European Transport \ Trasporti Europei (2025) Issue 104, Paper n° 2, ISSN 1825-3997

Capacity and Level of Service Analysis of Uncontrolled Intersections: State-of-the-Art Review and the Way Forward for Developing Countries

Arathi A. R. [1*], **Harikrishna M.**[2], **Mithun Mohan**[3], **Yogeshwar V. Navandar**[4]

[1] *Former PhD Scholar, Department of Civil Engineering, NIT Calicut, Kerala, India*
[2] *Associate Professor, Department of Civil Engineering, NIT Calicut, Kerala, India*
[3] *Assistant Professor, Department of Civil Engineering, NIT Karnataka, Surathkal, India*
[4] *Assistant Professor, Department of Civil Engineering, NIT Calicut, Kerala, India*

Abstract

Uncontrolled intersections are at-grade intersections that lack explicit traffic control measures. Traffic behaviour at uncontrolled intersections becomes complicated due to the lack of appropriate regulation, especially in mixed traffic situations. Furthermore, drivers with varying characteristics, aggressive behaviour, and violation of priority regulations exacerbate the problems at such uncontrolled intersections. Consequently, traffic at uncontrolled intersections tends to be unpredictable. Considering that most of the road intersections in developing countries like India are uncontrolled, it is necessary to assess the performance of uncontrolled intersections based on capacity and safety perspectives. This article provides a comprehensive state-of-the-art review of various research works over the past three decades, which deals with various aspects such as critical gap/lag, passenger car unit/equivalent, conflicting flow, capacity level of service, and simulation at uncontrolled intersections. Moreover, insights into the scope for further studies on uncontrolled intersections are also discussed. This article can act as a guide for researchers to take up further research on uncontrolled intersections.

Keywords: Critical gap/lag; Passenger car unit/equivalent; Conflicting flow; Capacity; Level of service; Simulation.

1. Introduction

An unsignalised intersection is an intersection that is not governed by traffic signals (HCM, 2000). In general, unsignalised intersections include Uncontrolled Intersections, Two-Way Stop-Controlled (TWSC) intersections, All-Way Stop-Controlled (AWSC) intersections, and Roundabouts. Uncontrolled intersections are unsignalised intersections that lack traffic management, such as traffic signals or police enforcement. Due to the lack of control systems for vehicular movements, uncontrolled intersections are typically relegated to rural or residential roads with relatively low traffic volumes. Despite this,

---

[*] Corresponding author: Arathi A. R. (arathirajkumar@gmail.com)

increased vehicle volumes are recorded at such intersections, even in rural areas. This creates a capacity deficit at the existing uncontrolled intersections, resulting in increased delays. Moreover, due to the necessity of the gap acceptance judgement and peripheral awareness of other vehicles, unsignalised intersections exert more demands on perceptual and cognitive skills than signalised ones (Ulak et al., 2019). Therefore, analysing the capacity and LOS of uncontrolled intersections is necessary. Capacity and LOS can be assessed through a clear understanding of the gap acceptance process and its parameters, as this is the primary foundation for the analysis of uncontrolled intersections (Bhasin et al., 2014). The treemap depicting the research areas are shown in Figure 1.

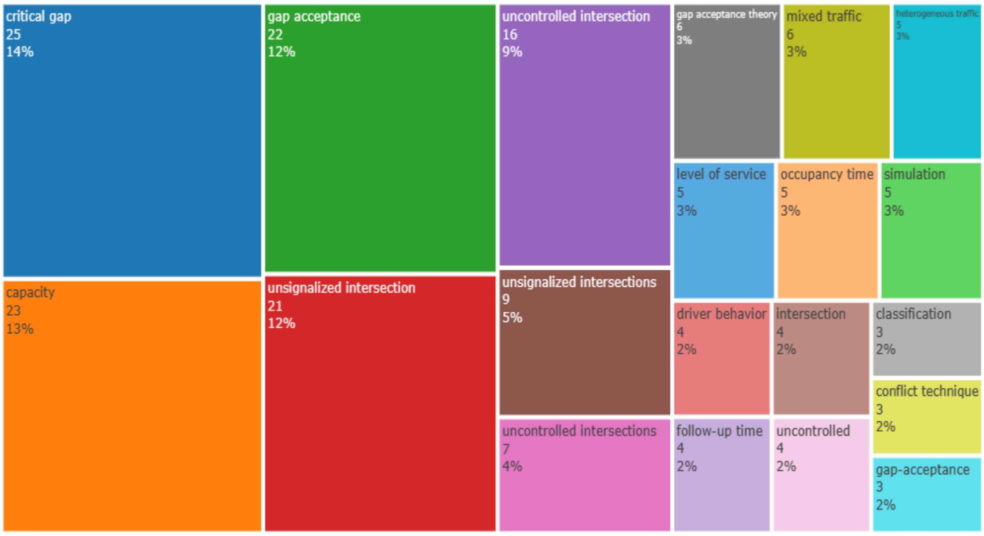

Figure 1: Treemap depicting the research areas.

According to the treemap of the top 20 research areas shown in Figure 1, critical gap, capacity, gap acceptance, LOS, and simulation are the major discipline areas that are covered by the literature, and the driver behaviour, follow-up time, conflicting technique are the less explored disciplines. The distribution of the research works across the countries in the world is shown in Figure 2.

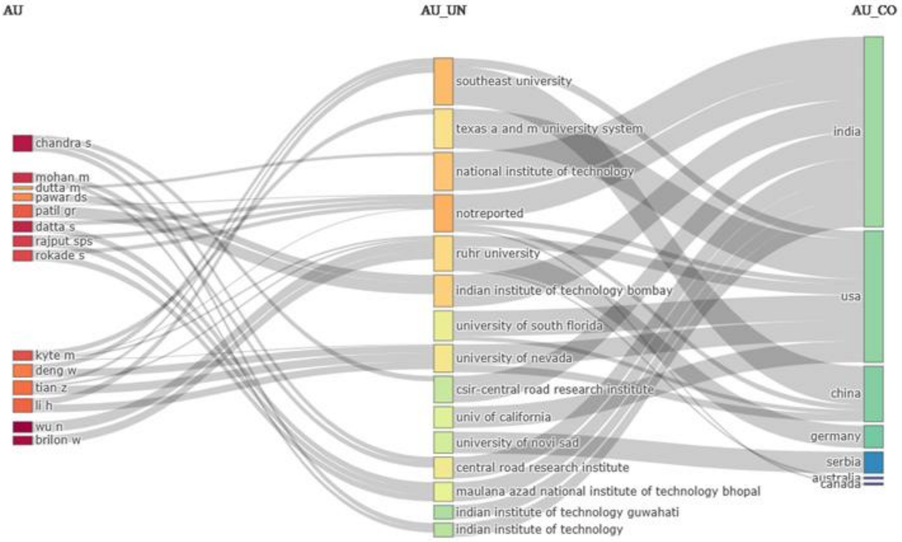

Figure 2: Contribution from authors across different countries.

As most road intersections in developing countries like India are uncontrolled, it is necessary to assess the performance of uncontrolled intersections based on capacity and safety perspectives. Performance assessment can be undertaken by clearly understanding the gap acceptance process and its parameters, which is the primary foundation for analysing uncontrolled intersections. Moreover, uncontrolled intersections are crash-prone locations since drivers utilise the same space for traffic manoeuvres, which results in substantial potential conflict points. As per the latest available road crash reports by the Federal Highway Administration (FHA, 2020) and the Ministry of Road Transport and Highways (MORTH, 2021), the percentage share of fatalities that occur at uncontrolled intersections in developed and developing nations is 18% and 25%, respectively. The complexities in traffic movements and road accident statistics highlight the importance and necessity of studying uncontrolled intersections. Figure 3 provides a country-wise contribution of research in the area of uncontrolled intersections.

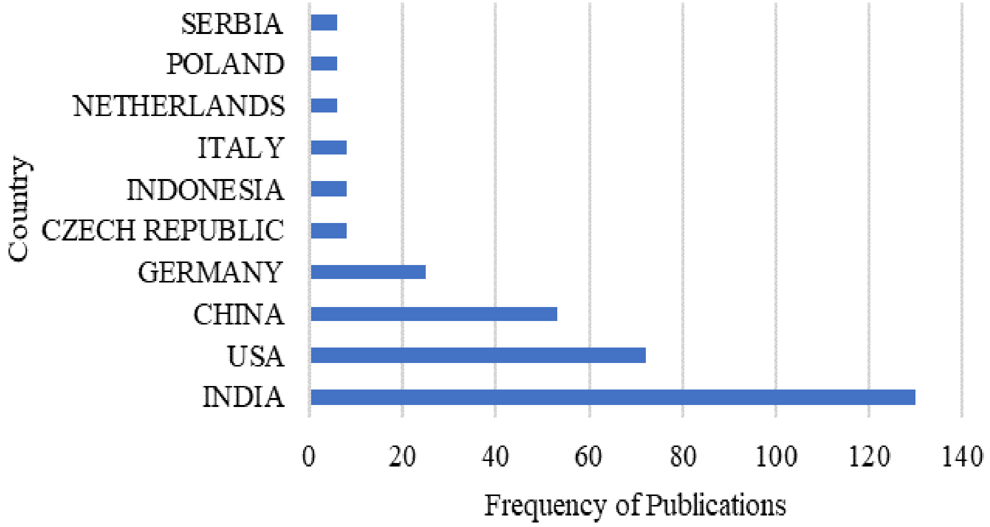

Figure 3: Distribution of research works across the countries.

Although researchers around the world have studied uncontrolled intersections, a majority of the research publications are in the context of developing countries, followed by those from the USA, China, and Germany (Figure 3). This makes a comparison between the studies conducted in the contexts of developing and developed countries pertinent. This state-of-the-art review paper presents a comprehensive review of various research works over the past three decades, which deals with various areas of study such as critical gap/lag, passenger car unit/equivalent, conflicting volume, capacity, LOS, and simulation studies at uncontrolled intersections under homogeneous and heterogeneous traffic conditions. The authors have taken a concerted effort to highlight the research gaps for future researchers, particularly in the context of developing nations. These include the emphasis on the evaluation of capacity using conflicting techniques and identifying user-perceived LOS. The paper is organized into nine sections in total, including the introduction section. Sections 2 to 7 summarise the studies related to critical gap/lag, passenger car unit/equivalent (PCU/PCE), conflicting flow, capacity, LOS, and simulation at uncontrolled intersections. Basic theories and related studies are described in general at the start of each section along with the criteria that are more applicable to Indian conditions at the end of each section. Finally, sections 8 to 9 present the conclusions noted from the studies and directions for future research.

2. Critical gap/lag at uncontrolled intersections

The gap acceptance theory is used as a theoretical basis for analysing uncontrolled intersections. As per the theory, the driver of a minor road vehicle should assess if the gap on the major road is sufficient for entry and when to enter based on the relative importance of the movements. The gap is the difference in time between subsequent vehicles on a major road, while lag is the first gap encountered by vehicles upon reaching the intersection. Lag can be measured as the time difference between the arrival of the subject vehicle from a minor road and the first conflicting vehicle on a major road. The gap acceptance process can be defined by the parameters "critical gap" and "follow-up time". The critical gap is the shortest gap in which a minor-road vehicle may manoeuvre between two major-road vehicles. In contrast, the follow-up time is the interval between the passage of one vehicle from a minor road and the passage of the following minor street vehicle using the same gap when there is a continuous queue. In field conditions, the critical gap and critical lag are not the same (Golias and Kanellaidis, 1990). The critical gap values were found to be higher than the critical lag values (Amin and Maurya, 2015; Gattis and Low, 1999; Serag, 2015). Researchers considered different parameter combinations, as depicted in Figure 4, for estimating the critical gap.

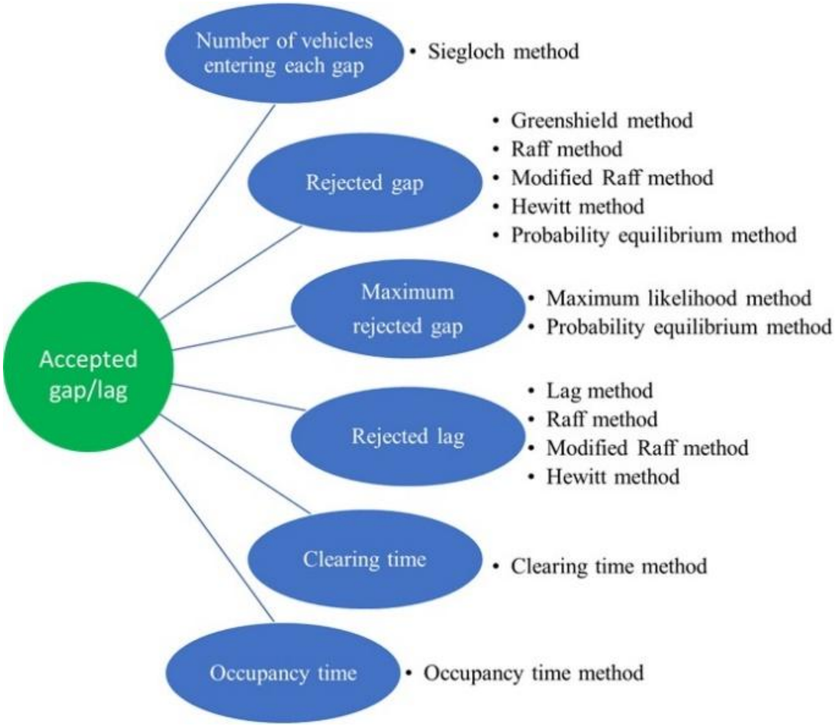

Figure 4: Factors considered for critical gap estimation.

Generally, gaps larger than or equal to their critical gaps are accepted by drivers (Cassidy et al., 1995). They used the accepted gap/lag in combination with either the number of vehicles entering each gap or rejected gap/lag or maximum rejected gap or clearing time or occupancy time to estimate the critical gap/lag (Figure 4). Accepted gap/lag is a commonly used parameter by all authors for finding critical gap/lag. In estimating the critical gap, the rejected gap is mostly used in combination with the accepted gap (Ashalatha and Chandra, 2011; Maurya et al., 2016; Chandra and Mohan, 2018; Pawar and Patil, 2021). However, in their recent studies of 2014, 2018, 2020 and 2021, Mohan and Chandra came up with the concept of using occupancy time instead of accepted/rejected gap. Ashalatha and Chandra (2011), Chandra et al. (2014), and Mohan and Chandra (2016b, 2018a) used actual driver behaviour for critical gap analysis. Maurya et al. (2016) consider the vehicle, driver characteristics, and arrival time apart from any other author. The work also incorporates vehicle manoeuvring characteristics such as movement type and clearing time. Out of these studies, Ashalatha and Chandra (2011) considered only clearing time for arriving at the driver's actual behaviour, and all other works considered occupancy time. However, actual driver behaviour is very sensitive to various driver and social characteristics and may require future research with driving simulator studies.

Estimating the critical gap is difficult because it changes depending on the driver and the intersection. Some of these techniques are computationally simple, while others are not. Figure 5 depicts some of the most prevalent critical gap estimation approaches used in developed and developing countries.

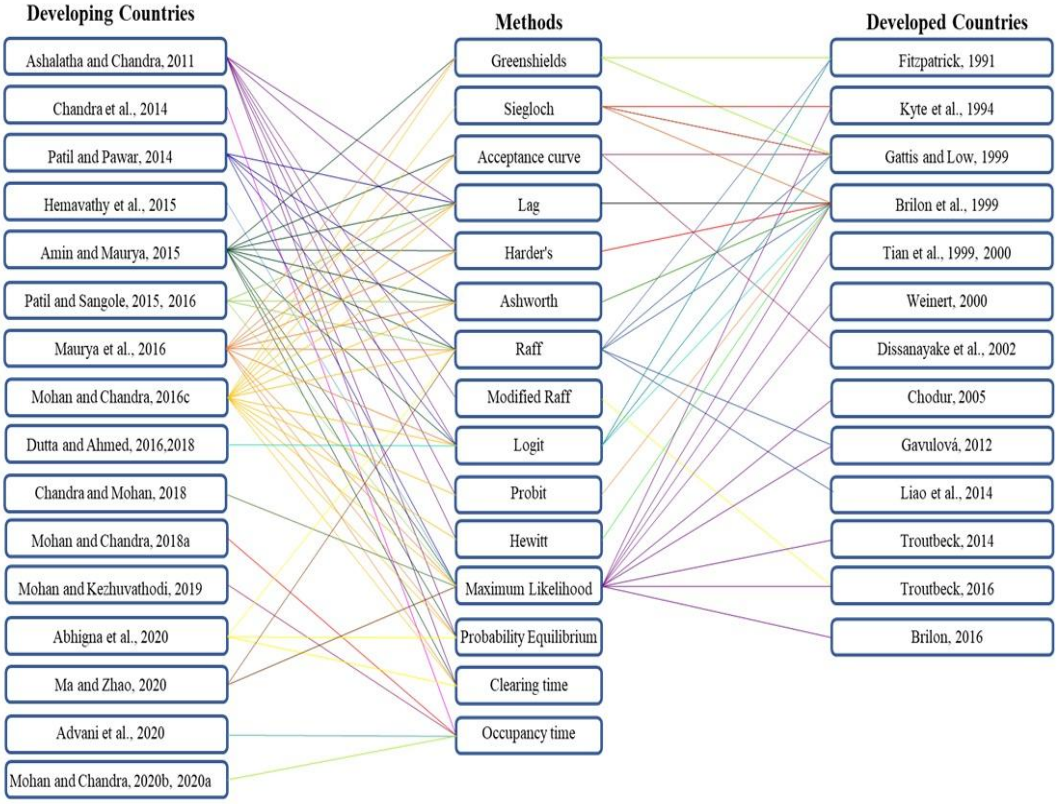

Figure 5: Critical gap estimation methods used by various researchers.

Raff's technique was the first approach for estimating the critical gap and is used in many nations due to its inherent simplicity. Many researchers have emphasised that the Maximum Likelihood Method (MLM) yields the most accurate estimations of the mean critical gap (Brilon et al., 1999; Gavulová, 2012; Kyte et al., 1994; Mohan and Chandra, 2016b; Patil and Sangole, 2015, 2016; Troutbeck, 2014, 2016). Most of these methods, excluding the clearing time method and occupancy time method, were incapable and inefficient in producing actual critical gaps (Amin and Maurya, 2015; Chandra et al., 2014; Mohan and Chandra, 2016a, 2016b, 2018a). The Occupancy Time Method (OTM) considered the actual driver behaviour, which helps to predict field capacity at uncontrolled intersections more closely (Mohan and Chandra, 2018a).

3. Passenger car unit/equivalent (PCU/PCE) estimation at uncontrolled intersections

Developing countries have mixed traffic conditions compared to developed countries. Different types of vehicles have different static and dynamic characteristics. Hence, PCU is used to convert the mixed traffic flow to equivalent passenger car units. Mohan and Chandra (2016a) developed a method for computing PCE based on the queue clearance rate at priority intersections. The model was developed and tested under the diverse traffic conditions prevalent in developing countries, and it was also proved to be useful in developed nations. They suggested using the occupancy time method to calculate PCE at intersections without signals (2018b). Their study results in fixed values of PCE at base uncontrolled intersections and thus provides evidence for the static nature of PCE. Later, they introduced three methods for determining PCU for different vehicle types under mixed traffic conditions (Mohan and Chandra, 2018c). They are PCU based on occupancy time, PCU based on potential capacity, and PCU based on queue clearance rate. Calculation of PCU based on potential capacity was considered as least favourable since the influence of vehicle type on the traffic fades out with increased conflicting flow. Queue clearance rate-based PCU estimation method only applies where queue formation is expected. Therefore, the method based on occupancy time was found to be simple and, at the same time, realistic. The PCU values suggested in Indo-HCM (2017) are based on the occupancy time method. The effect of geometric factors on PCU and the suitability of the above-mentioned methods can be checked in further studies.

4. Conflicting flow at uncontrolled intersections

Conflicts may arise in areas where more than one vehicular movement approaches for a right-of-way in the same area. The capacity may reduce, the delay may increase, and the potential for road crashes may increase because of the conflicts (Mathew, 2019). The main purpose of intersection control is to reduce these conflicts to ensure the safe and efficient movement of vehicles. The conflict area is the portion of the intersection that is frequently used by various types of traffic movements. The approach considered for the study purpose is termed a subject approach. The approach opposite to the subject approach is termed as an opposing approach, and the approach that conflicts with the vehicles from both the subject approach and opposing approach is termed a conflicting approach (Kyte et al., 1991). The total traffic volume of different movements that affect a non-priority movement at an intersection is called conflicting flow (Mohan and Chandra, 2020a). Eq. (1) is an expression developed by Kyte et al. (1996) for the computation of the conflicting flow rate (v_c).

$$v_c = \frac{n}{t_n - t_0} \tag{2}$$

where, t_0 = subject vehicle's arrival time

n = observed conflicting vehicles' count, inclusive of the one passing immediately after the departure of subject vehicle

t_n = n^{th} conflicting vehicle's arrival time

HCM (2010) ranks movements at unsignalised intersections, assigning the highest priority for Through (TH) and Right-Turn (RT) movements and the lowest priority for minor Left-Turn (LT). It has also been accepted by the Indian standard for the design of at-grade intersections (Indian Roads Congress (IRC) SP: 41, 1994), however, with certain adjustments to accommodate the country's left-hand driving. HCM (2010) assigns weights of 0, 0.5, 1, and 2 to conflicting streams to account for their effects on the subject stream. A weightage of 0 has no influence on gap acceptance behaviour, but a weightage of 2 has a large effect. Later, the applicability of the conflicting flow equations provided in HCM (2010) was checked for Indian intersections because a change was observed in the movement priorities. The merging seemed to be easier and safer compared to crossing movements in India. Indo-HCM (2017) modified the weights of conflicting streams for determining conflicting flow under mixed traffic scenarios.

5. Capacity at uncontrolled intersections

The capacity of uncontrolled intersections can be estimated by different methods, which can be broadly grouped into deterministic and probabilistic approaches. The four different methods commonly used to evaluate the capacity are:

(1) Gap acceptance method
(2) Empirical regression technique
(3) Traffic signal analogy technique
(4) Additive conflict flow technique

In Germany, Harders (1968) and Siegloch (1973) developed the gap acceptance method, which is the theoretical basis for estimating capacity. Capacity estimation using different approaches was conducted in various countries under various traffic conditions. Based on Harders model, several studies have been performed even from an early period. Kyte along with other researchers made many significant contributions to capacity estimations at uncontrolled intersections. Kyte et al. (1991) developed a set of models and arrived at factors influencing the capacity and LOS of AWSC intersections and TWSC intersections. The model developed by Kyte et al. (1991) depends on the traffic volume of conflicting and opposing approaches. In 1997, they proposed a practical method using the application of delay models provided by the 1994 update of HCM. Moreover, they suggested taking into account any conflicting vehicles that influence the driver behaviour of the subject vehicle. Further, the intersection's intricacy and geometry determine the conflicting stream's impact on the subject movement. Kyte and List (1999) developed an eight-step procedure for AWSC intersections based on stream interactions by considering the maximum possible output, maintaining other approach flows constant, and concentrating on maximum output for the intersection at constant volume distribution. Khatib and Kyte (2000) concluded that the volume forecasts and driver behaviour variables (saturation headway and critical gap) cause high uncertainty. They also conducted some simulation studies, which are listed in Table 4.

Brilon and Grossmann (1991) estimated minor stream capacity using the Seigloch formula and arrived at results similar to the Harders formula. Later, Brilon and Wu (1999) brought a couple of crucial findings using gap acceptance theory with and without simulation. With the two-stage priority condition, the capacity of minor street movement was found to be larger in the study of Brilon et al. (1996). Unsignalised intersections in Germany were reviewed by Brilon et al. (1997), providing information about contributions in the theory of TWSC intersections, including two-stage priority, flared minor road entries, short lanes, formulas for impedance factors, critical gap, and move-up time. Further, Robinson et al. (1999) studied upstream signals, pedestrian crossings, and delays to major streets through vehicles using shared LT and TH lanes and developed Adjustment Factors (AF). Brilon and Wu (1999) formulated equations to estimate the capacity of TH movement from the minor road in two-stage priority. In 2003, they converted complex formulas into graphical representations for field allocation. Other significant works based on gap acceptance behaviour are given in Table 1.

Table 1. Studies on capacity using gap acceptance method.

Year	*Author*	*Remarks*
1991	Wegmann	Gap-block model for the traffic on major road for non-poissonian stream, heterogeneous traffic, inconsistent driver behaviour of minor roads, and impedance effects
1997	Bonneson and Fitts	Minimum capacity represents the aggregate effect of factors affecting the capacity and delay of the non-priority movement
1997	Heidemann and Wegmann	Capacities were insensitive to intra-bunch headways, critical gaps, move-up times and merging times
2000	Chodur	Regression analysis indicated a lack of relationship between the minor road movement capacity and type of sign posted on the minor road
2002	Espada et al.	Capacity formula based on fluid approximation of gap acceptance mechanism is sensitive to control type and found similar to Plank fluid approximation model at zero for the control type parameter
2003	Li et al.	Proposed mixed-flow model better fits Chinese traffic conditions
2005	Chodur	Capacity model developed for major road LT movement, all minor road movements, and roundabouts
2016	Asaithambi and Anuroop	Occupancy time increases exponentially with conflicting flow, and does not depend much on the vehicle types
2017	Bogdanović et al.	Analysis of four-legged non-standard unsignalised intersections following HCM (2010)
2018	Datta	Determined v/c ratios of turning movements under mixed traffic conditions
2021	Ruškić and Mirović	Application of HCM formula is limited for higher conflict flow as it lacks accuracy

Based on the study by Kimber (1989) in the United Kingdom, the empirical regression technique based on statistical models was then developed. Afterwards, Akcelik (1994) developed the traffic signal analogy technique, in which the times when a priority stream is blocked and when it is not blocked were treated like red and green times. After that, Gleue (1972) developed the Additive Conflict Flows (ACF) method. Wu (2000a, 2000b) changed it to determine the capacity at AWSC intersections. Later, Brilon and Wu (2001) employed a similar technique to calculate the capacity of TWSC intersections. The different capacity models are represented in Eq.s (2), (3), (4), (5), (6), (7), (8), and (9).

- Harder's model (1968):

$$Q_m = q_p \frac{e^{-(q_p/3600)\,(t_c - t_f)}}{e^{-q_p t_f/3600} - 1} \tag{2}$$

Where, Q_m = total capacity of the minor street (veh/h)
q_p = volume of the priority stream (veh/h)
t_c = critical gap (seconds)
t_f = follow-up time (seconds)

- Siegloch model (1973):

$$Q_m = \frac{3600}{t_f} \times e^{-q_p t_0/3600} \tag{3}$$

Where, $t_0 = t_c - (t_f / 2)$;

- Troutbeck model (1986):

$$Q_m = \frac{\alpha q_p e^{-\lambda(t_c - t_f - t_m)}}{e^{-\lambda t_f}{}_{-1}} \tag{4}$$

Where, α = proportion of free vehicles
$\lambda = (\alpha q_p) / (3600 - t_m q_p)$
t_m = minimum intervehicle tracking headway

- Tanner model (1962, 1967):

$$Q_m = \frac{q_m(1-\lambda t_p)e^{-\lambda(t_c - t_p)}}{1-e^{-\lambda t_f}} \tag{5}$$

Where, q_m = number of major stream headways per time unit
t_p = follower headway between major stream vehicles

- Luttinen Model (1990):

$$Q_m = \frac{q_m\, e^{((-q_m(t_c - t_p))/(3600 - q_m t_p))}}{1-e^{((-q_m t_f))/((3600 - q_m t_p)}} \tag{6}$$

- Indonesian Highway Capacity Manual (IHCM, 1997):

$$C = C_0 \times F_W \times F_M \times F_{CS} \times F_{RF} \times F_{LT} \times F_{RT} \times F_{SP} \tag{7}$$

Where, F_W = AF for carriageway width
F_M = AF for major road median type
F_{CS} = AF for city size class
F_{RF} = AF for road environment and side friction class
F_{LT} = AF for percentage LT
F_{RT} = AF for percentage LT
F_{SP} = AF for percentage road flow split

- HCM (2000, 2010, 2016):

$$C_{p.x} = v_{c,x} \frac{e^{-v_{c,x} t_{c,x}/3600}}{1-e^{-v_{c,x} t_{f,x}/3600}} \tag{8}$$

Where, $v_{c,x}$ = conflicting flow rate for movement x (veh/h)

- Indo-HCM (2017):

$$C_x = a \times v_{c,x} \frac{e^{-v_{c,x}(t_{c,x} - b)/3600}}{1-e^{-v_{c,x} t_{f,x}/3600}} \tag{9}$$

Where, a, b = AF based on intersection geometry

Wu (2000a, 2000b) developed a simpler method based on the ACF method proposed for AWSC intersections found applicable to first-in-first-out intersections and offside priority intersections. In 2002, an ACF model was found to be more sensitive to the proportion of turning vehicles and street-flow-split than the HCM model. Brilon and Wu (2001) applied the same technique to the TWSC intersection. They presented an ACF-based model stating the drawbacks of the gap acceptance method that may hinder its practical application (Brilon and Wu, 2002). Some of the limitations are:

- Critical gaps cannot be measured directly in the field. It is difficult to figure out a real critical gap, which makes the gap acceptance method uncertain.
- The gap acceptance method cannot be used when drivers do not follow priority rules (like in developing countries).
- The gap-acceptance theory does not work when pedestrians or cyclists share the intersection area.

Brilon and Miltner (2005) used the conflict technique to obtain results more realistic than Kyte's (1996) method, considering non-motorised traffic. He et al. (2008) computed the capacities at AWSC intersections with shared lanes, short lanes, and flared entries using Kyte’s (1996) method. The result showed the significance of non-motorised traffic movements. In 2008 and 2009, they obtained results comparable to conventional methods such as gap acceptance and motorcade analysis (Li and Deng, 2008; Li et al., 2009). An improved capacity model based on the conflict technique for TWSC intersection with multilane approaches was developed by Li et al. (2011). On the other hand, Guler and Menendez (2016) arrived at a methodology for predicting approaches with larger delays.

Graph theory forms the basis of the ACF approach. The ACF method is analogous to the “traffic signal analogy technique”. It was made to determine how well the uncontrolled intersections can handle both motorised and non-motorised traffic. The HCM model involves iterative calculations to assess capacity and is insensitive to the percentage of turning vehicles and street-flow split (Wu, 2002). Some researchers modified the existing capacity models for right-angled uncontrolled intersections to account for the effect of mixed traffic scenarios prevailing in developing countries (Mohan and Chandra, 2020a; Prasetijo et al., 2011, 2014, 2016; Prasetijo and Ahmad, 2012), as indicated in Figure 6.

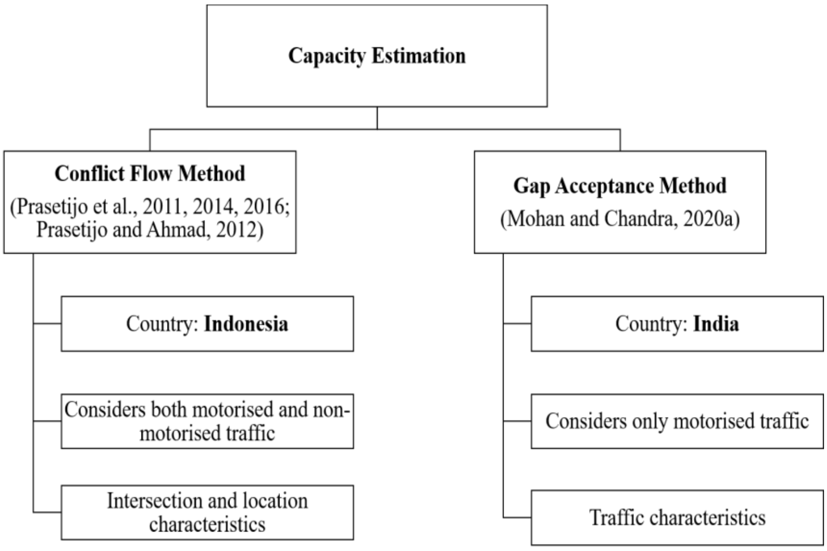

Figure 6: Variables and methods for capacity estimation in developing countries.

The studies conducted in developing countries commonly include variables such as traffic flow, movement type, median at major roads and occupancy time. Mohan and Chandra (2020a) modified Harders model based on the gap acceptance theory adopted in US HCM for Indian traffic conditions. They introduced adjustment factors based on intersection geometry at uncontrolled intersections. On the other hand, Prasetijo et al. (2011, 2012, 2014, 2016) observed the gap acceptance behaviour as uncommon at uncontrolled intersections in Indonesia. Hence, they used conflicting flow techniques incorporating both motorised and non-motorised traffic, including variables such as side friction, speed, intersection occupancy, and commonly used parameters.

Usually, an intersecting angle of 90^0 is preferred for designing purposes. However, many roads intersect at angles other than 90^0 due to physical constraints (Nightingale et al., 2017). Such intersections are named skewed intersections. The skewness is an important factor in the operation of stop-controlled intersections compared to signalised intersections (Harwood et al., 2000). The skew angle is the deviation of the minor road from 90^0 with respect to the major road. A minimum intersection angle of 60^0 (which means a skew angle of 30^0) is recommended by the AASHTO Green Book (1994), and many highway agencies adopted this as guidance in the geometric design policies (FHA, 2001). Based on the literature, the effect of skew angle on capacity remains a relatively unexplored area. Recently, using simulation models in PTV VISSIM, Arathi et al. (2023) found that the Indo-HCM (2017) capacity model overestimates capacity, except at zero skewness. Hence, they developed new capacity models and proposed adjustment factors for existing Indo-HCM (2017) capacity model to determine the capacity of uncontrolled intersections with any skew angle. It was also found that capacity increases linearly with an increase in the occurrence of priority violations due to the aggressive behaviour of drivers (Arathi et al., 2024).

6. LOS at uncontrolled intersections

The performance measures at uncontrolled intersections describe how well the facility operates in prevailing traffic conditions. From the first edition of the Highway Capacity Manual (HCM) of 1950, which adopts practical capacity as a performance measure, successive editions used service volume, reserve capacity, and LOS based on average control delay and v/c ratio. The different proposed LOS criteria by various researchers and HCM are summarised in Table 2.

Table 2. Different thresholds for LOS at uncontrolled intersections.

LOS	*Pan et al. (2008)*	*HCM (2010, 2016)*	*Indo-HCM (2017)*	*Datta et al. (2021)*	*Jena et al. (2022)*
	Delay and risk index	*Control delay (seconds/veh) and v/c ratio < 1*	*v/c ratio*	*Average total delay in %*	*User perception*
A	0-20	0-10	< 0.15	87	> 5.1
B	>20-35	>10-15	0.16 - 0.35	75	>4.33 – ≤5.1
C	>35-55	>15-25	0.36 - 0.55	55	>3.5 – ≤4.33
D	>55-75	>25-35	0.56 - 0.80	27	>2.67 – ≤3.5
E	>75-100	>35-50	0.81 - 1.00	29	>1.84 – ≤2.67
F	>100	>50	> 1.00	20 - 29	≤ 1.84

LOS is a performance measure that ascertains the quality of traffic operations, and it can be determined based on average control delay, v/c ratio and user perception. Usually, the delay experienced by the drivers is used to define the LOS at unsignalised intersections. Pan et al. (2008), Datta et al. (2021), and HCM (2010) considered delay as a measure for establishing LOS thresholds. However, illegal on-street parking turnover, vending activities, delays by slow-moving traffic or opposing encounters, etc., affect the driving environment at unsignalised intersections. Hence, Jena et al. (2022) examined the effects of road characteristics in mixed traffic flow conditions to validate current methods of assessing service quality at unsignalised intersections and proposed user-perceived LOS thresholds. HCM (2010, 2016) used the average control delay and v/c ratio to determine the LOS. At the same time, Indo-HCM (2017) used only the v/c ratio for the LOS determination due to the aggressive and impatient driver behaviour in Indian traffic conditions. However, none of the highway capacity manuals considered the road user perception for evaluating the LOS, which can be a topic for further research.

7. Simulation approach at uncontrolled intersections

The driving behaviour modelling can be done more accurately by simulation techniques than the analytical techniques for complex mixed traffic conditions. The process of developing a dynamic model of a real dynamic system is called simulation, which is done either to better understand the system's behaviour or to test out different operational techniques (Ingalls, 2001). Several studies have been taken on simulation model development. However, most of them deal with homogeneous traffic conditions in freeways, arterial roads, mid-blocks, and signalised intersections. The simulation models must be calibrated and validated to replicate the real traffic conditions. The methods used by different researchers for calibrating and validating the simulation models are listed in Table 3.

Table 3. Calibration and validation techniques.

Calibration Methods	*Validation Methods*
• Verbal description (Hourdakis et al., 2003; Kamrani et al., 2014)	• Verbal description (Hourdakis et al., 2003; Kamrani et al., 2014)
• Absolute percentage error (Mathew and Radhakrishnan, 2010)	• Absolute percentage error (Mathew and Radhakrishnan, 2010)
• Trial and error (Arroju et al., 2015; Dutta and Ahmed, 2019)	• Trial and error (Arroju et al., 2015; Dutta and Ahmed, 2019)
• Mean absolute percentage error (Dutta and Ahmed, 2019; Siddharth and Ramadurai, 2013)	• Mean absolute percentage error (Dutta and Ahmed, 2019; Siddharth and Ramadurai, 2013)
• Genetic algorithm (Ge and Menendez, 2014; K. O. Kim and Rilett, 2003; S. J. Kim et al., 2005; Lidbe et al., 2017; Ma and Abdulhai, 2002; Park and Qi, 2005; Schultz and Rilett, 2005; Siddharth and Ramadurai, 2013; Arathi et al.,2023)	• Genetic algorithm (Ge and Menendez, 2014; K. O. Kim and Rilett, 2003; S. J. Kim et al., 2005; Lidbe et al., 2017; Ma and Abdulhai, 2002; Park and Qi, 2005; Schultz and Rilett, 2005; Siddharth and Ramadurai, 2013)
• Statistical validation using two-sample tests (Barceló et al., 2005; Park and Qi, 2005; Park and Schneeberger, 2003)	• Statistical validation using two-sample tests (Barceló et al., 2005; Park and Qi, 2005; Park and Schneeberger, 2003; Arathi et al., 2023)
• Orthogonal genetic Algorithm (Qin et al., 2016)	• Orthogonal genetic Algorithm (Qin et al., 2016)

Most research papers on the simulation models dealt with homogeneous traffic conditions in developed countries (Dowling et al., 2004; Park and Qi, 2005). Very few research papers discuss model calibration and parameter optimisation in the context of mixed traffic conditions. The studies by Hossain (2001), Manjunatha et al. (2013), Mathew and Radhakrishnan (2010), and Siddharth and Ramadurai (2013) are focused on signalised intersections. There are very few works on the calibration of uncontrolled intersections under homogeneous conditions (Caliendo and Guida, 2012; Ehlert et al., 2017; Kamrani et al., 2014; Liu et al., 2012; Mueller and Claudio, 2014) and heterogeneous conditions (Dutta and Ahmed, 2019; Paul et al., 2017; Arathi et al., 2023). Dutta and Ahmed (2019) discovered that the values of the car-following parameters were significantly lower than the pre-set values. Mathew and Radhakrishnan (2010) have reported similar findings for mixed traffic situations. The simulation model calibrated using gap acceptance, a microscopic parameter, is the initial effort to investigate the unsignalised intersection performance in the simulation model using gap by Paul et al. (2017). Regarding capacity studies, simulation models were mostly based on the gap acceptance technique, as discussed in Table 4.

Table 4. Simulation model for capacity estimation.

Year	*Author*	*Simulation*	*Purpose and Remarks*
1991	Brilon and Grossmann	KNOSIMO	For estimating traffic performance at unsignalised intersections
1994	Akçelik and Chung	MODELC	For predicting traffic performance of sign-controlled approaches by converting the block and unblock period of gap acceptance modelling into red and green period using traffic signal analogy approach
1996	Kyte et al.	AWSIM	Analysed impact of volume distributions on capacity for each approach and turning movements
1996	Brilon et al.	KNOSIMO	With two-stage priority condition, the capacity of minor street movement found to be larger
1999	Wu	KNOSIMO	Analytical procedure using probability theory at shared and short lanes found. Capacity increases by flaring, and it was increased for left flaring compared to right
1999	Brilon and Wu	KNOSIMO	Formulated equations for TH movement from the minor road in two-stage priority
2003	Kyte et al.	CORSIM	Examined differences arise between field and model measurements
2011	Li et al.	VISSIM	Model based on conflict technique at TWSC intersection with multilane approaches
2015	Hemavathy et al.	VISSIM	Performance of uncontrolled intersection, critical gap estimated based on MLM
2016	Dorda et al.	A witness simulation software	Difference between simulated and calculated values increases with increased traffic intensities
2018	Datta	VISSIM	v/c ratios of turning movements at uncontrolled intersections under mixed traffic conditions
2021	Ruškić and Mirović	Trafficware Syhcnro/Simtraffic and AnyLogic-intersection simulation softwares	Compared the differences between theoretical and practical capacity values by simulation. For more intensive conflict flow, the capacity calculation does not show accurate value; thus, application of HCM formula is limited for higher conflict flow

The simulation model called KNOSIMO by Brilon et al. (1991) was among the most initial efforts for capacity estimation. Following this, the MODELC (Akçelik and Chung, 1994), AWSIM (Kyte et al., 1996), and CORSIM (Kyte et al., 2003) were used, as mentioned in Table 4. Later, most of the recent works used PTV VISSIM.

PTV VISSIM has grown to be a more well-liked and effective software package. Many professionals in the field of traffic engineering utilise it since it is a microscopic, time-step-oriented, and behaviour-based simulation tool for modelling urban and rural traffic and pedestrian flows (PTV VISSIM User Manual, 2022). GPSS II, SIMSCRIPT, GASP, SIMPAC, DYNAMO, and SIMULAE are other simulation packages (Naylor, 1966).

8. Conclusions

An estimate of the capacity of an uncontrolled intersection will aid in predicting the maximum number of vehicles that could potentially enter the intersection. In addition, the Level Of Service (LOS) can be used to evaluate the performance of uncontrolled intersections based on delay and the v/c ratio, to determine how efficiently the intersection operates under prevailing traffic conditions. The primary purpose of the present article is to investigate the previous studies on uncontrolled intersections and identify the research gaps that need to be bridged in the near future. The following are the key observations of this review:

- As per the studies on the gap acceptance parameter called critical gap, the Occupancy Time Method (OTM) is applicable in both developed and developing nations and provides reliable values, since it incorporates the actual driving behaviour (Mohan and Chandra, 2018a).
- The gap acceptance method of capacity estimation fails when the intersection space is shared by pedestrian and bicycle movements. However, it is the commonly adopted method for analysing unsignalised intersections in many capacity manuals in European countries and the U.S. The conflict technique is a viable solution for bridging the shortcomings of the gap acceptance method.
- The LOS standards are not fixed and may vary depending on traffic conditions and operations. The existing highway capacity manuals do not incorporate the road users’ perceptions when setting up LOS thresholds.
- PCU estimation based on the potential capacity method is appropriate for a given vehicle type at various volume levels. However, it makes the unrealistic assumption that both the subject and conflicting streams consist of the same vehicle type. In contrast, queue clearance rate-based estimation fails under low traffic conditions at intersections (Mohan and Chandra, 2017). The estimation of PCU based on occupancy time provides reliable values under different traffic conditions compared to other methods.

9. Future directions

The following are potential directions for future research that could help fill some of gaps in the existing literature on unsignalised intersections.

- The uninterrupted flow condition on the major road is often violated (Mohan and Chandra, 2020a, 2016b). The impact of priority violations on gap acceptance parameters and capacity is another area that requires proper attention from researchers.

- Some studies have concluded that crash frequency increases with the skew angle (Biancardo et al., 2019). The skewed intersections pose serious safety and operational challenges for both motorists and non-motorists (Biancardo et al., 2019). Research on skewed intersections is limited, indicating that this area warrants further investigation.
- It can also be observed that there are limited studies on capacity estimation using conflict techniques at uncontrolled intersections in developing countries. Therefore, researchers should examine the impact of pedestrian flow on capacity at locations where pedestrian movement is predominant, as such studies are rare in developing countries.
- Research on user-perceived LOS can be further pursued in future studies.
- Studies on PCU estimation at unsignalised intersections are limited. The effect of geometric factors on PCU remains an area to be explored.
- Regarding simulation studies, there has been limited work on developing and calibrating simulation models for four-legged uncontrolled intersections, especially under mixed traffic conditions.
- In the case of uncontrolled intersections, driver behaviour plays a vital role since there are no explicit control measures. Future research should employ driving simulators to capture driver's psychological and behavioural aspects to better understand their impact on gap acceptance and safety.

References

Abhigna, D., Brahmankar, D.P. and Ravishankar, K.V.R. (2020) ‘Multi vehicle-type right turning gap-acceptance and capacity analysis at uncontrolled urban intersections’, *Periodica Polytechnica Transportation Engineering*, 48(2), pp. 99–108.

Aghabayk, K. *et al.* (2013) ‘A novel methodology for evolutionary calibration of vissim by multi-threading’, in *Australasian Transport Research Forum*, pp. 1–15.

Akçelik, R. (1994) ‘Gap acceptance modelling by traffic signal analogy’, *Traffic Engineering and Control*, 35(9), pp. 498–506.

Akcelik, R. and Chung, E. (1994) ‘Traffic Performance Models for Unsignalised Intersections and Fixed- Time Signals’, *Proceedings of the Second International Symposium on Highway Capacity, Volume 1,* pp. 21–50.

Amin, H.J. and Maurya, A.K. (2015) ‘A review of critical gap estimation approaches at uncontrolled intersection in case of heterogeneous traffic conditions’, *Journal of Transport Literature*, 9(3), pp. 5–9.

Arathi, A.R., Harikrishna, M. and Mohan, M. (2023) ‘Simulation-based Performance Evaluation of Skewed Uncontrolled Intersections’, *International Journal of Intelligent Transportation Systems Research*, 21, pp. 349–360.

Arathi, A.R., Harikrishna, M. and Mohan, M. (2023) ‘Analysis of Critical Gap and Capacity at Skewed Uncontrolled Intersections’, *European Transport \ Trasporti Europei*, 93.

Arathi, A.R., Harikrishna, M. and Mohan, M. (2024). ‘Influence of Geometric and Traffic Characteristics on Priority Violations at Uncontrolled Intersections’, in *Cognizant Transportation Systems: Challenges and Opportunities. IMPACTS 2023. Lecture Notes in Civil Engineering, Volume 263,* Springer, pp. 99-112.

Arroju, R. *et al.* (2015) ‘Comparative evaluation of roundabout capacities under heterogeneous traffic conditions’, *Journal of Modern Transportation*, 23(4), pp. 310–324.

Asaithambi, G. and Anuroop, C. (2016) ‘Analysis of occupation time of vehicles at urban unsignalized intersections in non-lane-based mixed traffic conditions’, *Journal of Modern Transportation*, 24(4), pp. 304–313.

Ashalatha, R. and Chandra, S. (2011) ‘Critical gap through clearing behavior of drivers at unsignalised intersections’, *KSCE Journal of Civil Engineering*, 15(8), pp. 1427–1434.

Barceló, J. *et al.* (2005) ‘Methodological notes on combining macro, meso and micro models for transportation analysis’, in *Workshop on Modeling and Simulation*, pp. 1–40.

Biancardo, S.A. *et al.* (2019) ‘Design criteria for improving safety performance of rural intersections’, *Journal of Advanced Transportation*, 2019.

Bogdanović, V., Ruškić, N., Basarić, V., and Tanackov, I. (2017). Capacity analysis procedure for four-leg non-standard unsignalised intersections. Promet - Traffic and TransportationTransportation, 29(5), 543–550.

Bonneson, J.A. and Fitts, J.W. (1997) ‘Effect of upstream signal on nonpriority movement capacity and delay’, *Transportation Research Record*, (1572), pp. 174–182.

Brilon, W. (2016) ‘Some remarks regarding the estimation of critical gaps’, *Transportation Research Record*, 2553(1), pp. 10–19.

Brilon, W., Grossmann, M. and Stuwe, B. (1991) ‘New German guideline for capacity of unsignalized intersections’, pp. 63–73.

Brilon, W., Koenig, R. and Troutbeck, R.J. (1999) ‘Useful estimation procedures for critical gaps’, *Transportation Research Part A: Policy and Practice*, 33(3–4), pp. 161–186.

Brilon, W. and Miltner, T. (2005) ‘Capacity at intersections without traffic signals’, *Transportation Research Record*, 1920(1), pp. 32–40.

Wu, N. (2000a). Determination of capacity at all-way stop-controlled intersections. Transportation Research Record, 1710(1), 205–214.

Wu, N. (2000b). Capacity at all-way stop-controlled and first-in-first-out intersections. Proceedings of the 4th International Symposium on Highway Capacity, Hawaii, Transportation Research Circular E-C018.

Brilon, W. and Wu, N. (1999) ‘Capacity at unsignalized two-stage priority intersections’, *Transportation Research Part A: Policy and Practice*, 33(3–4), pp. 275–289.

Brilon, W. and Wu, N. (2001) ‘Capacity at unsignalized intersections derived by conflict technique’, *Transportation Research Record*, 1776(1), pp. 82–90.

Brilon, W. and Wu, N. (2002) ‘Unsignalized intersections-a third method for analysis’, in *Transportation and Traffic Theory in the 21 st Century*. Emerald Group Publishing Limited. A

Brilon, W. and Wu, N. (2003) ‘Two-stage gap acceptance: Some clarifications’, *Transportation Research Record*, 1852(1), pp. 26–31.

Brilon, W., Wu, N. and Bondzio, L. (1997) ‘Unsignalized intersections in Germany-A state of the art’, in *Proceedings of the Third International Symposium on Intersections Without Traffic Signals*, pp. 61–70.

Brilon, W., Wu, N. and Lemke, K. (1996) ‘Capacity at unsignalized two-stage priority intersections’, *Transportation Research Record*, (1555), pp. 74–82.

Caliendo, C. and Guida, M. (2012) ‘Microsimulation approach for predicting crashes at unsignalized intersections using traffic conflicts’, *Journal of Transportation Engineering*, 138(12), pp. 1453–1467.

Cassidy, M.J. *et al.* (1995) ‘Unsignalized intersection capacity and level of service: Revisiting critical gap’, *Transportation Research Record*, 1484, pp. 16–23.

Chandra, S. and Mohan, M. (2018) ‘Analysis of driver behaviour at unsignalized intersections’, in *Journal of the Indian Roads Congress*, pp. 5–10.

Chandra, S., Mohan, M. and Gates, T.J. (2014) ‘Estimation of critical gap using intersection occupancy time’, in *Nineteenth International Conference of Hong Kong Society for Transportation Studies. Hong Kong*, pp. 313–320.

Chodur, J. (2000) ‘Capacity of unsignalized urban junctions’, in *Transportation Research Circular EC108: 4th International Symposium on Highway Capacity*, pp. 357–368.

Chodur, J. (2005) ‘Capacity models and parameters for unsignalized urban intersections in Poland’, *Journal of Transportation Engineering*, 131(12), pp. 924–930.

Datta, S. (2018) ‘Assessment of uncontrolled intersections through calibration of VISSIM for Indian traffic conditions’, in *Industry Interactive Innovations in Science, Engineering and Technology*, pp. 323–338.

Dowling, R., Skabardonis, A., Halkias, J., McHale, G., and Zammit, G. (2004) 'Guidelines for calibration of microsimulation models: framework and applications', *Transportation Research Record*, 1876(1), pp. 1–9.

Devarasetty, P.C., Zhang, Y. and Fitzpatrick, K. (2012) ‘Differentiating between left-turn gap and lag acceptance at unsignalized intersections as a function of the site characteristics’, *Journal of Transportation Engineering*, 138(5), pp. 580–588.

Dissanayake, S., Lu, J.J. and Yi, P. (2002) ‘Driver age differences in day and night gap acceptance capabilities’, *IATSS Research*, 26(1), pp. 71–79.

Dowling, R. *et al.* (2004) ‘Guidelines for calibration of microsimulation models: framework and applications’, *Transportation Research Record*, 1876(1), pp. 1–9.

Dutta, M. and Ahmed, M. (2016) ‘Critical gap and critical lag estimation of uncontrolled t-intersections using clearing behaviour approach’, in *National Conference on Recent Advances in Civil Engineering (RACE)*.

Dutta, M. and Ahmed, M.A. (2018) ‘Gap acceptance behavior of drivers at uncontrolled T-intersections under mixed traffic conditions’, *Journal of Modern Transportation*, 26(2), pp. 119–132.

Dutta, M. and Ahmed, M.A. (2019a) ‘Calibration of VISSIM models at three-legged unsignalized intersections under mixed traffic conditions’, *Advances in Transportation Studies*, 48.

Dutta, Manish and Ahmed, M.A. (2019b) ‘Review of capacity estimation at unsignalized intersections in the Indian context’, in *International Conference on Innovation in Modern Science and Technology*. Springer, pp. 562–567.

Ehlert, A., Schneck, A. and Chanchareon, N. (2017) ‘Junction parameter calibration for mesoscopic simulation in Vissim’, *Transportation Research Procedia*, 21, pp. 216–226.

Espada, I.C., Nakatsuji, T. and Tanaboriboon, Y. (2002) ‘A discharge capacity formula for priority T-intersection and its application to macroscopic simulation of urban networks’, *Doboku Gakkai Ronbunshu*, 2002(695), pp. 177–186.

Federal Highway Administration (FHA), U. S. Department of Transportation (2020).

Federal Highway Administration (FHA), ‘Highway design handbook for older drivers and pedestrians’ (2001).

Fellendorf, M. and Vortisch, P. (2001) ‘Validation of the microscopic traffic flow model VISSIM in different real-world situations’, in *Transportation Research Board 80th Annual Meeting*.

Fitzpatrick, K. (1991) ‘Gaps accepted at stop-controlled intersections’, *Transportation Research Record*, 1303(11), pp. 103–112.

Gattis, J.L. and Low, S.T. (1999) ‘Gap acceptance at atypical stop-controlled intersections’, *Journal of Transportation Engineering*, 125(3), pp. 201–207.

Gavulová, A. (2012) ‘Use of statistical techniques for critical gaps estimation’, in *The 12th International Conference, Reliability and Statistics in Transportation and Communication*, pp. 20–26.

Ge, Q. and Menendez, M. (2014) ‘An efficient sensitivity analysis approach for computationally expensive microscopic traffic simulation models’, *International Journal of Transportation*, 2(2), pp. 49–64.

Gleue A.W. (1972). Vereinfachtes verfahren zur Berechnung sig- nalgeregelter Knotenpunkte. Forschung Strassenbau und Strassenverkehrstechnik 136, Bonn (in German)

Golias, J.C. and Kanellaidis, G.C. (1990) ‘Estimation of driver behavior model parameters’, *Journal of Transportation Engineering*, 116(2), pp. 153–166.

Guler, S.I. and Menendez, M. (2016) ‘Methodology for estimating capacity and vehicle delays at unsignalized multimodal intersections’, *International Journal of Transportation Science and Technology*, 5(4), pp. 257–267.

Harwood, D.W. *et al.* (2000) *Prediction of the expected safety performance of rural two-lane highways*.

Harwood, D.W. (2007) *Safety effects of intersection skew angle, Transportation Research Board (TRB).*

He, B., Li, H. and Varma, A. (2008) ‘Capacity of all-way stop-controlled intersections derived by conflict technique’, in *Transportation and Development Innovative Best Practices 2008*, pp. 401–406.

Heidemann, D. and Wegmann, H. (1997) ‘Queueing at unsignalized intersections’, *Transportation Research Part B: Methodological*, 31(3), pp. 239–263.

Hemavathy, M. *et al.* (2015) ‘Performance evaluation of uncontrolled intersection using microscopic simulation’, in *14th International Conference on Computers in Urban Planning and Urban Management (CUPUM)*.

Highway Capacity Manual (HCM) (2000) *Transportation Research Board (TRB), National Research Council, Washington, D.C.*

Highway capacity manual (HCM) (2010) Transportation Research Board (TRB), National Research Council, Washington, D.C.

Highway capacity manual (HCM) (2016) Transportation Research Board (TRB), National Research Council, Washington, D.C.

Holík, J. *et al.* (2016) ‘Universal simulation model for unsignalized intersection capacity analysis’, in *2016 17th International Carpathian Control Conference (ICCC)*. IEEE, pp. 236–241.

Hossain, M. (2001) ‘Estimation of saturation flow at signalised intersections ofdeveloping cities: a micro-simulation modelling approach’, *Transportation Research Part A: Policy and Practice*, 35(2), pp. 123–141.

Hourdakis, J., Michalopoulos, P.G. and Kottommannil, J. (2003) ‘Practical procedure for calibrating microscopic traffic simulation models’, *Transportation Research Record*, 1852(1), pp. 130–139.

Indian Highway Capacity Manual (Indo-HCM) (2017) *CSIR-Central Road Research Institute, New Delhi*.

Indian Roads Congress (IRC) SP-41:1994 'Guidelines for the design of At-grade intersections in Rural and Urban area'.

Ingalls, R.G. (2001) ‘Introduction to simulation’, in *2001 Winter Simulation Conference (WSC)*, pp. 1374–1388.

Ištoka Otković, I., Tollazzi, T. and Šraml, M. (2013) ‘Calibration of microsimulation traffic model using neural network approach’, *Expert Systems with Applications*, 40(15), pp. 5965–5974.

Jena, S. *et al.* (2020) ‘Assessment of service quality at unsignalized intersections using traffic simulation and computational intelligence’, *Transportation Letters*, pp. 1–13.

Kamrani, M., Hashemi Esmaeil Abadi, S.M. and Rahimpour Golroudbary, S. (2014) ‘Traffic simulation of two adjacent unsignalized T-junctions during rush hours using Arena software’, *Simulation Modelling Practice and Theory*, 49, pp. 167–179.

Khatib, Z. and Kyte, M. (2000) ‘Framework to consider the effect of uncertainty in forecasting the level of service of signalized and unsignalized intersections’, in *4th International Symposium on Highway Capacity, Transportation Research Circular E-C018. Maui, Hawaii, June*.

Kim, K.O. and Rilett, L.R. (2003) ‘Simplex-based calibration of traffic microsimulation models with intelligent transportation systems data’, *Transportation Research Record*, 1855(1), pp. 80–89.

Kim, S.J., Kim, W. and Rilett, L.R. (2005) ‘Calibration of microsimulation models using nonparametric statistical techniques’, *Transportation Research Record*, 1935(1), pp. 111–119.

Kyte, M. *et al.* (1991) ‘Capacity and delay characteristics of two-way stop-controlled intersections’, *Transportation Research Record*, 1320, pp. 160–167.

Kyte, M. *et al.* (1994) ‘New measurements for saturation headways and critical gaps at stop-controlled intersections’, in *Proceedings of the Second International Symposium on Highway Capacity , Volume 1*.

Kyte, M. *et al.* (1996) ‘Analysis of traffic operations at all-way stop-controlled intersections by simulation’, *Transportation Research Record*, 1555(1), pp. 65–73.

Kyte, M. and List, G. (1999) ‘A capacity model for all-way stop-controlled intersections based on stream interactions’, *Transportation Research Part A: Policy and Practice*, 33(3–4), pp. 313–335.

Li, H. *et al.* (2009) ‘Capacities of unsignalized intersections under mixed vehicular and nonmotorized traffic conditions’, *Transportation Research Record*, 2130(1), pp. 129–137.

Li, H. and Deng, W. (2008) ‘Research on capacity at urban intersections without traffic signals’, in *Transportation and Development Innovative Best Practices 2008*, pp. 389–394.

Li, H., Tian, Z. and Deng, W. (2011) ‘Capacity of TWSC intersection with multilane approaches’, *Procedia - Social and Behavioral Sciences*, 16, pp. 664–675.

Li, W., Wang, W. and Jiang, D. (2003) ‘Capacity of unsignalized intersections with mixed vehicle flows’, *Transportation Research Record*, 1852(1), pp. 265–270.

Lidbe, A.D., Hainen, A.M. and Jones, S.L. (2017) ‘Comparative study of simulated annealing, tabu search, and the genetic algorithm for calibration of the microsimulation model’, *Simulation*, 93(1), pp. 21–33.

Liu, P. *et al.* (2012) ‘Development of a VISSIM simulation model for U-turns at unsignalized intersections’, *Journal of Transportation Engineering*, 138(11), pp. 1333–1339.

Lu, J.J. and Lall, B.K. (1995) ‘Empirical analysis of traffic characteristics at two-way stop-controlled intersections in Alaska’, *Transportation Research Record*, 1495, pp. 49–56.

Ma, T. and Abdulhai, B. (2002) ‘Genetic algorithm-based optimization approach and generic tool for calibrating traffic microscopic simulation parameters’, *Transportation Research Record*, 1800(1), pp. 6–15.

Ma, W. and Zhao, J. (2020) ‘Investigating gap acceptance behavior at two-way stop-controlled intersections in China’, *Transportation Letters*, 12(3), pp. 202–212.

Manjunatha, P., Vortisch, P. and Mathew, T. (2013) ‘Methodology for the calibration of VISSIM in mixed traffic’, *Transportation Research Board 92nd Annual Meeting*, p. 11.

Mathew, T. V. and Radhakrishnan, P. (2010) ‘Calibration of microsimulation models for nonlane-based heterogeneous traffic at signalized intersections’, *Journal of Urban Planning and Development*, 136(1), pp. 59–66.

Maurya, A.K., Amin, H.J. and Kumar, A. (2016) ‘Estimation of critical gap for through movement at four leg uncontrolled intersection’, *Transportation Research Procedia*, 17, pp. 203–212.

Ministry of Road Transport and Highways, Government of India. 2021. “Road accidents in India”.

Mohan, M. and Chandra, S. (2016a) ‘Concept of queue clearance rate for estimation of equivalency factors at priority junctions’, *Canadian Journal of Civil Engineering*, 43(7), pp. 593–598. A

Mohan, M. and Chandra, S. (2016b) ‘Review and assessment of techniques for estimating critical gap at two-way stop-controlled intersections’, *European Transport - Transporti Europei*, (61).

Mohan, M. and Chandra, S. (2017) ‘Queue clearance rate method for estimating passenger car equivalents at signalized intersections’, *Journal of Traffic and Transportation Engineering (English Edition)*, 4(5), pp. 487–495.

Mohan, M. and Chandra, S. (2018a) ‘Critical gap estimation at two-way stop-controlled intersections based on occupancy time data’, *Transportmetrica A: Transport Science*, 14(4), pp. 316–329.

Mohan, M. and Chandra, S. (2018b) ‘Occupancy time-based passenger car equivalents at unsignalized intersections in India’, *Current Science*, 114(6), pp. 1346–1352.

Mohan, M. and Chandra, S. (2018c) ‘Three methods of PCU estimation at unsignalized intersections’, *Transportation Letters*, 10(2), pp. 68–74.

Mohan, M. and Chandra, S. (2020a) ‘Capacity estimation of unsignalized intersections under heterogeneous traffic conditions’, *Canadian Journal of Civil Engineering*, 47(6), pp. 651–662.

Mohan, M. and Chandra, S. (2020b) ‘Influence of major stream composition on critical gap at two-way stop-controlled intersections-a case study’, *Transportation Letters: the International Journal of Transportation Research*, 12(1), pp. 1–8.

Mohan, M. and Chandra, S. (2021) ‘Investigating the influence of conflicting flow’s composition on critical gap under heterogeneous traffic conditions’, *International Journal of Transportation Science and Technology*, 10(4), pp. 393–401.

Mohan, M. and Kezhuvathodi, V. (2019) ‘Simulation of gap acceptance at three-legged unsignalized intersections under heterogeneous traffic conditions’, *Advances in Transportation Studies*, 49.

Ministry of Road Transport and Highways (MORTH), Government of India, Road accidents in India. (2021).

Mueller, J. and Claudio, D. (2014) ‘Simulating unsignalized intersection right-of-way’, in *Proceedings of the Winter Simulation Conference 2014*. IEEE, pp. 2092–2100.

Nagalla, R., Pothuganti, P. and Pawar, D.S. (2017) ‘Analyzing gap acceptance behavior at unsignalized intersections using support vector machines, decision tree and random forests’, *Procedia Computer Science*, 109, pp. 474–481.

Naylor, T.H. (1966) *Computer simulation techniques*.

Nightingale, E., Parvin, N., Seiberlich, C., Savolainen, P. T., and Pawlovich, M. (2017). Investigation of skew angle and other factors influencing crash frequency at high-speed rural intersections. Transportation Research Record, 2636(1), 9–14.

Nyame-Baafi, E., Adams, C.A. and Osei, K.K. (2018) ‘Volume warrants for major and minor roads left-turning traffic lanes at unsignalized T-intersections: a case study using VISSIM modelling’, *Journal of Traffic and Transportation Engineering (English Edition)*, 5(5), pp. 417–428.

Oketch, T. and Carrick, M. (2005) ‘Calibration and validation of a micro-simulation model in network analysis’, in *Proceedings of the 84th TRB Annual Meeting, Washington, DC*.

Park, B. and Schneeberger, J.D. (2003) ‘Microscopic simulation model calibration and validation: case study of VISSIM simulation model for a coordinated actuated signal system’, *Transportation Research Record*, 1856(1), pp. 185–192.

Park, B.B. (2004) ‘Development and Evaluation of a Calibration and Validation Procedure for Microscopic Simulation Models’, *Virginia Transportation Research Council, Charlottesville, Virginia* [Preprint].

Patil, G.R. and Pawar, D.S. (2014) ‘Temporal and spatial gap acceptance for minor road at uncontrolled intersections in India’, *Transportation Research Record*, 2461(1), pp. 129–136.

Patil, G.R. and Sangole, J.P. (2015) ‘Gap acceptance behavior of right-turning vehicles at T-intersections - a case study’, in *Journal of the Indian Roads Congress*, pp. 44–54.

Patil, G.R. and Sangole, J.P. (2016) ‘Behavior of two-wheelers at limited priority uncontrolled T-intersections’, *IATSS Research*, 40(1), pp. 7–18.

Paul, M. *et al.* (2018) ‘Calibration methodology of microsimulation model for unsignalized intersection under heterogeneous traffic conditions’, in *Urbanization challenges in emerging economies: Energy and water infrastructure; transportation infrastructure; and planning and financing*. American Society of Civil Engineers Reston, VA, pp. 618–627.

Pawar, D. S., and Patil, G. R. (2021). Analyzing variations in spatial critical gaps at two-way stop-controlled intersections using parametric and non-parametric techniques. Journal of Traffic and Transportation Engineering (English Edition), 8(1), 129–138.

Prasetijo, J. *et al.* (2014) ‘Capacity analysis of priority intersections with flare under mixed traffic conditions’, *Procedia - Social and Behavioral Sciences*, 138, pp. 660–670.

Prasetijo, J. *et al.* (2016) ‘Capacity analysis of different geometric design of unsignalized iintersections based on occupation time’, *ARPN Journal of Engineering and Applied Sciences*, 11(20), pp. 11860–11863.

Prasetijo, J. and Ahmad, H. (2012) ‘Capacity analysis of unsignalized intersection under mixed traffic conditions’, *Procedia - Social and Behavioral Sciences*, 43, pp. 135–147.

Prasetijo, J., Pour, M.H. and Ghadiri, S.M.R. (2011) ‘Capacity of unsignalized intersections under mixed traffic conditions’, *Procedia - Social and Behavioral Sciences*, 16, pp. 676–685.

PTV Group (2022) *PTV VISSIM 2022 user manual*.

Qin, Y. *et al.* (2016) ‘Parameter calibration method of microscopic traffic flow simulation models based on orthogonal genetic algorithm’, in *22nd International Conference on Distributed Multimedia Systems (DMS)*, pp. 55–60.

Ruškić, N. and Mirović, V. (2021) ‘Estimation of left-turn capacity at the unsignalized intersection’, *Simulation Modelling Practice and Theory*, 106, p. 102170.

Schultz, G.G. and Rilett, L.R. (2005) ‘Calibration of distributions of commercial motor vehicles in CORSIM’, *Transportation Research Record*, 1934(1), pp. 246–255.

Serag, M.S. (2015) ‘Gap-acceptance behavior at uncontrolled intersections in developing countries’, *Malaysian Journal of Civil Engineering*, 27(1).

Shannon, R.E. (1975) *Systems simulation; the art and science*.

Siddharth, S.M.P. and Ramadurai, G. (2013) ‘Calibration of VISSIM for Indian heterogeneous traffic conditions’, *Procedia - Social and Behavioral Sciences*, 104, pp. 380–389.

Tian, Z. *et al.* (1999) ‘Implementing the maximum likelihood methodology to measure a driver’s critical gap’, *Transportation Research Part A: Policy and Practice*, 33(3–4), pp. 187–197.

Tian, Z.Z. *et al.* (2000) ‘A further investigation on critical gap and follow-up time’, in *Proceedings of the 4th International Symposium on Highway Capacity, Maui/Hawaii, Transportation Research Circular E-C018*, pp. 409–421.

Toledo, T. *et al.* (2004) ‘Calibration of microscopic traffic simulation models with aggregate data’, *Transportation Research Record*, 1876(1), pp. 10–19.

Troutbeck, R.J. (2014) ‘Estimating the mean critical gap’, *Transportation Research Record*, 2461(1), pp. 76–84.

Troutbeck, R.J. (2016) ‘Revised Raff’s method for estimating critical gaps’, *Transportation Research Record*, 2553(1), pp. 1–9.

Ulak, M.B. *et al.* (2019) ‘Assessment of traffic performance measures and safety based on driver age and experience: A microsimulation based analysis for an unsignalized T-intersection’, *Journal of Traffic and Transportation Engineering (English Edition)*, 6(5), pp. 455–469.

Wegmann, H. (1991) ‘A general capacity formula for unsignalized intersections’, in *Intersections without Traffic Signals II*. Springer, pp. 177–191.

Weinert, A. (2000) ‘Estimation of critical gaps and follow-up times at rural unsignalized intersections in Germany’, in *Fourth International Symposium on Highway Capacity*, pp. 409–421.

Wu, N. (1999) ‘Capacity of shared-short lanes at unsignalized intersections’, *Transportation Research Part A: Policy and Practice*, 33(3–4), pp. 255–274.

Wu, N. (2000a) ‘Capacity at all-way stop-controlled and first-in-first-out intersections’, in *Proceedings of the 4th International Symposium on Highway Capacity, Hawaii, Transportation Research Circular E-C018*.

Wu, N. (2000b) ‘Determination of capacity at all-way stop-controlled intersections’, *Transportation Research Record*, 1710(1), pp. 205–214.

Wu, N. (2002) ‘Total capacities at all-way stop-controlled intersections: validation and comparison of highway capacity manual procedure and addition-conflict-flow technique’, *Transportation Research Record*, 1802(1), pp. 54–61.

Zongzhong, T., Kyte, M. and Colyar, J. (1997) ‘Field measurements of capacity and delay at unsignalized intersections’, *Institute of Transportation Engineers. ITE Journal*, 67(4), p. 22.

Acknowledgements

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