European Transport \ Trasporti Europei (2023) Issue 93, Paper n° 6, ISSN 1825-3997

https://doi.org/10.48295/ET.2023.93.6

Analysis of Critical Gap and Capacity at Skewed Uncontrolled Intersections

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Abstract

Critical gaps and capacity of movements at uncontrolled intersections are influenced by intersection geometry, especially in mixed traffic conditions. However, existing models to compute the capacity of uncontrolled base intersections are only suitable for intersections with 0^0 to 10^0 skew angles. This study aims to bridge the gap by evaluating the effect of skew angle on the critical gap and capacity of uncontrolled intersections. The critical gap models are developed for different vehicle types. The capacity of uncontrolled intersections is determined for different skew angles (0^0 to 27^0) using simulation and Indo-HCM models. The comparison reveals that the Indo-HCM model over-predicts the capacities. Thus, new capacity models are proposed, and it is observed that the capacity varies as a quadratic function of the skew angle, where the constant indicates base capacity. This study also provides the adjustment factors for Indo-HCM capacity models to deduce the capacity of any skew-angled intersections.

Keywords: Uncontrolled intersections; Skew angle; Simulation; Critical gap models; Capacity models.

1. Introduction

The traffic movements at uncontrolled intersections are complicated, as no traffic control measures are provided over the intersections. The different driving behaviours add complexity under mixed traffic conditions (Hasain, 2022). The vehicles on the minor roads must stop until a sufficient gap is available on major roads to make the required manoeuvres. It incurs delays to vehicles and thereby reduces the capacity of the intersection. The critical gap is the primary determinant of intersection capacity and is an input parameter affecting the gap acceptance process (Viti et al., 2013). The popular critical gap estimation methods are Maximum Likelihood, Siegloch, Lag, Raff, Modified Raff, Ashworth, Harders, Logit, Probit, Hewitt, Acceptance Curve, Greenshield, Probability Equilibrium, Clearing Behaviour and Occupancy Time methods. Some of these methods are simple, whereas some involve complex computation tasks. All methods, excluding the clearing time method (CTM) and the occupancy time method (OTM), were developed for homogeneous traffic conditions in developed countries. In contrast, the CTM and OTM are the methods developed in developing countries like

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India. The CTM is helpful in heterogeneous traffic conditions, and the OTM is useful in both homogeneous and heterogeneous traffic conditions (Mohan and Chandra, 2016).

Among the existing methods, the Raff method is the earliest method for estimating the critical gap and is used in many countries because of its simplicity. Many researchers have emphasized that the Maximum Likelihood Method (MLM) is more consistent, produces unbiased estimates of the mean critical gap, and provides the best results (Kyte et al., 1994; Brilon, Koenig and Troutbeck, 1999; Gavulová, 2012; Troutbeck, 2014, 2016; Patil and Sangole, 2015, 2016; Mohan and Chandra, 2016). Most of these methods, excluding the CTM and OTM, were incapable and inefficient in producing actual critical gaps for traffic in developing countries (Chandra, Mohan and Gates, 2014; Amin and Maurya, 2015; Mohan and Chandra, 2016, 2018a). The OTM considers the actual driver behaviour at unsignalized intersections in developing countries (Mohan and Chandra, 2018a). Compared to MLM and Raff's method, the OTM estimates capacity closer to field capacity (Mohan and Chandra, 2018a). The critical gap values were much lower at intersections in India, which also shows a considerable difference from the HCM critical gap values (Chandra and Mohan, 2018). Driver behaviour, intersection geometry, and vehicular and traffic characteristics influence the operational efficiency of uncontrolled intersections. The critical gaps vary among intersections even when they have similar geometric conditions (Mohan and Chandra, 2020b). This variation is due to the difference in the proportion of large-sized vehicles in conflicting traffic (Mohan and Chandra, 2020b).

There are different methods to estimate capacity. It can be broadly classified as deterministic and probabilistic approaches. The four different methods used to evaluate the capacity of unsignalized intersections are,

i. Gap acceptance procedure
ii. Empirical regression technique
iii. Traffic signal analogy technique
iv. Additive conflict flow technique

The gap acceptance procedure is the theoretical basis for analyzing unsignalized intersections. Some researchers modified existing capacity models to account for the effect of mixed traffic scenarios prevailing in developing countries (Prasetijo, Pour and Ghadiri, 2011; Prasetijo and Ahmad, 2012; Prasetijo et al., 2014, 2016; Mohan and Chandra, 2020a). But all of these methods are suitable only for right-angled intersections. Usually, an intersecting angle of 90 degrees is preferred for designing purposes. However, many roads intersect at angles other than 90 degrees due to site constraints. Such intersections are named skewed intersections. The skew is a more critical factor at stop-controlled intersections than at signalized intersections (Harwood et al., 2000). A deviation of 10 degrees from 90 degrees would result in an increase of 3% more crashes at intersections with three legs and an increase of 4% more crashes at intersections with four legs (Nightingale et al., 2017). The difference between 90 degrees and the smallest acute angle between the intersection legs is the skew angle (Harwood, 2007). In other words, the skew angle is the deviation from 90 degrees. A minimum intersection angle of 60 degrees is recommended by AASHTO Green Book (1994), and many highway agencies adopted this as guidance in the geometric design policies (Federal Highway Administration, 2001). Limited visibility at skewed intersections causes safety concerns (Distefano and Leonardi, 2018; Wang *et al.*, 2021; Chittoori et al., 2015). The effect of geometric factors like the skew angle on capacity is an area yet to be explored in homogeneous and mixed traffic contexts. The HCM 2010 capacity model (Harder's model) is suitable for capacity estimation of right-angled unsignalized intersections under homogeneous traffic conditions. At the same time, the Indo-HCM (2017) capacity model is suitable for capacity estimation of right-angled unsignalized intersections under heterogeneous traffic conditions. Both models are unsuitable for determining capacity at uncontrolled intersections where the approach legs meet at an angle. Hence, a modified capacity model is necessary to incorporate the effect of skew angle under mixed traffic conditions. In addition to that, it is evident from previous research that the effect of geometric factors such as skew angle on the critical gap is not well researched in developing countries. Therefore, this study is focused on evaluating the impact of skew angle on critical gaps and the capacity of uncontrolled intersections.

The present study proposes models that can be used to determine the critical gap and capacity of uncontrolled intersections with skew angles. Simulation models were developed to replicate the actual traffic conditions, and capacity models were developed using the same. This study compares simulation output with capacities estimated using the Indo-HCM (2017) model and provides the adjustment factors for the existing Indo-HCM (2017) capacity model.

2. Methodology

This section explains the methodology followed in this study to investigate the impact of skew angle on critical gap and capacity of uncontrolled intersections. Intersections having approach legs meeting at different skew angles were selected for this study. Data such as traffic volume count, vehicle proportions, approach speed, the time when the vehicle stopped at the entry line, time when the vehicle started to move from the entry line, time when the vehicle crossed the exit line, accepted gaps, rejected gaps and occupancy time were extracted from the traffic video. This study adopts the passenger car unit (PCU) values and conflicting flow formulas from Indo-HCM (2017), since it incorporated the mixed traffic conditions commonly observed in developing countries like India. Indo-HCM (2017) provides a modified HCM (2010) capacity model for uncontrolled intersections as given in Eq. (1).

$$C_x = a \times v_{c,x} \frac{e^{\frac{-v_{c,x}(t_{c,x}-b)}{3600}}}{1-e^{\frac{-v_{c,x}t_{f,x}}{3600}}} \tag{1}$$

Where, C_x = capacity of movement x (PCU/h), $v_{c,x}$ = conflicting flow rate for movement x (PCU/h), $t_{c,x}$= critical gap for movement x (seconds), $t_{f,x}$= follow-up time for movement x (seconds) ≈ 60% of critical gap, a, b = adjustment factors based on intersection geometry (adjustment factors for HCM 2010 capacity model).

The traffic movements considered for this study are non-priority movements such as Right-Turn movement (RT) from major roads, RT from minor roads, and Through (TH) from minor roads. The movement-wise critical gaps were estimated using the extracted traffic data based on the OTM (Mohan and Chandra, 2018a). The conflicting volumes were calculated as per Indo-HCM 2017 equations for considered movements. First, the critical gap models were developed for different vehicle types executing the considered non-priority movements. Next, the simulation models were developed for all selected uncontrolled intersections using Weidemann 99 (W99) car-following model. They were calibrated and validated to replicate the actual traffic scenarios in developing countries. The capacity values for the non-priority movements were determined from simulation and Indo-HCM 2017 capacity models, and a comparison was performed. Then, new capacity models were developed to modify the Indo-HCM capacity model. Movement-wise adjustment factors were developed for the existing Indo-HCM capacity model for estimating capacity at uncontrolled intersections with different skew angles. Finally, generalized equations were proposed to determine the adjustment factors to deduce the capacity of uncontrolled intersections with skew angles.

3. Data collection

Skewed uncontrolled intersections are the intersections in which minor roads meet at an angle with a major road. The conditions considered for choosing the study sites are: four-legged uncontrolled intersections having two-lane undivided major and minor roads, skew angles including 0^0, level grade, negligible presence of non-motorized traffic, negligible curb parking on approaches, no bus stops and speed breakers on any approach within 75 m from intersection centre. Six uncontrolled intersections in Kerala, India, fulfilling the above criteria, were selected for the study (Figure 1). They are Manassery (site-1), Kacheripady (site-2), Kodakara (site-3), Chandakunnu (site-4), Polytechnic (site-5), and Vellangallur (site-6) intersections.

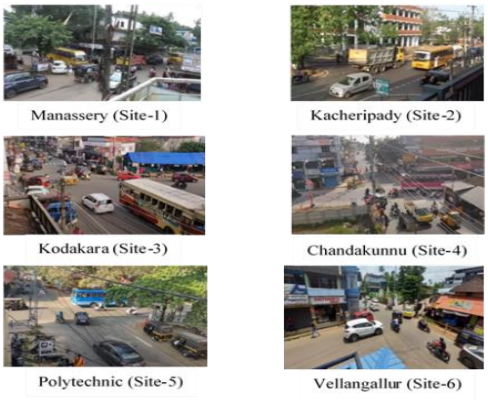

Figure 1: Study Sites.

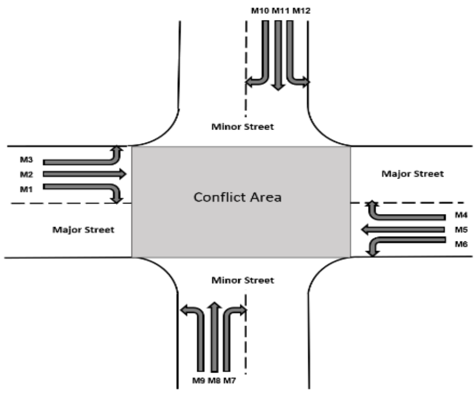

Figure 2: Conflict Area and Movements.

The traffic data was collected by conducting a videographic survey at the selected intersections. The traffic flow was recorded for the morning and evening peak hours (4 hr). The geometric data, such as carriageway width and approach width, were measured directly with the help of a measuring tape. The approach width was measured at the periphery of the intersection conflict area. The skew angle was measured by drawing the intersection geometry in CAD software, and the intersections considered have skew angles ranging from 0^0 to 27^0. The geometric details are shown in Table 1.

Table 1: Geometric Data.

Sites	*Carriageway Width (m)*			*Approach Width (m)*		*Skew Angle* (degrees)*	
	Major Road	*Minor Road 1*	*Minor Road 2*	*Minor Road 1*	*Minor Road 2*	*Minor Road 1*	*Minor Road 2*
1	6.5	5.5	5.5	10	12.9	0.0	-14.4
2	7.8	5.0	5.0	9.4	10	8.0	10.0
3	7.2	7.9	7.2	17.4	16.6	26.0	27.0
4	7.5	6.2	6.0	9.4	10	-12.0	-15.0
5	7.8	6.0	5.7	10	8.8	-12.1	-5.0
6	7.8	5.9	7.4	11	11	-16.6	-22.4

*Skew towards the right is taken as positive.

3.1 Traffic volume count.

Classified movement-wise traffic volume counts of vehicles passing through the selected intersections were retrieved from the recorded video. As per vehicle classification given in Indo-HCM, the vehicles were categorized into Two-Wheelers (TW), Auto-rickshaws (Auto), Standard/Small Cars (SC), Big Cars (BC), Light Commercial Vehicles (LCV), Two/Three Axle Trucks (TAT), and Buses (B). Total traffic volumes of 2900, 3581, 2998, 2746, 2715, and 2974 veh/h were observed at site-1, site-2, site-3, site-4, site-5, and site-6, respectively. The extracted vehicle counts in each type were converted into PCU (Indo-HCM, 2017; Mohan and Chandra, 2018c, 2018b, 2020a). They are 2266, 2937, 2064, 2231, 2058, and 2022 PCU/h at site-1, site-2, site-3, site-4, site-5, and site-6, respectively.

3.2 Vehicle proportions.

The traffic composition on selected study sites is highly heterogeneous, consisting of different modes of vehicles. Compared to other vehicle types, the proportion of TW is higher (54% - 64%), followed by SC (13% - 18%), Auto (9% - 17%), LCV (3% - 5%) and BC (2% - 4%). The proportion of buses and heavy vehicles such as TAT is only about 1 to 3%.

3.3 Approach speed.

The approach speed was determined by noting the time a major road vehicle passes each entry and exit line marked on the site at a known distance. The ratio of distance to time gives the speed of the corresponding vehicle. The average approach speeds were calculated for each vehicle type.

3.4 Conflicting volume.

The cumulative volume of traffic from different movements that affect the operation of a non-priority movement at an intersection is called conflicting volume (Mohan and Chandra, 2020a). It was calculated based on the extracted traffic volumes, as per the equation provided in Indo-HCM 2017. The boundary of the conflicting area is taken as the reference line, as shown in Figure 2. The movements 1 to 12 are abbreviated as M1 to M12.

3.5 Critical gap.

The critical gap is the minimum time between the arrival of vehicles on the major road that will allow a vehicle on the minor road to move into the intersection. The critical gap (CG) was estimated separately for each vehicle type in each movement at all sites based on OTM. Their values are summarized in Table 2.

Table 2**:** Critical Gap Values.

Sites	*Movement*		*Skew Angle (degrees)*	*Critical Gap (seconds)*		
				TW	*AUTO*	*SC*
1	RT from Major	M1	0.0	3.5	4.8	5.8
		M4	-14.4	2.8	3.5	4.5
	RT from Minor	M7	0.0	4.3	4.8	5.5
		M10	-14.4	2.9	3.5	4.3
	TH from Minor	M8	0.0	3.6	4.2	4.5
		M11	-14.4	5.2	5.8	6.1
2	RT from Major	M1	8.0	3.4	4.9	6.4
		M4	10.0	3.3	5.0	6.5
	RT from Minor	M7	8.0	4.0	4.8	5.5
		M10	10.0	4.3	5.2	5.6
	TH from Minor	M8	8.0	4.2	4.8	5.1
		M11	10.0	4.2	4.8	5.3
3	RT from Major	M1	26.0	2.9	3.0	3.5
		M4	27.0	2.7	2.9	3.3
	RT from Minor	M7	26.0	3.6	4.3	4.4
		M10	27.0	3.4	3.6	4.2
	TH from Minor	M8	26.0	5.5	6.4	8.0
		M11	27.0	7.0	7.5	9.1
4	RT from Major	M1	-12.0	2.8	3.7	3.8
		M4	-15.0	2.6	3.5	3.7
	RT from Minor	M7	-12.0	3.5	3.8	4.3
		M10	-15.0	2.6	3.0	4.0
	TH from Minor	M8	-12.0	4.2	4.8	5.1
		M11	-15.0	5.6	6.2	6.4
5	RT from Major	M1	-12.0	3.0	3.4	3.9
		M4	-5.0	3.2	3.9	5.2
	RT from Minor	M7	-12.0	3.1	3.6	4.5
		M10	-5.0	4.1	3.8	4.8
	TH from Minor	M8	-12.0	4.5	5.1	5.2
		M11	-5.0	3.5	4.1	5.5
6	RT from Major	M1	-16.6	2.8	3.1	3.4
		M4	-22.4	2.1	1.8	1.9
	RT from Minor	M7	-16.6	2.8	3.1	4.2
		M10	-22.4	1.8	2.1	2.9
	TH from Minor	M8	-16.6	5.9	6.4	6.8
		M11	-22.4	6.8	7.6	8.2

From Table 2, a general trend, as obtained in previous research (Mohan and Chandra, 2016, 2018a, 2020b; Chandra and Mohan, 2018), is visible where the value of the critical gap increases with the size of the vehicle. It is also observed that the critical gap of TW is less than other modes (Chandra, Mohan and Gates, 2014; Chandra and Mohan, 2018; Mohan and Chandra, 2018a, 2020b).

4. Development of critical gap models

Critical gap models were developed for TW, AUTO, and SC for RT from major, RT from minor and TH from minor roads, where the minor roads meet the major roads at different skew angles. Skew angle (θ) is in degrees in all developed models, and the critical gap (CG) is in seconds. A polynomial curve of order 2 fits well for the CG values of TW, AUTO and SC for all three movements. As the skew angle varies, a quadratic trend was observed for the critical gaps, and its general representation is given in Eq. (2), where a and b are model coefficients, θ is the skew angle, and c represents the base critical gap value.

$$CG = a \times \theta^2 + b \times \theta + c \qquad (2)$$

All the developed models are validated by applying the data of another skewed intersection. The error percentage comes within 5%. Hence, the output is in line with the expectation. Thus, it shows that the developed models are good. In addition, the skew angles corresponding to maximum and minimum critical gaps were identified for the considered vehicle type and movements. Those skew angles were observed to lie between 0 to 10 degrees (base condition).

4.1 Critical gap model for RT from major roads.

A quadratic trend was observed for the critical gap of TW, AUTO and SC under the variation in skew angle with an R^2 value of 0.91, 0.90 and 0.90 (Figure 3). The critical gap decreases as the skew angle towards the left/right increases. The critical gap reaches the maximum value when the skew angle varies from 0^0 to 10^0. When the skew towards the left increases, the critical gap decreases because the vehicles from the major road can turn right smoothly without much effort in steering. Also, the critical gap decreases as the skew towards the right increases due to a decrease in traversing distance. The CG models for TW, AUTO, and SC are represented by Eq.s (3), (4) and (5), respectively. The skew angle corresponding to maximum critical gaps are 6.1, 5.0, and 5.7 degrees.

$$CG = -0.0020 \times \theta^2 + 0.0244 \times \theta + 3.5 \qquad (3)$$
$$CG = -0.0042 \times \theta^2 + 0.0421 \times \theta + 4.8 \qquad (4)$$
$$CG = -0.0056 \times \theta^2 + 0.0637 \times \theta + 5.8 \qquad (5)$$

4.2 Critical gap model for RT from minor roads.

A similar trend is observed for RT movement from minor roads (Figure 4). As the skew angle increases towards left or right, the critical gap decreases. The developed CG models for TW, AUTO, and SC have R^2 values of 0.88, 0.85 and 0.95, respectively. The corresponding models are represented by Eq.s (6), (7) and (8). The skew angle corresponding to maximum critical gaps are 8.1, 8.5, and 6.6 degrees.

$$CG = -0.0031 \times \theta^2 + 0.0501 \times \theta + 4.3 \qquad (6)$$
$$CG = -0.0034 \times \theta^2 + 0.0581 \times \theta + 4.8 \qquad (7)$$
$$CG = -0.0035 \times \theta^2 + 0.0461 \times \theta + 5.5 \qquad (8)$$

4.3 Critical gap model for TH from minor roads.

For TH movement from minor roads, the critical gap of TW, AUTO and SC follows a quadratic relation with respect to skew angle, giving an R^2 value of 0.83, 0.88 and 0.93 (Figure 5). When the skew towards the left/right increases, the traversing distance increases and the critical gap increases. The CG models for TW, AUTO, and SC are represented by Eq.s (9), (10) and (11). The skew angle corresponding to minimum critical gaps are 2.7, 2.5, and 0.8 degrees.

$$CG = 0.0049 \times \theta^2 - 0.0263 \times \theta + 3.6 \quad (9)$$
$$CG = 0.0050 \times \theta^2 - 0.0252 \times \theta + 4.2 \quad (10)$$
$$CG = 0.0063 \times \theta^2 - 0.0106 \times \theta + 4.5 \quad (11)$$

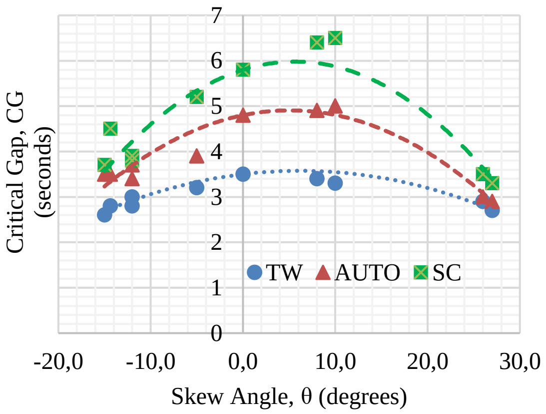

Figure 3: Critical Gap for Major RT.

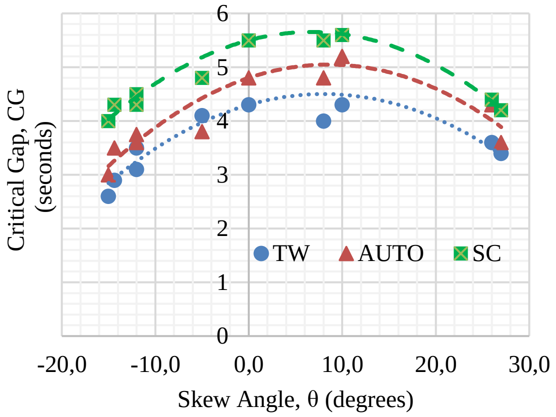

Figure 4: Critical Gap for Minor RT.

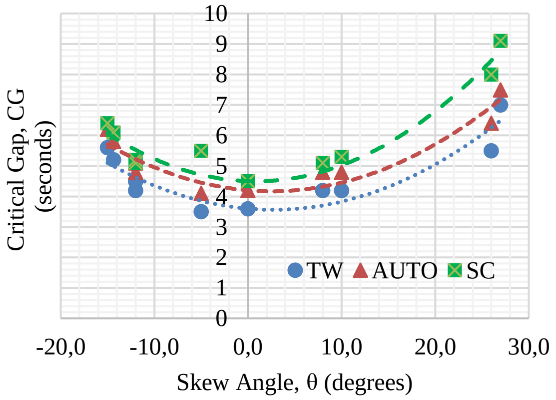

Figure 5: Critical Gap for Minor TH.

5. Development, calibration and validation of simulation models

Simulation models were developed in PTV VISSIM software for all selected uncontrolled intersections using morning peak hour data. Wiedemann 99 (W99) car-following model is adopted for this study. The urban motorized driving behaviour parameters are modified as follows to replicate Indian conditions:

- Desired position at free flow: Any
- Observe adjacent lane: Active
- Diamond queuing: Active
- Consider next turn: Active
- Overtake left: Active
- Overtake right: Active
- Cooperative lane change: Active

A code was developed in MATLAB to perform the sensitivity analysis, and the sensitive parameters were identified. The sensitive parameters are standstill distance (CC0), gap time distribution (CC1), following distance oscillation (CC2), the threshold for entering the following (CC3), oscillation acceleration (CC7), acceleration from standstill (CC8), lateral distance standing (LDS), and lateral distance driving (LDD). Simulations were performed for 3900 seconds, including a warm-up period of 300 seconds at the start of the simulation run. If the simulated result (speed and volume) does not match the observed data, further adjustments are made to the model to bring down the error to 15%, which is acceptable (Dowling et al., 2004). The developed model is considered well-calibrated if the error is within acceptable limits. Like this, automatic calibration was performed through a genetic algorithm using MATLAB. All simulation models were calibrated, and the calibrated parameter values are tabulated in Table 3. The calibrated simulation models are validated using evening peak hour data by checking the simulation results against field traffic volumes and speeds. The simulated speeds and volumes are statistically validated using t-statistics. The calculated t-statistic was less than the critical t-statistic for a significance level of 5%. It implies no significant difference between observed and simulated speeds and volumes.

Table 3: Calibrated Parameters.

Driving Behaviour Parameters	*Default Values*	*Range*	*Calibrated Values*					
			Site-1	*Site-2*	*Site-3*	*Site-4*	*Site-5*	*Site-6*
CC0	1.5	0 to 4	0.74	0.66	0.55	0.92	0.63	0.9
CC1	0.9	Distribution	0.6	0.6	0.6	0.6	0.6	0.6
CC2	4	0 to 10	4.55	2.71	1	1.54	1	7.54
CC3	-8	-30 to -8	-7.93	-6.45	-5	-7.31	-5	-6.62
CC7	0.25	0.15 to 0.95	0.79	0.4	0.71	0.63	0.31	0.46
CC8	3.5	0.5 to 4.0	1.18	0.94	3.86	3.99	3.95	1.47
LDS	0.2	0.1 to 0.3	0.2	0.17	0.25	0.12	0.12	0.14
LDD	1	0.3 to 1.0	0.58	0.35	0.33	0.43	0.32	0.54

6. Variation of simulated capacity with conflicting flow

The variation of simulated capacity (C_s) was plotted against the conflicting flow (V_c) for all considered movements (Figure 6). An exponential decrease in capacity was observed with an increase in conflicting flow, which is in line with expectations (Harder's model).

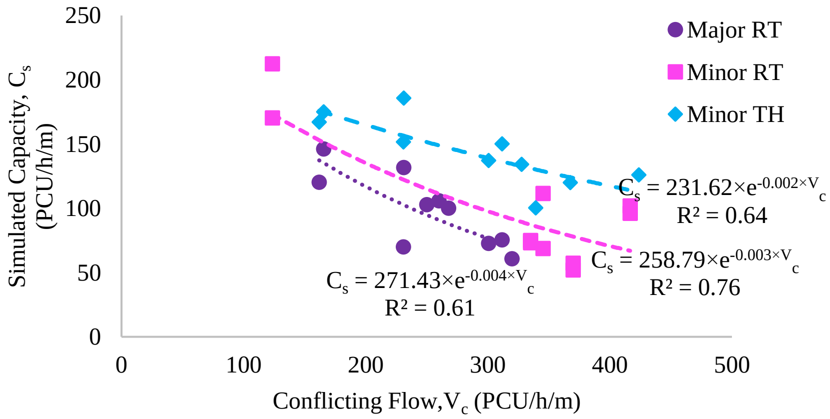

Figure 6: Capacity Versus Conflicting flow for Major RT.

7. Comparison of different capacity models

The capacity of all the selected uncontrolled intersections was determined using the simulation model and the Indo-HCM 2017 model for the same conflicting flow. The capacities obtained for different movements are represented in Figures 7 to 9. It was observed that the simulated capacity is different from capacity values from the Indo-HCM models because of the effect of the skew angle. With the help of scatter plot diagrams, it was observed that the Indo-HCM capacity over-predicts the capacity of skewed intersections. So, it is necessary to develop separate capacity models for RT from major, RT from minor and TH from major roads to account for the skew angle's effect on uncontrolled intersections' capacity.

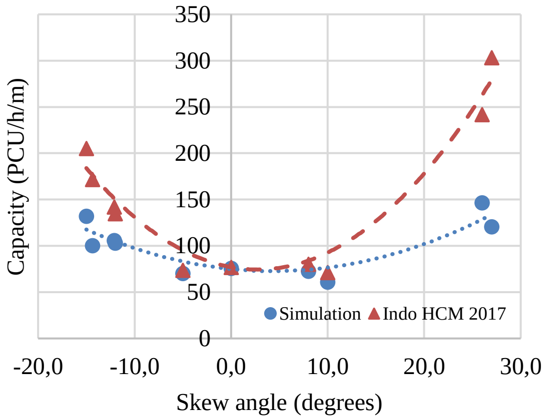

Figure 7: Capacity for Major RT.

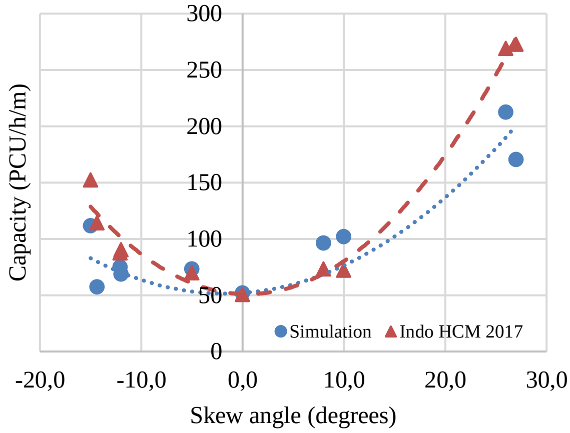

Figure 8: Capacity for Minor RT.

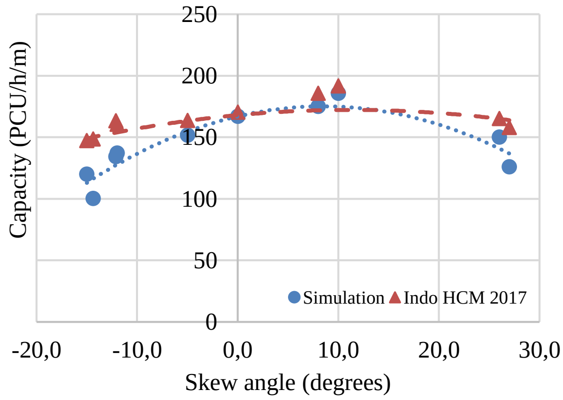

Figure 9: Capacity for Minor TH.

8. Proposed capacity models

The capacity models were developed to accommodate the skew angle (θ) effect on uncontrolled intersections' capacity (C) under mixed traffic conditions, where θ is in degrees and C is in PCU/h/m. The capacity of uncontrolled intersections varies as a quadratic function of skew angle, and its general representation is given in Eq. (12), where a and b are model coefficients, and c represents base capacity.

$$C = a \times \theta^2 + b \times \theta + c \tag{12}$$

The base capacities obtained for RT from major, RT from minor and TH from minor roads are 75, 52 and 167 PCU/h/m, respectively. The trend of capacity variation with the skew angle for RT from major and RT from minor, and TH from minor roads are shown in Figures 10, 11, and 12, respectively. The R^2 values of the developed capacity models were 0.84, 0.85, and 0.88. The proposed capacity models are given in Eq.s (13), (14) and (15) for RT from major, RT from minor, and TH from major roads.

$$C = 0.1194 \times \theta^2 - 1.0443 \times \theta + 75 \quad (13)$$
$$C = 0.1799 \times \theta^2 - 0.6430 \times \theta + 52 \quad (14)$$
$$C = -0.1124 \times \theta^2 + 1.9148 \times \theta + 167 \quad (15)$$

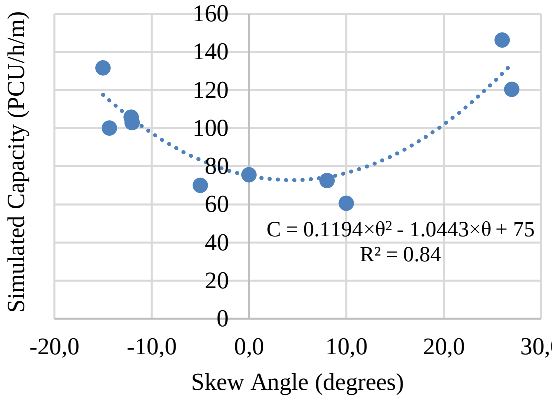

Figure 10: Capacity Model for Major RT.

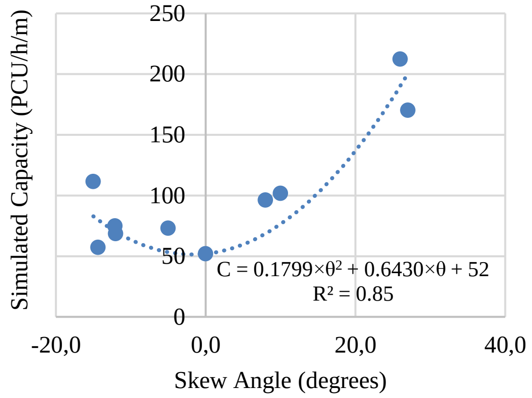

Figure 11: Capacity Model for Minor RT.

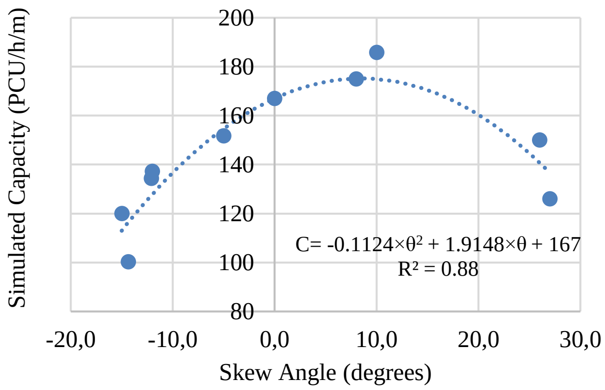

Figure 12. Capacity Model for Minor TH.

The proposed models are validated by simulating another uncontrolled intersection having a different skew angle. The error between simulated capacity and capacity determined using the proposed model is within 10%, which is acceptable (Dowling et al., 2004). Thus, the model is found to be good. These models can be used for finding the capacity of uncontrolled intersections in which approach legs meet at any angle. The trend of capacity variation is the same for RT from major and RT from minor roads. If the skew towards the left/right increases, the critical gap decreases (Figures 3 and 4), and capacity increases (Figures 10 and 11). In the case of TH movement from minor roads, as the skew angle towards the left/right increases, the critical gap increases (Figure 5), and capacity decreases (Figure 12). The skew angle corresponding to the minimum and maximum capacities are 4.5, 0.8 and 8.5 degrees which lie between 0 to 10 degrees (base condition).

9. Application of proposed capacity models

The capacities of RT from major, RT from minor and TH from minor roads were determined for all uncontrolled intersections using the proposed models. The corresponding level of service (LOS) was also determined based on volume to capacity ratio (V/C) as per Indo-HCM (2017). The capacity and the level of service at uncontrolled intersections having different skew angles are shown in Table 4.

Table 4: Capacity and Level of Service Based on Proposed Models.

Skew Angle (degrees)	*Volume (PCU/h/m)*			*Capacity (PCU/h/m)*			*V/C Ratio*			*Level of Service (LOS)*		
	Major RT	*Minor RT*	*Minor TH*	*Major RT*	*Minor RT*	*Minor TH*	*Major RT*	*Minor RT*	*Minor TH*	*Major RT*	*Minor RT*	*Minor TH*
0.0	28	35	50	75	52	167	0.38	0.67	0.30	C	D	B
-14.4	24	54	53	115	80	116	0.21	0.68	0.46	B	D	C
8.0	1	16	98	74	69	175	0.02	0.23	0.56	A	B	D
10.0	21	55	168	76	76	175	0.27	0.72	0.96	B	D	E
26.0	16	10	98	129	190	141	0.12	0.05	0.69	A	A	D
27.0	18	27	106	134	201	137	0.14	0.14	0.77	A	A	D
-12.0	33	34	58	105	70	128	0.32	0.49	0.46	B	C	C
-15.0	6	7	65	118	83	113	0.05	0.08	0.57	A	A	D
-12.1	12	25	52	105	71	127	0.12	0.36	0.41	A	C	C
-5.0	9	17	26	83	53	155	0.10	0.32	0.17	A	B	B
-16.6	18	29	44	125	91	104	0.14	0.32	0.42	A	B	C
-22.4	31	15	25	158	128	68	0.19	0.12	0.37	B	A	C

10. Adjustment factors for the Indo-HCM capacity model

Adjustment factors (AF) for the Indo-HCM capacity model were determined from the proposed model that incorporates the effect of skew since Indo-HCM over-predicts the capacities when the skew angle deviates from 0 degrees (as evident from Figures 7 to 9). The adjustment factors for different skew angles are given in Table 5.

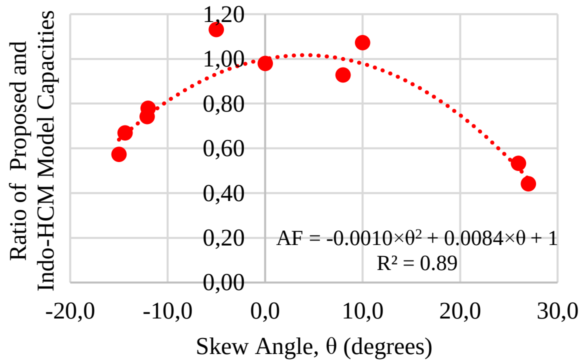

Figure 13. AF for Major RT Capacities.

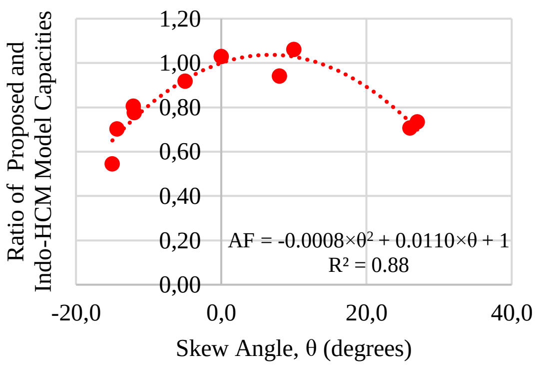

Figure 14. AF for Minor RT Capacities.

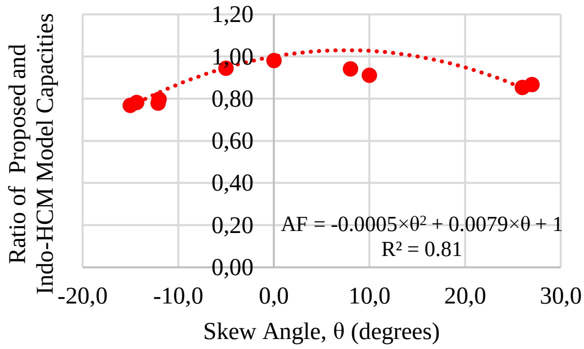

Figure 15. AF for Minor TH Capacities.

Table 5: Adjustment Factors for Indo-HCM Capacity Model.

Skew Angle (degrees)	*Adjustment Factors for Indo-HCM Capacity Model*		
	RT from Major	*RT from Minor*	*TH from Minor*
-15.0	0.57	0.54	0.77
-14.4	0.67	0.70	0.78
-12.1	0.74	0.81	0.78
-12.0	0.78	0.78	0.80
-5.0	1.13	0.92	0.94
8.0	0.93	0.94	0.94
10.0	1.07	1.06	0.91
26.0	0.53	0.71	0.85
27.0	0.44	0.73	0.87

The above adjustment factors for Indo-HCM are applicable only for the skew angles provided in Table 5. Eq.s (16), (17) and (18) generalize the adjustment factors for intersections with the skew angle for major RT, minor RT and minor TH movements, respectively (Figures 13 to 15) to deduce the capacity of any skew-angled intersections using the Indo-HCM model.

$$AF = -0.0010 \times \theta^2 + 0.0084 \times \theta + 1 \quad (16)$$
$$AF = -0.0008 \times \theta^2 + 0.0110 \times \theta + 1 \quad (17)$$
$$AF = -0.0005 \times \theta^2 + 0.0079 \times \theta + 1 \quad (18)$$

Where, AF is the adjustment factor, and θ is the skew angle (degrees). Thus, the capacity of any movement at skewed intersections could be determined by multiplying the capacity of movement from the Indo-HCM with the corresponding adjustment factor.

11. Summary and Conclusions

This study evaluated the critical gap values of different movements at skewed uncontrolled intersections. The critical gap models were developed for TW, AUTO, and SC for RT from major, RT from minor and TH from minor roads, where the minor roads meet the major roads at different skew angles. As the skew angle varies, a quadratic trend was observed for the critical gaps where the constant term represents the critical gap value for a base intersection with zero skew. In the case of RT from major and minor roads, the critical gap decreases when the skew towards the left/right increases. The critical gap reaches the maximum value when the skew angle lies in 0^0 to 10^0 range. In the case of TH from minor roads, the critical gap increases as the skew angle increase towards left/right. The critical gap is minimum when the skew angle lies in 0^0 to 10^0 range.

Simulation models were developed for the uncontrolled intersections using the W99 car-following model in PTV VISSIM software. CC0, CC1, CC2, CC3, CC7, CC8, LDS, and LDD are the sensitive driving behaviour parameters to the considered measure of effectiveness, such as flow and speed. The developed simulation models were calibrated by adjusting these parameters until the error reached an acceptable limit. An exponential decrease was observed for simulated capacity with an increase in conflicting flow. A comparison was performed between the capacities obtained from simulation and Indo-HCM models. It was observed that the capacity obtained from simulation models differs from the Indo-HCM capacity model. Hence, new capacity models are proposed that consider the effect of skew angle on the capacity of uncontrolled intersections under mixed traffic conditions. It was found that the capacity of uncontrolled intersections varies as a quadratic function of the skew angle, where the constant term indicates the capacity value for a base intersection. The trend of capacity variation was the same for RT movements from major and minor roads. The capacity increases as the skew angle increases and is minimum when the skew angle lies between 0 and 10 degrees. For TH from minor roads, the capacity decreases with an increase in skew angle and is maximum when the skew angle lies between 0 and 10 degrees. In addition, this study provides the adjustment factors for Indo-HCM capacity models that can be used to determine the capacity of movements at intersections with any skew angle. The results may vary with the presence of pedestrians and changes in driver behaviour in different regions of the country. Future studies can include the effect of variables like forced entry/aggressive behaviour, other driver-behaviour-related variables, the presence of pedestrians/gradients etc. It is also advisable to perform a similar analysis for three-legged uncontrolled intersections.

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Acknowledgements

The authors would like to express gratitude to the Centre for Transportation Research (CTR), Department of Civil Engineering, NIT Calicut.