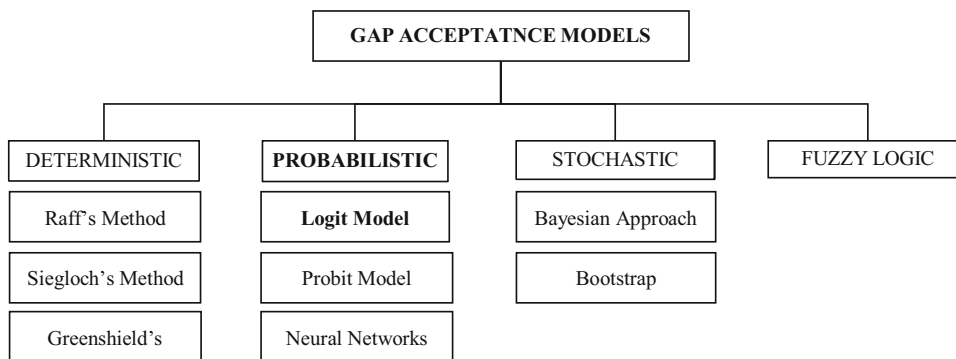
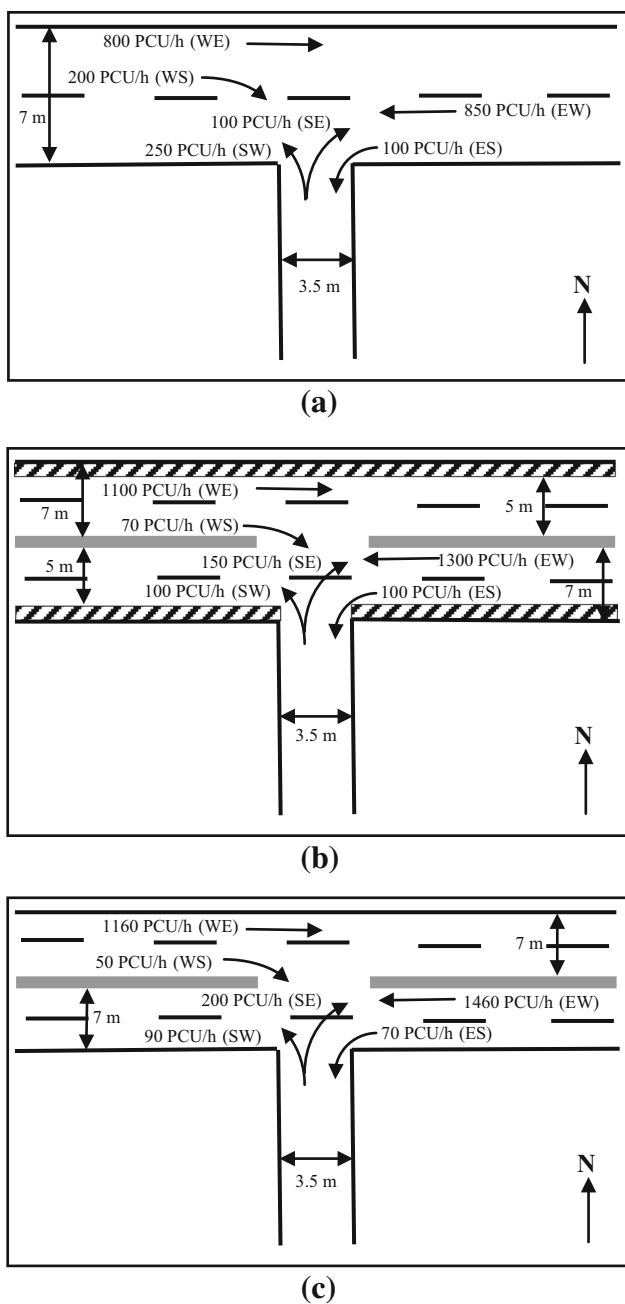


Fig. 3 Classification of various approaches for gap acceptance modeling



**Fig. 4** Geometric features and traffic composition of **a** intersection A, **b** intersection B and **c** intersection C

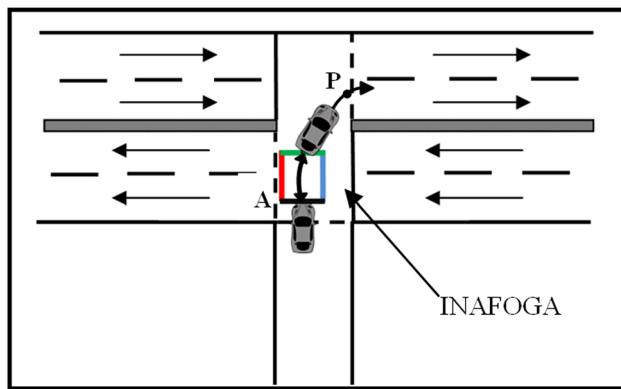
factors like drivers’ psychological and socioeconomic status, factors related to weather, pavement and light conditions, and factors related to the vehicle occupancy. The complexity is further increased in the case of heterogeneous traffic conditions that typically exist in developing countries, where the rules regarding assignment of the right of way are often neglected.

Maze [6] modeled the gap acceptance behavior using a logit model which closely approximates the probit model. Madanat et al. [7] proposed queuing delay as a new

parameter describing the elapsed time between joining the queue and arriving at the intersection stop bar. Stop bar delay have also been included in the proposed gap acceptance logit models. Brilon et al. [8] gave a comparison of lag, Harder, Raff, Ashworth, logit and probit method, Hewitt, maximum likelihood procedure and Siegloch methods of critical gap estimation. Gattis and Low [9] compared Siegloch, Greenshields, Raff, acceptance curve, and logit methods to derive critical lag and gap values. Zohdy et al. [10] analyzed the effects of wait time and rain intensity on drivers’ gap acceptance behavior. They used logit models to study the gap acceptance behavior. The logit models developed revealed that the acceptable gap duration decreases as a function of driver’s wait time at the intersection and increases as the rain intensity increases. Devarasetty et al. [11] made an effort to model gap acceptance behavior of drivers by logistic regression using various traffic and geometric characteristics. A binary logit model using all gap and lag data was developed, and the gap acceptance behavior was found to be influenced by a gap or lag, and two separate models for gap and lag were developed. Serag [12] used a gap/lag acceptance binary logit model considering the aggressive behavior of drivers as a factor which influences the probability of acceptance of a gap or lag. Kaisy and Abbany [13] had also investigated the aggressive behavior of minor street drivers at priority unsignalized intersections. A behavioral model is formulated which is incorporated into a simulation framework to estimate the delay and conflict measures at unsignalized intersections. Liu et al. [14] considered a four-legged intersection to investigate the factors affecting through stream vehicles’ preemptive/yielding decisions when it comes across another vehicle on the conflicting through stream. Among all the parameters found to be significant, the difference in approach speed between the conflicting straight moving vehicles is found to be the most influencing parameter affecting driver’s preemptive/yielding decisions.

Ashalatha and Chandra [5] has developed an alternate procedure for estimation of critical gap known as ‘clearing behavior approach (CBA)’ which can be used for Indian road condition. Amin and Maurya [15] calculated the critical gap using logit model along with others methods and compared them. Sangole et al. [16] used an adaptive neuro-fuzzy interface system (ANFIS) approach to model the gap acceptance behavior of two-wheelers at uncontrolled intersections. Patil and Sangole [17] studied the behavior of two-wheelers at limited priority uncontrolled T-intersections using various approaches along with logit method. The critical gap values estimated for young drivers was significantly less compared to middle and old age drivers.

The literature review [12–14] revealed that very few studies are available which considers the aggressive

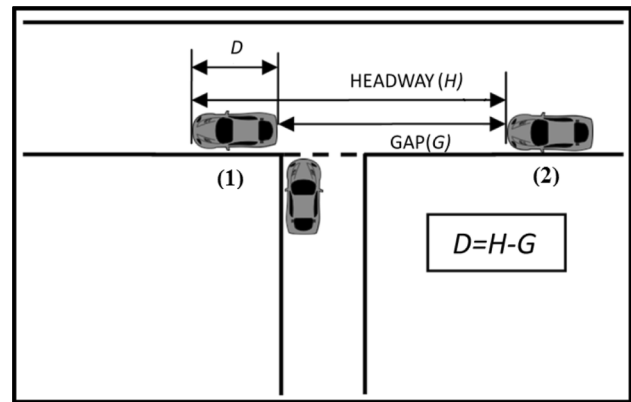


**Fig. 5** Definition of clearing time

behavior of drivers. Most of the studies on unsignalized intersections have been conducted in developed countries where drivers are, in general, found to be not aggressive. Studies on uncontrolled intersections under mixed traffic conditions have focused on various aspect of heterogeneity of traffic [5, 15–17], but the aggressive behavior of drivers has not been specifically considered yet. The present study focuses on the effect of aggressive driving behavior on critical gap at uncontrolled intersections. The critical gap thus obtained may be used to estimate the capacity of such intersection more realistically.

### 3 Study of selected intersections

Three uncontrolled T-intersections, viz. two in Silchar city (named as A and B) and the third in Guwahati (named as C) are selected as the case study area. The geometrical features and traffic composition of the intersections A, B and C during peak hours (10:00 am–12:00 noon) are shown in Fig. 4a–c, respectively. The movements EW (east to west), SE (south to east), etc. are shown along with peak hour traffic volumes in parenthesis. The number of vehicles is converted into passenger car unit (PCU) values to account for the heterogeneity of the traffic. The minor roads at all the intersections are of width 3.5 m. The major road at intersection A is two-lane undivided, whereas, at intersections B and C, it is four-lane divided. All approaches of each intersection have sufficient sight distance and are on level ground. No side friction, such as vehicle parking and bus stops, is observed at intersections A and C at the time of data collection. However, on-street parking was seen on the major road of intersection B. As a result, the effective carriageway width of the major road at intersection B is reduced from 7 to 5 m. The upstream and downstream intersections are sufficiently away from the study intersections.



**Fig. 6** Difference between gap and headway

The traffic scenario at the selected uncontrolled intersections is found to be very complex. So, a new understanding of the situation is deemed necessary. After careful observation, the following strategies have been adopted for modeling the gap acceptance behavior under mixed traffic condition using a logit model.

#### 3.1 Consideration of clearing time in logit model under mixed traffic condition

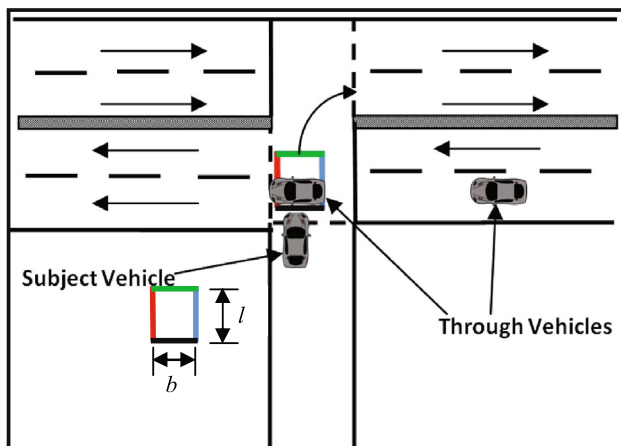
The minor road vehicles at the selected intersections are found to clear the intersection in an unusual manner. The time required to clear the intersection area is varying over a wide range of values. Thus, the value of gap accepted will depend on the time needed in clearing the intersection. The concept of the clearing phenomenon of the minor street driver has been adopted from Ashalata and Chandra [5]. The influence area in an uncontrolled intersection is termed as influence area for gap acceptance (INAFOGA) which has a rectangular shape. A detailed description of the INAFOGA is given in Sect. 4. A right turning vehicle from the minor street waits at position A marked in Fig. 5. To clear the intersection safely, it should accept a gap/lag which gives enough time for its back bumper to cross the point P [5]. However, it has been observed in our case study area that the minor street vehicle chooses a gap or lag if the time interval is large enough for it just to cross the INAFOGA. So, the vehicle is considered to have cleared the intersection if the back bumper just reaches the green line of the INAFOGA from position A.

#### 3.2 Gaps need to be measured from the back bumper of the leading vehicle to the front bumper of the following vehicle

The speed of major road traffic has been found to drop to about 20 km/h when the traffic volume becomes very high. At such low speed, the difference between the values of the



**Fig. 7** Forced entry made by the car bringing the two-wheeler to a complete halt



**Fig. 8** Schematic representation of INAFOGA for minor road right turn movement

gap ( $G$ ) and headway ( $D$ ) becomes quite significant which is explained in Fig. 6. So, considering the average length of the leading vehicle (vehicle-1) to be 4.343 m (IRC: SP-41), and speed of the vehicle as 20 km/h, values of the gap have been found to be about 0.78 s lower than headway values. Therefore, gaps have been measured from the back bumper of the leading vehicle to the front bumper of the following vehicle which is more realistic than taking headway as a gap, irrespective of the speed of vehicles.

### 3.3 Consideration of forced entry and ideal entry separately

A minor street vehicle is considered to have made a forced entry into the intersection area when it forces the major road vehicles to slow down or sometimes even come to a complete stop to clear the intersection (Fig. 7). However, clearing the intersection without interrupting the flow of major road vehicles is taken to be an ideal entry. Under mixed traffic scenario, forced entry is quite a common phenomenon. As a result, these two types of entries have

been considered separately in this study to calculate the percentage of aggressive drivers at these intersections.

## 4 Data collection and extraction

Videographic survey was carried out for data collection. Data were collected in the month of September and October 2016. Video recording was done during peak hours (10:00 am–12:00 noon). The video camera was so placed that all movements of the vehicles could be recorded. The available modes at those intersections were two-wheelers, auto rickshaws, and four-wheelers. Cycle-rickshaws and heavy vehicles were rarely observed at the minor approaches of those intersections, and hence were not considered in the analysis. After the video shooting of the uncontrolled T-intersections, extraction of relevant decision variables was carried out based on the concept of 'INAFOGA' as given by Ashalatha and Chandra in their theory of gap acceptance under mixed traffic conditions in India [5]. The video data collected from the field was played in a video player named as KM Player capable of running videos at a frame rate of 25 frames per second.

The figure shown below represents the schematic diagram of an uncontrolled T-intersection on a 4-lane divided carriageway representing the 'INAFOGA' method (Fig. 8). The INAFOGA of a right turning vehicle is the rectangular area bounded by the red, green, blue and black lines. The black line represents the stop line of the minor road vehicle while the blue and red lines form the upstream and downstream ends of 'INAFOGA'. The length ( $l$ ) of the area measures 3.5 m (lane width), while the breadth ( $b$ ) is almost 1.5 times the width of the crossing vehicles.

The time frames chosen during data extraction are as follows:

- $T_0$ : the time instant when the front bumper of the subject vehicle touches the black line of the INAFOGA.
- $T_1$ : the time instant when the front bumper of the first through traffic vehicle after the arrival of the subject vehicle touches the upstream end of INAFOGA (blue line).
- $T_n$ : the time instant when the back bumper of the  $n$ th through traffic vehicle after the arrival of the subject vehicle touches the upstream end of the INAFOGA.
- $T_{n+1}$ : the time instant when the front bumper of the  $(n + 1)$ th through traffic vehicle after the arrival of the subject vehicle reaches the upstream end of INAFOGA.
- $T_p$ : the time instant when the back bumper of the subject vehicle touches the green line of the INAFOGA.

**Table 1** Statistical summary of the obtained data

Intersection A			
	Aggressive drivers (%)	Non-aggressive drivers (%)	Total (%)
<i>Total observations</i>	37	63	100 (200 observations)*
<i>Distribution by mode</i>			
Two-wheeler	13	41	54
Auto rickshaw	11	12	23
Car	13	10	23
<i>Distribution by number of rejected gaps</i>			
0	27	48	75
1	7	12	19
2	2	2	4
3	1	1	2
<i>Type of gap</i>			
Gap	10	18	28
Lag	27	45	72
Intersection B			
	Aggressive drivers (%)	Non-aggressive drivers (%)	Total (%)
<i>Total observations</i>	35	65	100 (238 observations)*
<i>Distribution by mode</i>			
Two-wheeler	13	45	58
Auto rickshaw	7	8	15
Car	15	12	27
<i>Distribution by number of rejected gaps</i>			
0	18	38	56
1	5	13	18
2	4	7	11
3	2	3	5
4	3	1	4
5	1	1	2
> 5	2	2	4
<i>Type of gap</i>			
Gap	17	27	44
Lag	18	38	56
Intersection C			
	Aggressive drivers (%)	Non-aggressive drivers (%)	Total (%)
<i>Total observations</i>	36	64	100 (198 observations)*
<i>Distribution by mode</i>			
Two-wheeler	8	36	44
Car	28	28	56
<i>Distribution by number of rejected gaps</i>			
0	11	26	37
1	16	10	26
2	1	9	10
3	1	6	7
4	3	3	6
5	2	3	5
> 5	2	7	9

**Table 1** continued

Intersection C			
	Aggressive drivers (%)	Non-aggressive drivers (%)	Total (%)
<i>Type of gap</i>			
Gap	24	40	64
Lag	12	24	36

\*Number of accepted gap/lag data sets

The time frames extracted from survey video were then compiled and entered into an MS Excel spreadsheet and the following decision variables were calculated:

- Gap/lag:  $G = T_{n+1} - T_n$  ( $n = 0, 1, 2, \dots$ ). When  $n = 0$ ,  $G = T_1 - T_0$  is the lag; when  $n = 1, 2, 3, \dots$ ,  $G$  is the gap.
- Clearing time:  $T_c = T_p - T_0$ .
- Forced entry: If a minor road vehicle clears the intersection by slowing the major road vehicles, it is considered to be a forced entry, represented by a dummy 1, otherwise 0.

## 5 Preliminary data analysis

Data are extracted from the video, and a set of 1414 observations have been recorded for all the selected study area. Out of these, the accepted gap/lag data are used to understand the aggressive behavior of the minor street drivers and a statistical summary is presented in Table 1.

The primary statistics obtained from Table 1 are as follows:

- The percentage of two-wheelers at intersection A was 54%, whereas intersection B had 58% two-wheelers and intersection C had 56% four-wheelers.
- The percentage of vehicles showing aggressive behavior is found to be quite high (Table 1). 24% two-wheelers at intersection A, 22% two-wheelers at intersection B and 18% four-wheelers at intersection C are found to have shown aggressive behavior. A new parameter 'forced entry (F)' is introduced to address the aggressive behavior of the minor street drivers.
- The percentage of aggressive drivers forcing themselves through in the first available gap (i.e., lag) at intersections A, B, and C are 73%, 53% and 31%, respectively.
- The percentage of aggressive drivers who had to reject three or more than three gaps (which includes the lag) at intersection A, B and C are 4%, 23%, and 22%, respectively.

Based on the statistics mentioned above, the following conclusions (1–4) are drawn:

- Only the vehicle categories with higher proportion have been selected for each intersection; i.e., two-wheelers at intersections A and intersection B and four-wheelers at intersection C.
- No direct relation between aggressive behavior and the number of rejected gaps is evident from the data as the maximum forced entry occurs with zero rejected gap (i.e., lag) at all the intersections. It can be said that the minor street drivers behave aggressively not because they have to wait for a long time, but because of their lack of respect for traffic rules.
- A significant amount of vehicles (37%–75%) are found to be entering the intersection forcibly or ideally at the first available gap, i.e., lag, so, a separate parameter 'gap/lag ( $I_{GL}$ )' is taken which indicates whether the driver has accepted a gap or lag.
- The percentage of aggressive drivers accepting 'lag' is the highest at intersection A. This suggests that a vast number of the minor road drivers clear the intersection area as soon as they reach the intersection. The vehicles approaching from the minor road pay less attention to the major road traffic and do not wait for a suitable gap to clear the intersection safely. Thus, if we compare these three intersections, the major road gets the least priority at intersection A (73%) and the highest priority at intersection C (31%).

The gap acceptance behavior of two-wheelers (intersections A and B) and four-wheelers (intersection C) at forced and ideal entry situations are graphically shown in Fig. 9.

The cumulative percentage of gap acceptance of aggressive and non-aggressive drivers is plotted with respect to gap duration. All the aggressive drivers are found to have accepted a gap less than or equal to 6 s, whereas non-aggressive drivers accept gaps as high as 11 s. Additionally, it is evident from the graph that for a given gap, a higher percentage of aggressive drivers accept the gap than

**Table 2** List of variables extracted from videotape

Variable	Symbol	Description
Gap/lag time (s)	$G$	Lag or gap duration in seconds
Clearing time (s)	$T_c$	Time taken in seconds by the minor street vehicle to clear the intersection area
Gap or lag	$I_{GL}$	Type of interval presented to the driver, represented by a dummy = 1 for gap and 0 for lag
Yield	$F$	Forced entry of minor street vehicles, represented by a dummy = 1 if major street vehicle yields (stopped or speed is reduced) and 0 if not
Accept or reject	$O_{AR}$	Driver accepted or rejected the gap/lag, represented by a dummy = 1 in the case of acceptance and 0 in the case of rejection

**Table 3** Statistical parameters for accepting gap distribution

Intersection	Gap accepted (s)		K–S test statistic				Critical values (K–S test)*	
	Mean	SD	Normal	Lognormal	Gamma	Dagum		Dagum (4p)
A	5.2528	1.8835	0.10894	0.06143	0.06197	0.05225	0.05229	0.13067 (108)**
B	4.1162	1.2204	0.12334	0.07622	0.09005	0.03731	0.03743	0.10943 (154)
C	5.8630	2.0283	0.07269	0.06055	0.05296	0.06341	0.04562	0.12609 (116)

\*95% confidence interval, \*\*number of observations

the non-aggressive drivers. It indicates that the aggressive behavior of drivers affects their gap acceptance decision.

Based on the results obtained by preliminary analysis of the data and field observations, the following utility explanatory variables are considered in this study to address the traffic condition prevalent in Indian roads (Table 2).

### 5.1 Distribution of gaps

Gap acceptance data of two-wheelers (for intersections A and B) and four-wheelers (for intersection C) are tried to fit into a normal distribution, lognormal distribution, gamma distribution, Dagum distribution and Dagum (4p) distributions separately for each intersection. Kolmogorov–Smirnov test (K–S test) was performed on the gap acceptance data to measure the goodness of fit of these distributions. The K–S test statistic of fitting these distributions is presented in Table 3. The critical value at 95% confidence level for each intersection is also given in Table 3. The critical value depends on the sample size which is provided in the parenthesis along with the critical values in the last column of Table 3.

As may be seen, at 95% confidence interval, Dagum distribution has the lowest K–S test statistic for two-wheelers, whereas Dagum (4p) distribution has the lowest K–S test statistic for four-wheelers. Moreover, all the K–S values for Dagum and Dagum (4p) distributions are quite lower than the critical values. Thus, it is concluded that the gaps accepted by two-wheelers follow Dagum distribution,

whereas, in the case of four-wheelers, it is Dagum (4p) distribution.

## 6 Gap acceptance model

A driver approaching an uncontrolled intersection through the minor road observes a lag and numerous gaps in the major roadway. The driver evaluates the lag/gap on the major road and makes a choice whether to accept or reject it. This decision to accept/reject a gap varies from driver to driver, and it is considered to be random. Moreover, binary explanatory variables such as type of interval accepted by the driver (gap or lag), aggressive or non-aggressive maneuvers, which are used to address the driver characteristics can be incorporated into the logit model. Logistic regression is used to formulate the model based on such discrete choice behavior phenomenon which is explained in the subsequent paragraphs.

### 6.1 Model structure

To find out a sufficient gap in the major road traffic, minor street drivers need to choose between the two alternatives, i.e., ' $i$ ' and ' $j$ ', where  $i$  means accepting the gap for crossing or merging maneuver and  $j$  means rejecting the gap.

A driver waiting to make a maneuver has a utility for accepting or rejecting a given gap. If the driver accepts a gap, he/she can avoid any further delay at the intersection,



**Table 4** Statistical results considering aggressive behavior of drivers

Variable	Coefficient	Standard error	<i>t</i> -statistic	<i>p</i> value
<i>Intersection A (two-wheelers)</i>				
Intercept	− 5.6812	2.3457	− 2.4219	0.016
<i>G</i>	3.0490	0.6979	4.3690	0.000
<i>T<sub>c</sub></i>	− 1.7998	0.7736	− 2.3266	0.020
<i>F</i>	2.8305	1.0249	2.7618	0.006
McFadden $R^2 = 0.746$			Log-likelihood function = − 19.698	
Percentage of right predictions = 93.8%			Chi-squared statistic = 115.892	
<i>Intersection B (two-wheelers)</i>				
Intercept	− 3.8802	1.7153	− 2.2624	0.024
<i>G</i>	3.1074	0.4791	6.4877	0.000
<i>T<sub>c</sub></i>	− 2.6051	0.6779	− 3.8431	0.000
<i>F</i>	2.8122	1.1372	2.4731	0.013
McFadden $R^2 = 0.745$			Log-likelihood function = − 41.173	
Percentage of right predictions = 94.4%			Chi-squared statistic = 240.951	
<i>Intersection C (four-wheelers)</i>				
Intercept	− 1.0166	1.4871	− 0.6846	0.494
<i>G</i>	1.4770	0.2274	6.5160	0.000
<i>T<sub>c</sub></i>	− 1.6171	0.4131	− 3.9196	0.000
<i>F</i>	3.9504	0.8624	4.5880	0.000
McFadden $R^2 = 0.752$			Log-likelihood function = − 39.156	
Percentage of right predictions = 96.7%			Chi-squared statistic = 237.507	

**Table 5** Statistical results without considering aggressive behavior of drivers

Variable	Coefficient	Standard error	<i>t</i> -statistic	<i>p</i> value
<i>Intersection A (two-wheelers)</i>				
Intercept	− 4.1068	1.9419	− 2.1148	0.034
<i>G</i>	2.6159	0.53912	4.8523	0.000
<i>T<sub>c</sub></i>	− 1.5004	0.63727	− 2.3544	0.019
McFadden $R^2 = 0.680$			Log-likelihood function = − 24.867	
Percentage of right predictions = 92.3%			Chi-squared statistic = 105.554	
<i>Intersection B (two-wheelers)</i>				
Intercept	− 5.1412	1.6871	− 3.0474	0.002
<i>G</i>	3.2029	0.46253	6.9246	0.000
<i>T<sub>c</sub></i>	− 1.9146	0.62149	− 3.0806	0.002
McFadden $R^2 = 0.720$			Log-likelihood function = − 45.251	
Percentage of right predictions = 94.0%			Chi-squared statistic = 232.797	
<i>Intersection C (four-wheelers)</i>				
Intercept	− 1.1211	1.2120	− 0.92496	0.355
<i>G</i>	1.5372	0.20316	7.5668	0.000
<i>T<sub>c</sub></i>	− 1.3763	0.34848	− 3.9493	0.000
McFadden $R^2 = 0.643$			Log-likelihood function = − 56.418	
Percentage of right predictions = 93.0%			Chi-squared statistic = 202.982	

whereas rejecting the gap will increase safety because taking a short gap can be risky.

The total utility ( $U$ ) is considered as an additive combination of a deterministic term (i.e., observed utility ( $V$ ))

and a random term (i.e., unobserved utility ( $\varepsilon$ )) [18]. A simple utility function for accepting and rejecting a gap is given by Eqs. (1) and (2), respectively:

**Table 6** Prediction success table (considering aggressive behavior)

	Intersection A			Intersection B			Intersection C		
	Suc-obs	Fail-obs	Total	Suc-obs	Fail-obs	Total	Suc-obs	Fail-obs	Total
Suc-pred	13	3	16	27	3	30	28	3	31
Fail-pred	2	14	16	2	26	28	2	28	30
Total	15	17	32	29	29	58	30	31	61
Sensitivity = 0.87	Specificity = 0.82			Sensitivity = 0.93		Specificity = 0.90	Sensitivity = 0.93		Specificity = 0.90
Type II error = 0.13	Type I error = 0.18			Type II error = 0.07		Type I error = 0.10	Type II error = 0.07		Type I error = 0.10

Suc-pred: success prediction, Suc-obs: success observation, Fail-pred: failure prediction, Fail-obs: failure observation

**Table 7** Prediction success table (without considering aggressive behavior)

	Intersection A			Intersection B			Intersection C		
	Suc-obs	Fail-obs	Total	Suc-obs	Fail-obs	Total	Suc-obs	Fail-obs	Total
Suc-pred	13	3	16	28	5	33	26	5	31
Fail-pred	2	14	16	1	24	25	4	26	30
Total	15	17	32	29	29	58	30	31	61
Sensitivity = 0.87	Specificity = 0.82			Sensitivity = 0.96		Specificity = 0.83	Sensitivity = 0.87		Specificity = 0.84
Type II error = 0.13	Type I error = 0.18			Type II error = 0.04		Type I error = 0.17	Type II error = 0.13		Type I error = 0.16

Suc-pred: success prediction, Suc-obs: success observation, Fail-pred: failure prediction, Fail-obs: failure observation

**Table 8** Equation sets for estimating critical gap

	Equation set I (from Table 4)	Equation set II (from Table 5)
Intersection A	$G_{cr} = 1.8632 + 0.5903 T_c - 0.9283 F$	$G_{cr} = 1.5699 + 0.5736 T_c$
Intersection B	$G_{cr} = 1.2487 + 0.8384 T_c - 0.9050 F$	$G_{cr} = 1.6052 + 0.5978 T_c$
Intersection C	$G_{cr} = 0.6883 + 1.0948 T_c - 2.6746 F$	$G_{cr} = 0.7293 + 0.8953 T_c$

$G_{cr}$  denotes critical gap in seconds

**Table 9** Estimation of critical gap (s) by various approaches

Intersection	Logit model considering aggressive behavior (using equation set I)		Logit model without considering aggressive behavior (using equation set II) ( $E_3$ )	Clearing behavior approach ( $E_4$ )	Variation $[(E_2 - E_3)/E_2] \times 100$ (%)	Variation $[(E_2 - E_4)/E_2] \times 100$ (%)
	Aggressive ( $E_1$ )	Non-aggressive ( $E_2$ )				
A (two-wheeler)	2.44	3.37	3.03	3.15	10.09	6.53
B (two-wheeler)	2.06	2.97	2.83	2.90	4.71	2.36
C (four-wheeler)	2.12	4.79	4.09	4.55	14.61	5.01

$$U_i = V_i + \varepsilon_i, \tag{1}$$

$$V_i = \alpha + \beta_1 X_{i1} + \beta_2 X_{i2} + \dots + \beta_k X_{ik}, \tag{3}$$

$$U_j = V_j + \varepsilon_j, \tag{2}$$

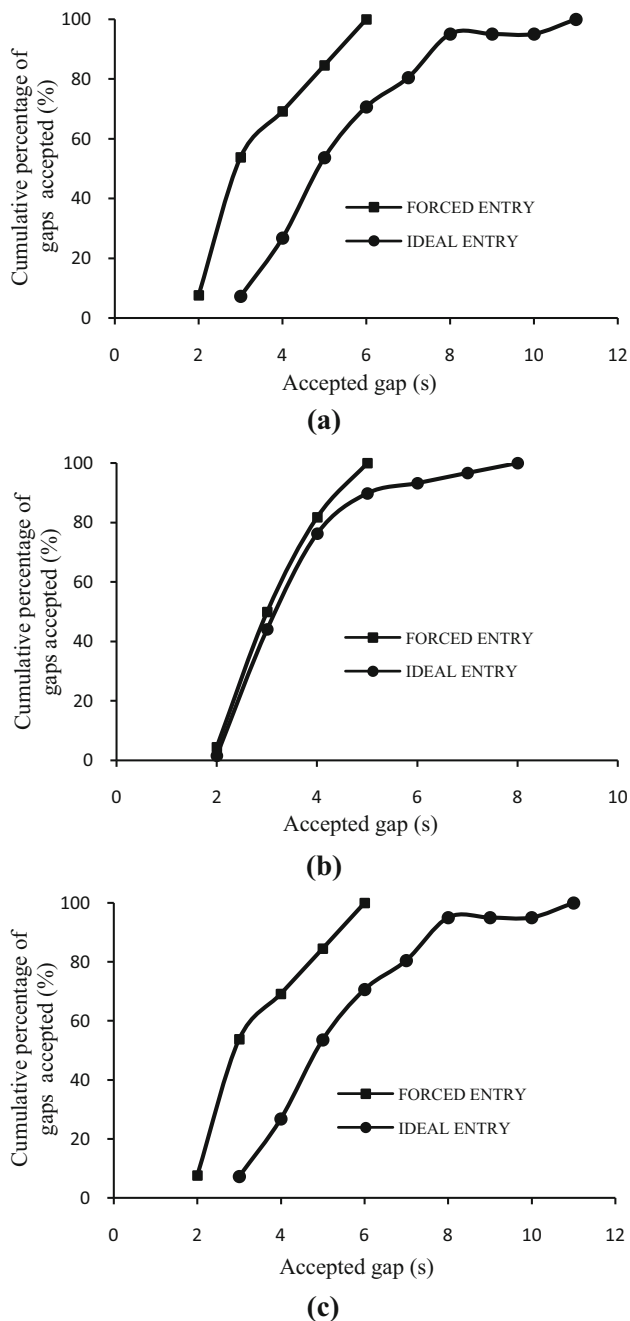
$$V_j = \alpha + \beta_1 X_{j1} + \beta_2 X_{j2} + \dots + \beta_k X_{jk}, \tag{4}$$

where  $U_i$  is the total utility for accepting a gap and  $U_j$  the total utility for rejecting a gap.

where  $\alpha, \beta_1, \beta_2, \dots, \beta_k$  are unknown parameters to be estimated;  $X_{ik}$  is the  $k$ th attribute in case of acceptance;  $X_{jk}$  is the  $k$ th attribute in case of rejection; and  $k$  is the number of attributes.

The deterministic component ( $V_i$ ) is the observed utility, which is a function of different variables ( $X_{ik}/X_{jk}$ ) that affect gap/lag acceptance. This utility function can be expressed as Eqs. (3) and (4):

The logit model assumes that in Eqs. (1) and (2), the error terms ( $\varepsilon_i, \varepsilon_j$ ) are Gumbel distributed [3]. Under this assumption, the probability that a randomly selected driver



**Fig. 9** Cumulative percentage of gap acceptance for aggressive and non-aggressive drivers of **a** intersection A, **b** intersection B and **c** intersection C

will accept a gap,  $P_i(t)$ , is given by the logit function as Eq. (5):

$$P_i(t) = 1/[1 + \exp(-V_i)] \tag{5}$$

The utility equation for gap acceptance obtained from Eq. (5) is shown in Eq. (6):

$$\begin{aligned} \ln[P_i(t)/\{1 - P_i(t)\}] &= V_i \\ &= \alpha + \beta_1 X_{i1} + \beta_2 X_{i2} + \dots + \beta_k X_{ik}. \end{aligned} \tag{6}$$

**6.2 Model estimation**

As discussed in the preliminary data analysis section, two-wheelers from intersections A and B and four-wheelers for intersection C have been considered for gap acceptance modeling. Totally, 162 observations for two-wheelers at intersection A, 292 for two-wheelers at intersection B, and 304 for four-wheelers at intersection C are recorded. Then, 80% of these observations are randomly selected to develop the model, and the rest has been kept for model validation. Logistic regression is carried out by using SHAZAM to obtain the gap acceptance models. The binary variable  $I_{GL}$ , indicating whether a gap or lag has been accepted, was not found to be significant, thus not included in the models.

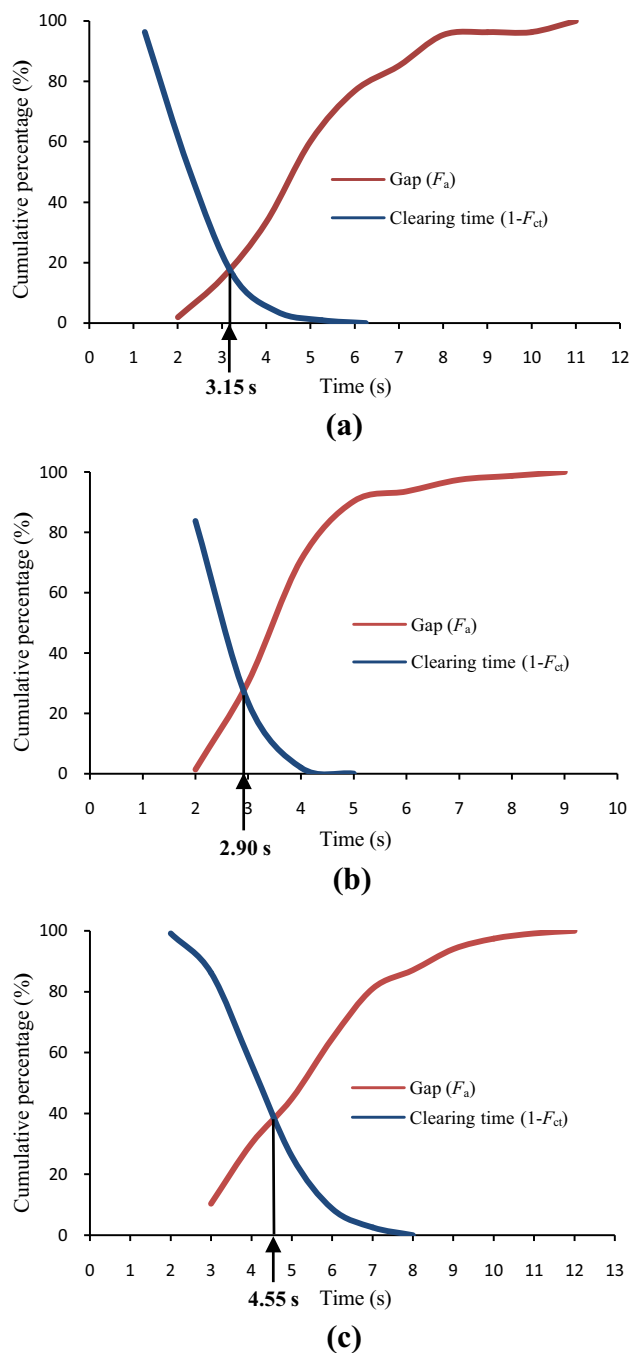
Gap acceptance models are also developed considering gap duration and clearing time. Forced entry into the intersection is not considered in these models, which mean that all the minor street drivers clearing the intersections are deemed to behave alike. The statistical results of the most significant models are reported in Tables 4 and 5. Log-likelihood function, McFadden  $R^2$  values, percentage of right predictions and Chi-squared statistics are also shown in the tables.

The models in Table 4 show that the gap acceptance probability increases with an increase in the gap duration ‘ $G$ ’ and a decrease in the clearing time ( $T_c$ ). It is so because accepting a larger gap is easier which increases the probability of gap acceptance. The likelihood of accepting a gap increases with a decrease in clearing time because it becomes easier for drivers to take smaller gaps. The  $t$ -statistic values show that the weight of ‘ $G$ ’ is more than that of ‘ $T_c$ ’ at all the intersections. Given values of ‘ $G$ ’ and ‘ $T_c$ ’, the positive sign of the coefficient of forced entry ‘ $F$ ’ shows that aggressive drivers have a larger probability of accepting a gap as compared to non-aggressive drivers.

The models in Table 5 are developed considering gap duration and clearing time only. McFadden  $R^2$  values and percentage of right predictions are found to be lesser than the corresponding values in Table 4.

**7 Model validation**

The models are validated using 20% randomly selected data from complete collected data for all the selected locations. Selections of the 20% random data are different for different intersections. The 20% data are taken for



**Fig. 10** Estimation of critical gap by clearing behavior approach for **a** intersection A **b** intersection B and **c** intersection C

selected category of the vehicle of respective intersections. The probability values derived from the models were rounded to 0 or 1 to compare with the actual observation. It is assumed that, if the probability of accepting a gap is less than 0.5, the gap is rejected, and it is designated as 0. Similarly, if the probability is found to be greater than or equal to 0.5, the gap is accepted, and it is identified as 1. Type I error, type II error, sensitivity and specificity are

also calculated for each of the prediction models. Type I error is said to have occurred when the null hypothesis is rejected, but it is, in fact, true. Type II error occurs when a null hypothesis is accepted, but it is, in fact, false. Sensitivity (one minus type II error) represents the ability of a model to identify correctly whether a gap is accepted, whereas specificity (one minus type I error) shows the ability of a model to identify correctly whether a gap is rejected. The prediction success table for the three intersections is presented in Tables 6 and 7.

The values of sensitivity and specificity are above 80% in all the models which indicates that the models perform reasonably well in predicting whether a gap would be accepted or rejected.

## 8 Estimation of critical gap

The critical gap is computed by setting the probability of accepting a time interval to 0.5 from the given equations (Tables 4, 5). The values of critical gap obtained by various procedures are shown in Table 8.

It is found that the average value of clearing time of vehicles at intersections A, B and C are 2.55 s (two-wheelers), 2.05 s (two-wheelers) and 3.75 s (four-wheelers), respectively. The critical gap values are estimated for each intersection considering the average values of clearing time. The critical gaps are estimated using the equation set I for aggressive and non-aggressive drivers. Critical gap values were also estimated using equation set II in which aggressive behavior of drivers is not considered. The estimated critical gaps are shown in Table 9.

Clearing behavior approach has proven to give satisfactory results in mixed traffic conditions so far [5, 15]. The clearing time curve ( $1-F_{ct}$ , where  $F_{ct}$  is the cumulative frequency distribution curve for clearing time) and the corresponding gap acceptance cumulative frequency curve ( $F_a$ ) intersect at a point which indicates a situation when clearing time is just equal to the gap accepted. The time axis coordinate of the intersection point gives the value of critical gap. Figure 10 shows the critical gap estimation by clearing behavior approach for the selected vehicle categories in the study areas. The values are presented in Table 9.

It is observed from Table 9 that the values of critical gap in column A is less than column B while using the equation set I. That is because aggressive drivers attempt to clear the intersection by taking a gap which might force the major road vehicles to either slow down or even come to a complete stop. A non-aggressive driver under similar circumstances would have waited for a larger gap to clear the intersection safely. As a result, the critical gap of

aggressive drivers is found to be smaller than that of non-aggressive drivers.

Another observation is that the critical gap values obtained by equation set I for non-aggressive drivers is greater by 4.44%–14.61% as compared to those given by equation set II. These values are also found to be greater by 1.62% to 5.40% than the values obtained by the clearing behavior approach. The values obtained by equation set II are found to be the lowest among the three methods. The results suggest that the clearing behavior approach gives higher values of critical gap than the logit method if the aggressive behavior is not taken into consideration. This observation is consistent with the studies under mixed traffic conditions [5, 15]. However, incorporating aggressive behavior helps to visualize the actual scenario because the critical gaps can be obtained for aggressive and non-aggressive drivers separately.

Another observation is that the value of critical gap achieved by any approach for two-wheelers is lower in intersection B as compared to intersection A. A possible reason for this is the side friction on the major road which reduces the speed of vehicles. Hence, smaller gaps are accepted by minor street drivers at this intersection.

## 9 Summary and conclusion

In this paper, gap acceptance behavior analyses of two-wheelers and four-wheelers at uncontrolled T-intersections are presented. The videographic survey was carried out at three uncontrolled intersections with the help of video camera—two in Silchar, and one in Guwahati. The purpose was to model gap acceptance behavior of drivers and to find the critical gaps which are widely used in the intersection operational analysis and capacity estimates. Erratic maneuvers in the intersection area and aggressive driving are two common behavior of drivers observed at these intersections. Preliminary analysis of the data revealed that the gap accepted by two-wheelers follow Dagum distribution, whereas, in the case of four-wheelers, it follows Dagum (4p) distribution. It was also concluded by analyzing the data that drivers behave aggressively because of their lack of respect for traffic rules, rather than due to drivers losing his patience because of unavailability of a suitable gap.

Binary logit models were developed for two-wheelers at intersections A and B and four-wheelers at intersection C, to predict the probability of accepting or rejecting a given gap or lag. The manner in which a driver clears the intersection is not consistent at these intersections, thus affecting the value of critical gap. Apart from considering the gap duration which is an obvious factor, the variables considered in the models are clearing time and aggressive

nature of drivers (forced entry). The variable, ‘forced entry’ of minor street vehicles, which had not been introduced in previous studies under mixed traffic condition, was found to be significant in the models. The model analyzes yielded critical gap in the range of 2.93–4.79 s for non-aggressive drivers, whereas the values are in the range of 2.02–2.40 s for aggressive drivers. The critical gaps were also obtained using logit model without considering the aggressive behavior of drivers. The values were in the range of 2.80–4.09 s. Clearing behavior approach was also used to determine the values of critical gap at these intersections. It is found that the results obtained by the proposed method help in differentiating between aggressive and non-aggressive drivers at an uncontrolled intersection.

The data extraction procedures and the analysis presented in this study can be implemented at uncontrolled intersections in countries where mixed traffic condition exists. Moreover, the methodology adopted in this study addresses the aggressive behavior of drivers. Considering the scarcity of studies on the aggressive behavior of drivers, this approach can be a valuable reference for similar studies at uncontrolled intersections where rules of priority are often neglected. Further studies are underway to analyze how the speed and type of oncoming vehicles affect a driver’s decision-making. In this study, only minor street right turning movement at T-intersections has been considered; the procedure can be extended to analyze the gap acceptance behavior of major street right turning vehicles as well. Studies on four-legged intersections and effect of other parameters such as geometric features, side friction, driver’s characteristics can be taken into account to gain further understanding of traffic behavior at uncontrolled intersections.

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## References

1. Elefteriadou L (2014) An introduction to traffic flow theory. Springer, New York
2. Polus A (1983) Gap acceptance characteristics at unsignalised urban intersections. *Traffic Eng Control* 24:255–258
3. Hamed MM, Easa SM, Batayneh RR (1997) Disaggregate gap-acceptance model for unsignalized T-intersections. *J Transp Eng* 123:36–42. doi:10.1061/(ASCE)0733-947X(1997)123:1(36)
4. Yan X, Radwan E (2008) Influence of restricted sight distances on permitted left-turn operation at signalized intersections. *J Transp Eng* 134:68–76. doi:10.1061/(ASCE)0733-947X(2008)134:2(68)

5. Ashalatha R, Chandra S (2011) Critical gap through clearing behavior of drivers at unsignalised intersections. *KSCE J Civ Eng* 15:1427–1434. doi:[10.1007/s12205-011-1392-5](https://doi.org/10.1007/s12205-011-1392-5)
6. Maze TH (1981) A probabilistic model of gap acceptance behavior. *Transp Res Rec* 795:8–13
7. Madanat SM, Cassidy MJ, Wang M-H (1994) Probabilistic delay model at stop-controlled intersection. *J Transp Eng* 120:21–36. doi:[10.1061/\(ASCE\)0733-947X\(1994\)120:1\(21\)](https://doi.org/10.1061/(ASCE)0733-947X(1994)120:1(21))
8. Brilon W, Koenig R, Troutbeck RJ (2011) Useful estimation procedures for critical gaps. *Third Int Symp Intersect Without Traffic Signals*. doi:[10.1016/S0965-8564\(98\)00048-2](https://doi.org/10.1016/S0965-8564(98)00048-2)
9. Gattis JL, Low ST (1999) Gap acceptance at atypical stop-controlled intersections. *J Transp Eng* 125:201–207. doi:[10.1061/\(ASCE\)0733-947X\(1999\)125:3\(201\)](https://doi.org/10.1061/(ASCE)0733-947X(1999)125:3(201))
10. Zohdy I, Sadek S, Rakha H (2010) Empirical analysis of effects of wait time and rain intensity on driver left-turn gap acceptance behavior. *Transp Res Rec J Transp Res Board* 2173:1–10. doi:[10.3141/2173-01](https://doi.org/10.3141/2173-01)
11. Devarasetty PC, Zhang Y, Fitzpatrick K (2011) Differentiating between left-turn gap and lag acceptance at unsignalized intersections as a function of the site characteristics. *J Transp Eng* 138:580–588. doi:[10.1061/\(ASCE\)TE.1943-5436.0000368](https://doi.org/10.1061/(ASCE)TE.1943-5436.0000368)
12. Serag MS (2015) Gap-acceptance behaviour at uncontrolled intersections in developing countries. *Malays J Civ Eng* 27:80–93
13. Kaysi IA, Abbany AS (2007) Modeling aggressive driver behavior at unsignalized intersections. *Accid Anal Prev* 39:671–678. doi:[10.1016/j.aap.2006.10.013](https://doi.org/10.1016/j.aap.2006.10.013)
14. Liu M, Lu G, Wang Y, Zhang Z (2014) Analyzing drivers' crossing decisions at unsignalized intersections in China. *Transp Res Part F Traffic Psychol Behav* 24:244–255. doi:[10.1016/j.trf.2014.04.017](https://doi.org/10.1016/j.trf.2014.04.017)
15. Amin HJ, Maurya AK (2015) A review of critical gap estimation approaches at uncontrolled intersection in case of heterogeneous traffic conditions. *J Transp Lit* 9:5–9. doi:[10.1590/2238-1031.jtl.v9n3a1](https://doi.org/10.1590/2238-1031.jtl.v9n3a1)
16. Sangole JP, Patil GR, Patare PS (2011) Modelling gap acceptance behavior of two-wheelers at uncontrolled intersection using neuro-fuzzy. *Procedia Soc Behav Sci* 20:927–941. doi:[10.1016/j.sbspro.2011.08.101](https://doi.org/10.1016/j.sbspro.2011.08.101)
17. Patil GR, Sangole JP (2016) Behavior of two-wheelers at limited priority uncontrolled T-intersections. *IATSS Res* 40:7–18. doi:[10.1016/j.iatssr.2015.12.002](https://doi.org/10.1016/j.iatssr.2015.12.002)
18. Ben-Akiva ME, Lerman SR (1985) *Discrete choice analysis: theory and application to travel demand*. MIT press, Cambridge