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State-of-Art Review on Capacity, Delay and Level of Service Analysis Procedures for Urban Unsignalized Intersections

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Abstract

Unsignalized intersections standout amongst the riskiest areas on highways and inter-urban road networks. Unsignalized intersections are normally controlled with stop or caution signs and markings in developing nations, however, in developing nations like India, signs typically don't work and such intersections are considered as uncontrolled ones. The vehicular interactions at unsignalized intersections are mind-boggling and every driver needs to make individual decisions about when, where and how to complete the merging and crossing conflicts. Capacity and level of service play imperative parts in assessment of an unsignalized intersection. Delay and queue length are the vital service measures for assessing unsignalized intersection capacity and levels of service. This paper conceals and reviews the various estimation procedures for capacity, delay and level of service present in existing literature which evaluate the overall traffic performance and operation of urban unsignalized intersections. In this paper, critical and comparative reviews on the gap acceptance probabilistic procedure (GAP), the empirical regression based deterministic procedure, the additive conflict flow technique (ACF) and the microscopic simulation procedures are discussed upon. Furthermore, this paper also appraises the time-dependent and time independent type control and service delay estimation procedures along with various unsignalized intersection level of service (LOS) estimation procedures followed by several nations around the world. After successful completion of the appraisals, it can be concluded that the Additive conflict flow (ACF) and the Indian highway capacity manual gap acceptance (GAP) capacity estimation procedures are quite operative in estimating capacity and level of service under Indian traffic conditions. Nevertheless, there are precincts of the Indo-HCM procedure which need to be addressed by conducting capacity and level of service studies at every state/regional levels in India.

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Keywords: capacity; critical gap; control delay; level of service; unsignalized

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1. Background of the Paper

Roadway links and intersections are the chief components of any road network. Overall performance of a transportation network is influenced by the performance of each road link and intersection of links in the network. A bottleneck or congestion at one place can affect the wider area of the network. Thus, in order to evaluate and analyse a transportation network it is necessary to understand the traffic flow characteristics on road links and at intersections. Analysing and evaluating a transportation facility usually involves finding its capacity and judge its performance. For intersections, delay is usually considered as an essential performance parameter. Analysing traffic flow characteristics on road links is less complex as there are not many conflicting movements. In developing countries like India, traffic signals are installed only on major arterials, thus majority of intersections are unsignalized. Unsignalized intersections in Indian terms include "*priority unsignalized intersection*", whereby priorities for different movements are indicated by yield or stop signs and markings, and "*uncontrolled intersections*" where no explicit priorities exists. Most of the intersections in India do not have stop or yield sign with unpretentious driver behaviour prevailing along with lack of priority discipline among them. Drivers usually do not care much about the conflicting traffic; they attempt to enter intersection, even if a conflicting vehicle is about to collide resulting in forceful gap acceptance leading to formation of unnecessary bottlenecks and sometimes fatal accidents. Many studies on heterogeneous traffic have concluded that approaches developed for disciplined traffic that exists in developed countries may not be suitable for the traffic in India.

For capacity estimation, in general, the GAP approach (*widely followed by most of the European, Asian and American countries*), ACF technique (*a new technique introduced in Germany but currently being adopted by Asian countries like China, Japan, Indonesia*), empirical regression based deterministic approach *(followed by countries like China, U.K., Indonesia, Poland*) along with microscopic simulation procedures are followed widely by both developed and developing countries. Recently, the Indo-HCM in its recent publication for the year 2018 chapter 6, used the GAP for capacity estimation of unsignalized intersections. Control delay and queue length are the measures of effectiveness (MOEs) for unsignalized intersections (*HCM, 2010*). Some of the important estimation techniques for control delay estimation are Co-ordinate Transformation, Tanner's hypothesis, Brilon's hypothesis which are still being followed by countries like United States of America, India, Indonesia, China, Australia and other parts of the world. Level of Service is an qualitative aspect which is generally defined as '*a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to manoeuvre, safety, driving comfort and convenience, and operating costs*'. LOS is estimated using v/c ratio as the primary MOE in Indo-HCM. Some of the currently followed guidelines for Level of Service (LOS) estimation for unsignalized intersections by several countries like Sweden, United States of America, Malaysia, Finland, and India have found great importance over a few decades. Currently, there is a deficiency of pertinent literature which can suffice and abridge all these aforesaid parameters in the form of a critical and comparative review. Therefore, this paper, summarizes and critically appraises all the above mentioned concepts along with secondary emphasis on other important attributes like gap, lag, follow-up-time, occupancy time, etc which are essential in evaluating the performance of urban unsignalized intersections.

Nomenclature

GAP	*Gap Acceptance Procedure*
ACF	*Additive Conflict Flow Technique*
OT	*Occupancy Time*
VISSIM	*Visual Simulation*
AIMSUN	*Arithmetic Simulation*
HCS	*Highway Capacity Software*
HCM	*Highway Capacity Manual*
Indo-HCM	*Indian Highway Capacity Manual*
TWSC	*Two Way STOP Controlled Intersection*
AWSC	*All Way STOP Controlled Intersection*
LOS	*Level of Service*

TRRL	*Transport and Road Research Laboratory*
IT	*Intersection Type*
v/c	*Volume to capacity ratio*
MOE	*Measure of Effectiveness*
FIFO	*First-in-First-Out*

2. Appraisal of Previous Literature on Capacity, Control Delay and Level of Service Analysis Procedures

In an assorted traffic circumstance of the class common in India, individual experience exhibits that lane discipline, regard for stop or yield signs and stop line pre-eminence is not stringently obeyed. Due, to isolated structure of the traffic rules and law administrative framework in numerous parts of the country, the vehicles in some cases compel their entry into the intersections, even in lesser gaps resulting in forceful entry into the intersection conflict area. Such incidences, leads to delays for the major road vehicles as well as leads to congestion and lesser manoeuvrability of vehicles in the minor road approaches. This results in decreased comfort levels or quality of service at unsignalized intersections which may result in frequent formation of bottlenecks and congestion on both the intersecting roads. According to Highway Capacity Manual 2010 edition, "*Capacity represents the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions"*. Similarly, according to HCM 2010, level of service (LOS) can be defined as *"a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs"*. According to US-Highway Capacity Manual 2010, control delay, 95th percentile queue length are the primary measures of effectiveness (MOEs) for evaluating control delay. Control Delay can be defined as per HCM 2010 as "*the delay fetched about by the occurrence of a traffic regulator device—is the prime service measure for estimating LOS at signalized and unsignalized intersections*".

2.1. Former Literature on Capacity Estimation Procedures

Most of the analysis procedures of unsignalized intersections are based on stochastic models; i.e., *gap acceptance theory*. In this theory, it is assumed that a minor stream vehicle can enter an intersection, when the time interval to the next arriving higher priority vehicle is larger than a critical gap, and a safe time interval (follow-up time) has passed since the departure of the preceding minor stream vehicle. In Britain and in Indonesia, the capacity analysis of unsignalized intersections has been based on *statistical multiple regression models* (*Kimber & Coombe 1980; Kimber 1980; IHCM 1997*). Regression analysis has been used to find the parameters and to estimate the values of the coefficients which give a decent fit between estimated and measured capacity. This method is not sensitive to the headway distribution models, it gives a clear method to estimate the effect of intersection geometry, and can model heavily congested conditions under which the process of simple gap-acceptance gives way to a more interactive one, in which major road vehicles adjust their headways to allow minor road vehicles to enter, as well as situations, such as multi-lane roundabouts, where the anticipated vehicle interaction rules become very arbitrary. *The third strategy* in calculating capacity of unsignalized intersections is the "*Conflict Technique*". This new approach is focused around the concept of "Addition of critical movement flows" (*Gleue, 1972*). This novel theory was first introduced by (*Wu, 1999)* to serve the need for an American solution to the All–way Stop–controlled (AWSC) intersections with an intention of applying the FIFO discipline on AWSC operations. The model considers all plausible traffic streams and conflict points at intersections simultaneously. The interaction and impact between varying streams at the intersection is formulated by a numerical methodology. This methodology can similarly consider the effect of pedestrian movements and non-motorized interferences at unsignalized intersections.

(*Wu, 2001; Wu, 2012*) presented a new theoretical approach based on the idea of "Additive Conflict flows" for estimating capacity of ten All –way STOP controlled (AWSC) intersections with 32 shared lane approaches from Germany following First-In-First-Out (FIFO) discipline. The author used a combination of graph theory along with the ACF technique to estimate capacity of right turn streams, left turn streams and of all the approaches which were then used to find queue lengths and control delays for all the intersection approaches considering an M/M/1 queue discipline in the minor roads.(*Ruskin and Wang, 2002*) in their experimental analysis for TWSC performance evaluation, found that Cellular Automata (CA) models can overcome the shortcomings of the US-HCM gap acceptance capacity model. Therefore, the authors developed CA models of 4 four-legged TWSC intersections and found out that the capacity of minor streams depended on flow-rates of major streams and also on flow rate ratio[FRR] (i.e. flow rate of near lane / flow rate of far lane) for a particular movement. Capacity of minor streams decreases with decrease in left-turning ratio [LTR] (i.e. flow rate of major stream left turns/ flow rate of major stream) and with decrease in FRR ,which demarcates that increase in flow rate of near lanes. The CA model developed by the authors was able to describe the stochastic interaction between individual vehicles and can be used during situations for which headway distributions fails to describe traffic flow during occasions of non-priority. (*Prasetijo, 2007*) conducted further investigations and reviewed the current standards for unsignalized intersections capacity analysis followed by Indonesia. The author also developed a new methodology to define in actual sense the basic and actual capacity of unsignalized intersections given in IHCM through conflict and service times of each steams of the approaches of the intersection based on the actual departure headways of these streams. Using the theoretical framework of the "Additive Conflict Flow" technique, the author analysed intersections operating under First-In-First-Out (FIFO) discipline with 12 vehicular and 4streams of pedestrian crossing. These studies were conducted in Indonesia from December 1990 to February 1997. The author concluded that the values of basic and actual capacity obtained from the departure headways were satisfactorily validated for the Indonesian conditions. (*Chancey and Jackson, 2010*) studied the effects of volume on driver's critical gap acceptance at a TWSC. The authors pointed that HCM's critical gap estimation model neglects the account for the effects due to increasing traffic volume. The authors also compared the HCM delay equations with the field estimated control delay values. They also stated that the HCM procedure does not take into consideration a driver's typical behavioral characteristics due to time-in-queue and volume on the major street and also stated that the HCM critical gap is based on the average driver. The results concluded that HCS underestimates delay while it overestimates critical gaps. This study demonstrates that as volumes increases at a TWSC intersection, the critical gap accepted by the average driver decreases. Review of the data shows that an average decrease of 0.007 seconds of critical gap will occur with a one vehicle increase in volume. Critical gap was estimated by some of the existing empirical techniques like lag, Harders, binary logit, modified Raff and Hewitt methods at unsignalized T-intersections by (*Ashalatha et. al., 2011*). The critical gap variation by these methods highlights the incapability of the existing methods to address the mixed traffic conditions. Therefore, the authors formulated an alternate procedure for critical gap estimation making use of clearing behavior of vehicles in conjunction with gap acceptance data. (*Prasetijo et al. 2011*) used the Additive conflict flows (ACF) technique to formulate another method for capacity investigation at unsignalized intersections in Indonesia where driver behavior, traffic compositions, level of street side activities are very surprisingly different from developed nations (i.e. heterogeneous traffic stream conditions). The authors utilized the real field information from ten three-legged unsignalized intersections in a sub-urban city in Indonesia where traffic rules like give-way or lane control were totally neglected. Associations between all conceivable traffic streams were considered through empirical regression models. Speed and flow were measured in 5 minute interims amidst one hour observations. The results of capacities obtained from the ACF technique were contrasted with the Indonesian Highway Capacity manual and it was found that it delivered similar estimations of capacity in the speed range of 11 to 12 km/hr. (*Maurya, Amin and Kumar, 2014*) studied the crossing behaviour of drivers at uncontrolled intersections in India through gap acceptance technique. The authors used ten methods namely the Raff's method, Lag, Maximum Likelihood, Harders, Macroscopic Probability Equilibrium, Greenshield's, Logit, acceptance curve and clearing behaviour methods for estimating critical gaps for through movements from a minor road. Some of the conclusive remarks as per the authors are:

- The critical gap values obtained from all the nine methods were quite low compared to that estimated using the clearing behaviour method (developed for Indian mixed traffic conditions) which can also work well under homogeneous, under-saturated and over-saturated traffic conditions.
- The preciseness of capacity estimation depends upon the most realistic evaluation of critical gaps which was obtained using the clearing behaviour technique.

- From the analysis, driver's gender, age, speed of oncoming vehicles, waiting time and number of rejections were affecting two-wheeler gap acceptance.
- However, vehicle occupancy and waiting time did not affect three-wheeler gap acceptance.
- The authors also recommended to conduct studies on two-stage gap acceptance at four-legged uncontrolled intersections in which limited research has been devoted.

(*Zhou, Ivan, Garder and Ravishankar, 2014*) attempted to identify factors which affect gap acceptance of drivers turning left at unsignalized intersections. Technique employed for data collection was video-graphy (five cameras were installed) at each of the six unsignalized intersections on both four and two-lane roads in the city of Connecticut, United States. The presence of left turn lanes (LTL) and both high and low speed limits were included in the data sets. Driver gap acceptance (i.e. accepted/rejected) was considered as a binary decision and correlated logit models were used to assess the probability of accepting a gap. Some of the findings from the eight models developed in the study are:

- The modelling results showed that presence of LTL and the number of lanes on the major road have no significant effects on the driver's probability of accepting a given gap.
- The effects of speed limit (*high* > *45 Kmph* or *low* < *45Kmph*) were too insignificant.
- Female drivers are more conservative than male drivers in accepting gaps which is indicated by odds ratio of 0.55.
- Age does not affect driver's gap acceptance.
- The model with both the number of rejected gaps and the mean interval of the rejected gaps has the best model fit and was selected as the gap acceptance model. Probability of accepting a gap rises as both values of the factors increases.

(*Hemavathy et.al., 2015*) estimated critical gaps considering different vehicle types by different methods namely Maximum Likelihood Method (MLM), Clearing Behaviour Method (CBM), Ashworth Method, Greenshield Method, Harder's Method and Raff's Method. In order to collect gap information accurately, authors devised a new reference line for realistic measurement of gaps. The study reiterated the fact that clearing behaviour method (CBM) of critical gap estimation under mixed traffic conditions in India.(*Parmeshwaram and Asaithambi, 2016)* estimated and compared capacity of two uncontrolled T-intersections in Mangalore and Calicut using the gap acceptance procedure (GAP) and the additive conflict flows technique (ACF). The authors used Chandra's method for dynamic PCU estimation in this regard. They estimated critical gaps for priority movements (minor RT, major RT and major LT) using Raff, Greenshield's, Ashworth's and Clearing Behaviour method. The authors compared the capacities obtained by using HCM 2000 field data, gap acceptance procedure (GAP) and Additive conflict flows (ACF) technique for all the three priority movements for both the cities. For both the cities, the ACF technique overestimated capacity for minor left turns at the T-intersections. The gap acceptance capacities were also found to be lower compared to those estimated using the HCM 2000 field data values.(*Rao et al. 2017*) estimated critical gaps at three uncontrolled TWSC T-intersections in the city of Vishakhapatnam using Raff's, Harders, Wu and a newly proposed method by IIT Roorkee. The authors also estimated and compared capacity of major and minor right and left turns using the HCM 2010 technique for critical gaps estimated using the above stated methods. In addition, the authors compared control delay for the selected major and minor road movements along with a critical gap comparison using HCM 2010 TWSC control delay estimation technique. They also evaluated and compared the Levels of service (LOS) for both morning and afternoon peak hours using HCM 2010 LOS estimation procedure. For determining the capacity, an occupation/service time of 3.6 seconds has been adapted in case of AWSCs. Earlier studies for single–lane AWSC intersections found that turning movements did not affect the occupation time significantly. (*Mohan and Chandra, 2017*) estimated critical gaps and later then translated them in estimation of capacity at four Indian uncontrolled intersections using the Maximum Likelihood method (MLM), Harder's Method, Modified Raff's method, Logit (weighted linear regression) method and the Ashworth's method. The authors used a new concept of "Occupancy Time" (i.e. the time spent by a subject movement or vehicle type in occupying the intersection influence area) and used its theoretical background along with cumulative distributions of accepted gaps and lags to estimate critical gaps for the four intersections. The validation of this proposed method was demonstrated by the authors by comparing field capacity of non-priority movement at one of the intersections with the theoretical obtained capacity value.

The Indian highway capacity manual in its first and recent publication (*Indo-HCM 2018*) has included a chapter (chapter no. 6) on critical gap and capacity analysis of unsignalized/uncontrolled intersections exclusively considering Indian mixed traffic behaviour. In this manual for the first time the occupancy time method (OTM) has been conceived for the calculation of critical gaps. Unlike other methods, OTM incorporates actual driver behaviour observed on unsignalized intersections largely. As such, OTM accounts for the actual clearing pattern of the conflict area and the traffic interaction that occurs within this region. Thereafter, the capacity for various movements observed at an unsignalized intersection is carried out through a series of steps which will be described in this sub-section. Some of the presumptions under which the capacity analysis were carried out during the formation of the guidelines are as follows:

- An unsignalized intersection refers to "an intersection without signal or manual control or any central island".
- It is formed when two roads intersect or join each other at grade.
- Based on the relative importance of the two roads, one of them is generally designated as major and the other as minor road.
- When traffic on minor road is controlled by STOP signs, the intersection is called a Two-way STOP controlled (TWSC).
- In case, STOP signs are placed on all the approaches of an intersection, then it becomes an All-Way-STOP controlled intersection (AWSC).
- Due to weak enforcement of traffic regulations and lack of understanding of priority rules among road users in India, no distribution in terms of utility of intersections can be made between a TWSC and an AWSC.
- Based on patterns and geometry, intersections can be three-legged, four-legged or multi-legged types.
- A typical three-legged intersection is formed when a side street joins a major street.
- A four-legged intersection is formed when two roads cross each other. One of these two roads are generally a minor street but sometimes both the streets can be called as minor or major streets.
- Limited priority of movements are followed by road users in India and in developing countries like India.
- A Major road in Indian terms can be defined as that road which is wider among the two or which carries heavy volume of traffic in an unsignalized intersection.
- Capacity at an unsignalized intersection is defined for each non-priority movement or stream. It is the maximum number of vehicles that can execute a certain non-priority movement under the given traffic flow condition on all remaining approaches which is generally expressed in terms of Passenger Car Units per Hour (PCU/hr).
- Capacity of an unsignalized intersection (*as a whole*) is of not so much importance because by the time traffic volume increases to the level comparable to capacity (*generally at volume much lower than capacity*), the intersection will normally be installed with traffic signals.
- Unsignalized Intersections to be considered for capacity and LOS analysis in India shall be categorized and should conform to the conditions listed below:
    - Number of Intersecting approaches = 3 or 4
    - Angle of the intersection may be at 90 degrees on a three or four legged intersection with a slight deviation of +/- 10 degrees.
    - 2 or 4 lane divided major road
    - Negligible presence of non-motorized traffic, on street-parking, hawkers or any other land use activities within 75 meters from the centre of the intersection.
    - No gradient on the intersecting approaches
    - Safe stopping and intersection sight distance should be available.

- Absence of speed breakers on any approach within 75 meters from the centre of the intersection.

Exceptions are always greeted conveniently only if the analyst finds that the intersection does not conform to above mentioned conditions. In any such cases, the intersections to be analysed are to be classified as non-base intersections and necessary adjustment factors need to be applied for deviations from the base conditions. The basis of capacity and LOS analysis performed in the Indian Highway Capacity Manual, includes twelve unsignalized intersection with varying geometry located in eight metropolitan cities of the country namely, Delhi, Navi Mumbai, Maraimalainagar (*outskirts of Chennai*), Thiruvanthapuram, Bhubaneswar, Meerut, Faridabad and Noida. Therefore, any deviation from these base intersections can cause fraudulent analysis in capacity and LOS prediction. The methodology suggested by Indian Highway capacity manual (*Indo-HCM 2018*) is shown in the figure 1. Indo-HCM methodology estimates primarily capacity and LOS of three movements i.e. right turn from Major Street, right turn from Minor Street and through movement on Minor Street occurring on three-legged unsignalized intersections. Using the critical gaps for passenger cars (seconds), conflicting flow (PCUs/hr) and assuming follow-up-time as 60 % of critical gap, the capacity (in PCUs/hr.) for individual movements is estimated.

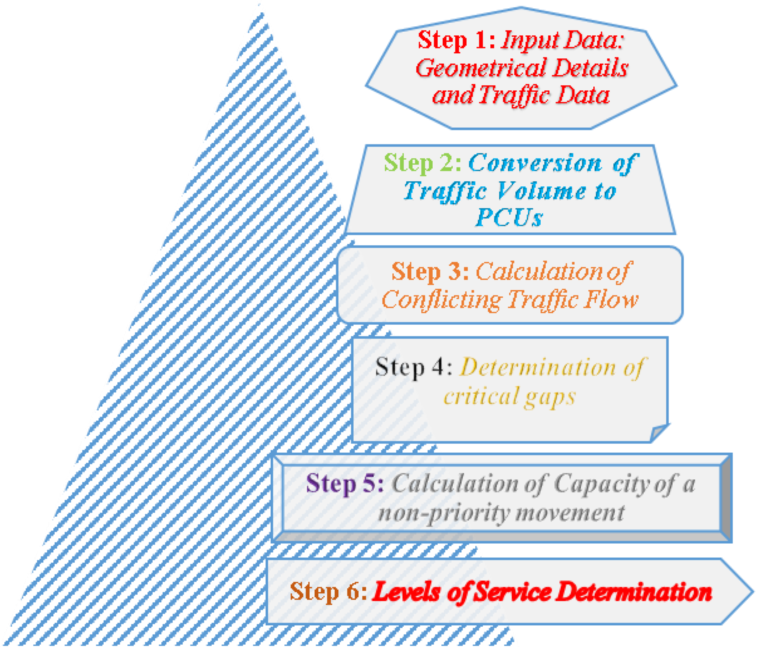

Fig. 1. Methodology Suggested by Indian Highway Capacity Manual 2018

All the capacity estimation procedures mentioned in the former paragraphs of this section are either empirical or deterministic is sense. Empirical methods needs a lot of data collection on a larger scale. For example, if proper understanding of heterogeneous traffic flow behaviour is to be achieved, then a large number of real life observations is required in terms of vehicle composition, flow, speed, nature of manoeuvrability, geometric characteristics, vehicular characteristics, road-user characteristics, climatic considerations, situational environments, etc. Such kind of a procedure is time consuming, expensive and tedious. The other alternative for estimation of capacity is through microscopic analysis using simulation tools like VISSIM, CORSIM, etc. or by using numerical soft computing techniques such as Cellular Automata (CA), Fuzzy Logic, Artificial Neural Networks (ANN), etc. Microscopic simulation is a numerical technique for conducting virtual replica of traffic facilities on a digital platform which may include stochastic macroscopic or microscopic characteristics involving creation of simple mathematical models to describe the behaviour of a transportation system over extended periods of real time. The widely used microscopic simulation software VISSIM uses the Weidmann 99 and 95 road user behaviour model along with the gap acceptance concept to model unsignalized intersection traffic flow behaviour under both homogenous and heterogeneous flow conditions. VISSIM has been widely been used to model driver and traffic flow behaviour for heterogeneous conditions since a decade.(*Wu, Li, Hu and Jiang, 2005*) investigated traffic flow at unsignalized T-intersections in which three input directions of vehicles and two right-turning and one left-turning using the cellular automata (*Nagel and Schreckenberg, 1997*) traffic model. The authors also analysed interactions between vehicles on different lanes and effects of traffic flow states of different roads on capacity of T-shaped intersection system. The results indicate that this model can be applied to real traffic analysis and traffic forecast. In short, the model considers the variation of vehicle velocity and uses temporal (time) gaps instead of special gaps to determine which vehicle is allowed to pass the intersection. Illustration of the T-intersection and the traffic is shown in the figure below. The lanes are divided to CA cells. Every vehicle takes a single cell. The lengths of lane 1-5 and 2-4 both L = 1999. The lengths of lane 3 and 6 are $L_3 = L_6 = 500$. The intersection locates at the middle point of lane 1-5 (b = 1000). The conflicts at the turning point are handled with following rules:

- The conflict of vehicles on lane 1 with the left-turning vehicles on lane 2
- The conflict of straight steering vehicle on lane 1 with the right-turning vehicles on lane 3

The variation of intersection capacity is determined by the net increment or decrement of flux on all the three lanes. The increase of input flux on lane 2 decreases the flux on lane 1 but increases the flux of lane 3. The increase of input flux on lane 3 will decrease the flux on lane 1 and lane 2. (*Fellendorf and Vortisch, 2010*) explained along with visualizations and applications of a microscopic, behaviour-based multi-purpose traffic simulation software named as VISSIM. The study presented a review on the history, typical applications and is followed by modelling principles presenting the overall architecture of the simulator. The authors also presented some techniques to calibrate the traffic flow models with remarks of interfacing VISSIM with other tools. VISSIM is a microscopic, discrete traffic simulation system modelling motorway traffic as well as urban traffic operations which is based upon several mathematical car-following and lane-changing or lateral driving models. The right-of-way for non-signal-protected conflicting movements is modelled with priority rules. Priority rules are used to model uncontrolled intersections where traffic has to give way to traffic on left, uncontrolled intersections where traffic on the terminating road must give way to traffic on the continuing road and TWSC/ AWSC intersections. The priority rules in VISSIM consists of a stop line indicating a waiting position for vehicles of minor movements (vehicle 2 in figure 2). At stop-line the minor vehicle will check if a vehicle of the major movement (vehicle 1) is within the headway area. The headway area is defined as a segment starting slightly before both movements merge. In VISSIM, this position can be set manually. Additionally, the minor vehicle checks if a major vehicle will reach the conflict marker within the minimum gap time if travelling with its present speed.

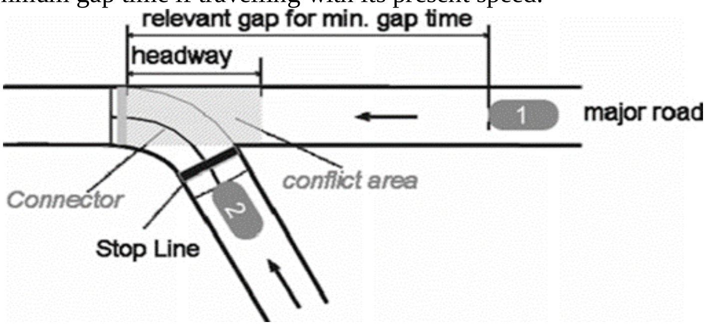

Fig. 2. Concept of modelling priority rules at unsignalized intersections in VISSIM
(*Source: Fellendorf and Vortisch, 2010*)

(*Holik et al., 2016*) developed a universal simulation model of three T-intersections based on gap acceptance theory using a web-based software Witness. Four levels of priority based on movement ranks (Rank 1, 2, 3 and 4) as per HCM 2010 were fed in the simulation module. This web based application for input data enables to set almost all attribute values. Secondly, using the application does not require a user license. The script is based on UNIX systems and each user gets his/her login information. The web application consists of following bookmarks:

- Input data – Traffic intensities, basic parameters, direction parameters and lane settings.
- Simulation – A data consistency test runs and the simulation run is generated.
- Output data – Consists of two sub-pages (Queue Lengths and Waiting Times)

- Settings – enables to edit basic information about the user (email, password)
- Help – enables to provide information regarding software usage
- Sign out – enables user to sign out of the web application.

The results obtained on the basis of gap acceptance gave much more optimistic results in comparison to results according to HCM 2010.

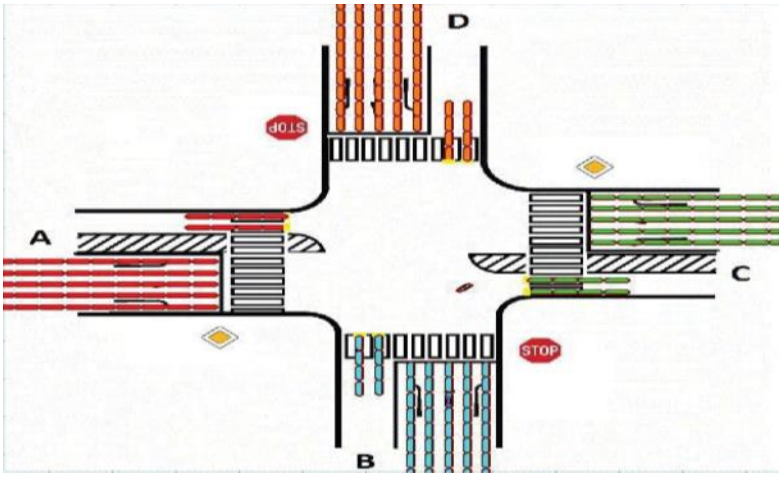

Fig. 3. Sample Layout of the Simulation Model Developed in Witness
(*Source: Holik and Graf, 2016*)

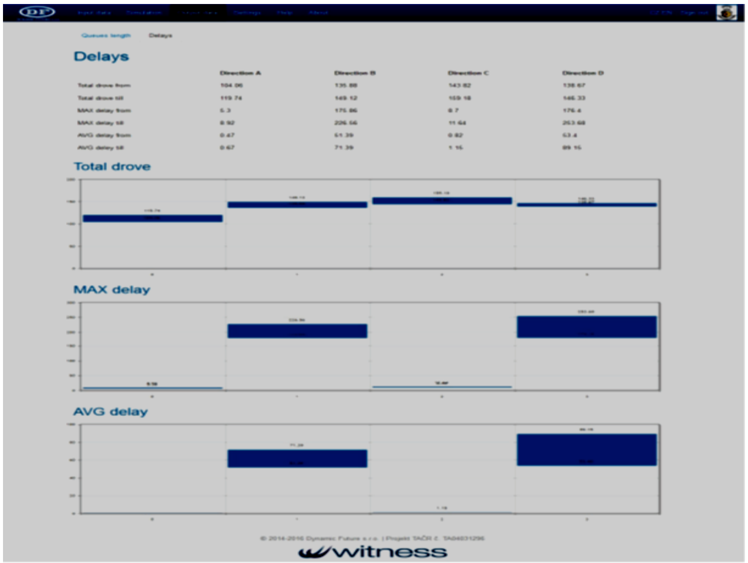

Fig. 4. An example of output data presentation in Witness
(*Source: Holik and Graf, 2016*)

2.2. *Former Literature on Control Delay Estimation Procedures*

This section goes on to describe the prior and recent advancements in predicting and analysing delay as measure of effectiveness/ service measure for predicting Levels of Service for urban unsignalized intersections by the previous researchers over the past few decades. This section also details the hypothesis behind the concept of queueing theory at priority/uncontrolled intersections. This section also illustrates the newly introduced Traffic Assignment Delay models primarily developed in Iran partaking the proficiency of describing developing city traffic movement conditions at uncontrolled intersections. Illustration regarding estimation of time-dependent delay using the mathematical concept of the hybrid (stochastic as well as deterministic) Co-ordinate Transformation Technique which forms the backbone for estimating average control delay models at unsignalized intersections for the recent Highway Capacity Manual 2010 (as per Transportation Research Board of United States of America) is also portrayed in this section.

Delay is usually very difficult to measure in field thus researchers now-a-days are much more interested in simulating intersection delay with the help of several traffic analysis micro-simulation tools which are very easy to calibrate in terms of varying geometric and traffic characteristics as necessitated for the type of study and intersection location. Micro-simulation allows somewhat allows the user to correlate closely with the traffic flow conditions on the field and thus by running simulations multiple times one can obtain more accurate results as may be obtained from traditional video-graphic and statistical analysis. This is the topic of discussion for chapter 5. As per Tanner, β_1 is the time required by major street vehicles to pass through the intersection; β_2 = time required by minor street vehicles to pass through the intersection influence area. In fig. 5, represents Major Road Vehicle and denotes the arrival and departures of a series of seven vehicles on the minor road.

According to his theory (*Tanner, 1982*), the major road traffic can be represented as series of blocks and gaps as depicted in figure no 5. Tanner hypothesized the whole arrival and departure sequence as a combination of blocks of major road vehicles with α being the time interval between arrival of last block vehicle and departure of subject minor road vehicle from major road stop line before merging. So,

For Minor Road Vehicle no. 1: Waiting Time before clearing = $4.\beta_1 + \alpha$

For Minor Road Vehicle no. 2: Waiting Time after clearing the intersection = $4.\beta_1 + \alpha + \beta_2$

Therefore, according to Tanner's hypothesis, Block A will start from the first minor road vehicle waiting to clear the intersection and will end a time α + arrival of last vehicle in the queue.

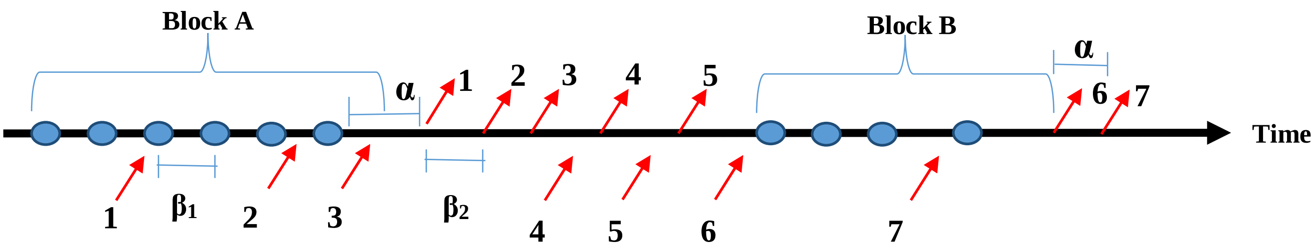

Fig. 5. Formation of Blocks and Gaps on Major Road Traffic-*Tanner's Hypothesis for Control Delay Estimation*
(Source: Caliendo, 2014)

Tanner determined the expressions for minor stream control delay using Kendall's method of regenerating points. The commonly used regeneration points as assumed by Tanner are:

- Time instants at which minor road vehicles pass through the intersection
- Time at which the major blocks of vehicles ends

So, if $\beta_1 = 0$, then the vehicles on the major road are considered to enter the intersection influence area at random. This model has been modified and utilized in HCM 2010 for computation of unsignalized intersection control delay considering a combination of queue (during service), geometric (5 secs) and stopped delay. HCM 2010 uses the control delay values obtained from this hypothesis to find Levels of Service (LOS) based on limiting values of Volume –to-capacity ratio (v/c).

Delay is usually very difficult to measure in field thus researchers now-a-days are much more interested in simulating intersection delay with the help of several traffic analysis micro-simulation tools which are very easy to calibrate in terms of varying geometric and traffic characteristics as necessitated for the type of study and intersection location. Micro-simulation allows somewhat allows the user to correlate closely with the traffic flow conditions on the field and thus by running simulations multiple times one can obtain more accurate results as may be obtained from traditional video-graphic and statistical analysis. Major portion of transportation networks in developing countries like India constitute of unsignalized intersections (priority-controlled or uncontrolled). They are a major source of vehicular conflicts resulting in delay, congestion and accidents. User cost in delay and accidents can be reduced by improving the design and operation of unsignalized intersections. Improvements in operations can be possible only when there is proper estimation and analysis of delay and delay parameters. Delay demonstrates the excess time devoured in a transportation facility in comparison to a reference value. It is the time distinction between a realized and a perfect operation time. It is the measure of effectiveness (MOE) of an intersection witnessed by road users and drivers. The performance of an unsignalized intersection is incredibly impacted by delay brought on by low-priority movements on minor streets.

One of the first delay models appears to be that of (*Kimber and Jovanis, 1997*) who proposed relationships between delay and traffic intensity (ratio of demand flow to capacity) which consolidated time-dependent behavior of queues. (*Kimber and Hollis, 1979*) introduced methods for foreseeing queue length and delay at street intersections. The methodology is truly thorough and considers the stochastic nature of traffic demand and capacity. (*Troutbeck and Brilon, 1999*) developed an empirical delay equation model at unsignalized intersections as a function of the following parameters: the average delay when the minor stream flow is low (also known as Adam's delay), the degree of saturation of minor stream (entry flow/entry capacity), and a form factor that quantifies the effect of queuing in the minor stream. (*Kyte et al. 1991*) divided the total delay for two-way stop-controlled (TWSC) into two parts, namely queue delay and service delay. "Queue delay is defined as the time between the vehicle's arrival at the end of the queue and the time when the vehicle arrives at the stop line". "Service delay is the time between the vehicle's arrival at the stop-line and its departure from the stop-line". The authors inferred that queue delay is affected by the approach traffic volume, whereas service delay was mainly dependent on the conflicting traffic volume. (*Khattak and Jovanis, 1997*) compared two main approaches to capacity and delay estimation that are probabilistic and deterministic. (*Bakare and Jovanis, 1998*) compared the conceptual basis for Swedish Highway Capacity Manual procedure and U.S. Highway Capacity Manual procedures through field data evaluation for four unsignalized intersections from Chicago in the Illinois region of USA. The Swedish method was based upon empirical queuing theory based on Swedish conditions overestimated capacity and underestimated delay whereas the U.S. Highway Capacity Manual method underestimated capacity but overestimated delay when validated for US field conditions. Also, the authors compared the British and Australian procedures with both the other methods. A correction towards the values of critical gaps were formulated based on the data extracted from field data collection. The corrected values were then used to find capacity and level of service of minor roads (based on field extracted service and stopped delay estimates). The corrected LOS and capacity values were then provided in the revised Transportation Research Circular 212 after comparing them with the Swedish guidelines. (*Rao and Rengaraju, 1998*) proposed a methodology to simulate delay and model vehicular conflicts at an uncontrolled intersections. A multi-variate distribution was formulated for vehicle arrivals and these vehicles were formulated and implemented in general programming language of C. As implementation of results, 82 % increase in conflicts were observed for 50 to100 % increase in traffic volume in vehicles per hour on major road approaches. Also an increment of 2 to 3% increase in number of conflicts were observed for 10 to 20% increase in the number of right turning vehicles in the four-legged intersection. A comparative study for observed and simulated conflicts were also done to find out percentage errors and then evaluation of the errors in the intersection. Comparison between occupation times of priority movements like (Major LT; Minor RT and Major LT) were also represented in this study. An ANOVA analysis assuming a null hypothesis that the occupation times for TWs, Cars and auto-rickshaws (AWs) are equal was also performed. (*Al-Omari and Benekohal, 1999*) developed two different models for estimating queue delay and service delay, respectively, at TWSC intersections; in particular, service delay is estimated as a utility of conflicting traffic volumes, while service delay average and variance of service delay are used as inputs for estimating queue delay. All these formulations were approximate in nature whereas under oversaturation conditions (when demand volume is variable over time and where it could even exceed the capacity during a specific peak period) delay estimation turns out to be a more general problem of mathematical queuing theory.

(*Brilon, 2008*) introduced the concept of M/M/1 queue in any queue counter system where M denotes the random distribution of poisson's arrivals M/1 denotes formation of single approach queue. Random arrivals according to the author denotes: arrivals of vehicles as poisson's distribution and gap distribution to be negative exponential. Occupation or service time is defined as the time spent by vehicles in the first position and is represented as inverse of capacity of that movement in M/M/1 queue condition. In this condition, the minor road queue length has been represented as M/1 queue with vehicles representing blocks (by assuming a particular distribution for service times) for which vehicles will clear the queue based on average service delay measured on the basis of queue counter methods.

Control delay can be calculated if stopped delay for a non-priority movement can be estimated using certain approximations of queuing theory which assumes the following conditions:

- Distribution for arrivals of vehicles on the minor and major roads during continuous queuing
- Queue Discipline (whether First-In-First-Out or Random Service)
- Number and Lane configuration with distribution of collective occupation times of each queue on the major or minor roads.
- Queue length distribution and waiting time statistics for each vehicle ahead of the queue
- Two more alternatives towards queueing theory approximations are :Regular Service – The condition in which each vehicle expends the same time at the first positions (i.e. constant service time in the priority system)

Service Delay is the time wasted by a particular vehicle in waiting for acceptance of a gap during continuous queueing process at unsignalized intersections. Some of the commercially developed simulation software which have been used previously in some studies is the TRaffic Simulation tool (SITRA) and HCS 2010 which are based on the Highway Capacity Manual. (*Chandra, Agarwal and Rajamma, 2009*) established mathematical relations for service delay considering different types of vehicles for priority movements at uncontrolled intersections based upon microscopic simulation. The proposed service delay model was also compared with Kyte's linear control delay model. The authors also checked the influence of heavy vehicles (truck or bus) composition in the conflicting flow on the proposed service delay model. Kyte's microscopic analysis states that: If *t_0 = time at which subject vehicle arrives at the reference stop line, t_d = time at which the subject vehicle departs from the reference line, n= number of observed conflicting vehicles for the subject vehicle including the conflicting vehicle passing just after departure of the subject vehicle, t_n = time of arrival of n^{th} conflicting vehicle at the reference line, the conflicting flow rate = $n/(t_n-t_0)$ and service delay = $t_d - t_0$*. The comparison between the two models ensured that the proposed model is able to actually yield accurate estimates of service delay whereas Kyte's model underestimated the values. (*Ashalatha and Chandra, 2010*) developed a simulation program which could represent various aspects of service delay which was able match the field extracted values. The authors developed this model considering four categories of vehicle namely cars, two-wheelers, three-wheelers and heavy vehicles for all the priority vehicles. The authors also varied the magnitudes of turning (both right and left turns) percentage, vehicular composition percentages of the conflicting stream and modelled the service delay sensitivity against adverse conditions. For most of the cases, the statistical significance was found to be highly correlative ($R^2 = 0.85 – 0.97$) with the field extracted values. Studies indicate that the HCM delay model is fairly good for practical purposes, especially under under-saturated conditions in which each approach has a volume-to-capacity under 0.8. However, if volume to capacity ratio exceeds 0.8, the estimated delay is not stable. Also, at intersections where traffic volume exceeds 2500 vehicles per hour, the HCM delay model overestimates the actual control delay (*Shahpar et al., 2011*). The delay model developed by (*Shahpar et al. 2011*) determines control delay of each approach at an unsignalized intersection by taking into account not only the subject approaching traffic, but also the function of conflicting traffic volumes in accordance to the well-known Bureau of Public Roads (BPR) function. The control delay estimated can easily be used in traffic assignment models and thus no need to be considered as a constant unlike HCM delays. Transportation Research Board (TRB) even in its recent publication of *HCM 2010* estimates delay for each minor-street movements and for major-street left turns. According to the HCM 2010, delay includes delay due to *deceleration to a stop at the back/end of queue, move-up time within the queue, and delay due to acceleration to depart from stop line*. In other words, unsignalized intersection delay is defined as "*the total time elapsed from the time a vehicle stops at the end of the queue to the time the vehicle departs from the stop line*". Thus queue length (*95^{th} Percentile queue length by HCM for intersections*) is also an important consideration in estimating hourly delay at intersections. The main disadvantage of using these models in developing countries like India, is that it considers *zero delay for major street movements*, which is not practically viable. Some researchers (*Kimber and Hollis 1978, Akcelik and Troutbeck 1991, Brilon 2008*) tried to relax the model assumptions of homogeneity and consistency of driver population and defined some realistic gap distributions in major approaches.

(*Tang and Wagner, 2011*) estimated delay of low priority traffic flows by using the priority queueing system at unsignalized four-legged intersections of London. The authors only considered movements on exclusive lanes. The coordinate transformation technique for Delay estimation has been used under oversaturated conditions in this study. The estimated delay values were compared against the results from a microscopic simulation, HCM 2000 and field observed data. For low priority movements the control delay per vehicle is counted as the sum of uniform delay and incremental delay. Incremental delay is obtained by coordinate transformation of the steady-state and deterministic delay. The principle for coordinate transformation is that the difference between control delay and the traffic density for steady-state delay is equal to the difference between the traffic density of deterministic delay and the traffic density of the transformed curve according to the equation below:

$$1-\rho_s=\rho_d-\rho \quad (1)$$

Where, ρ_s, ρ_d and ρ are the steady-state density, deterministic density and density of the transformed curve respectively.

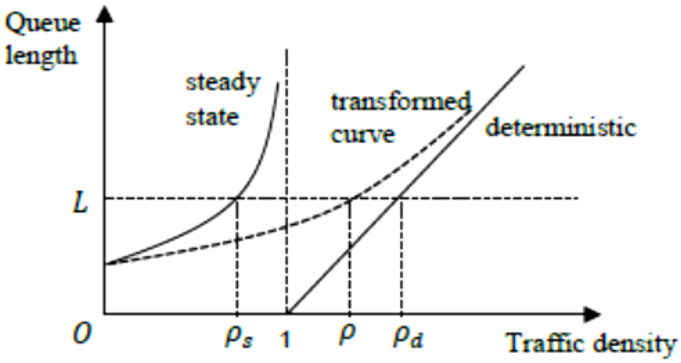

Fig. 6. Coordinate Transformation Technique for Incremental Delay Estimation (*Source: Tang and Wagner, 2011*)

The authors conducted a hypothesis test HCM 2000 with field estimated values of potential capacity for single exclusive right-turn lanes. The maximum flow for high priority movement was found to be 2065 veh/hr. whereas for low priority movement it was 1523 veh/hr. The figure below represents the comparison between HCM 2000 and the proposed model for control delay per vehicle for every 0.1m/sec increase of traffic density ranging from 0.1 to 1.6. The proposed model showed good fitting with the HCM 2000 values.

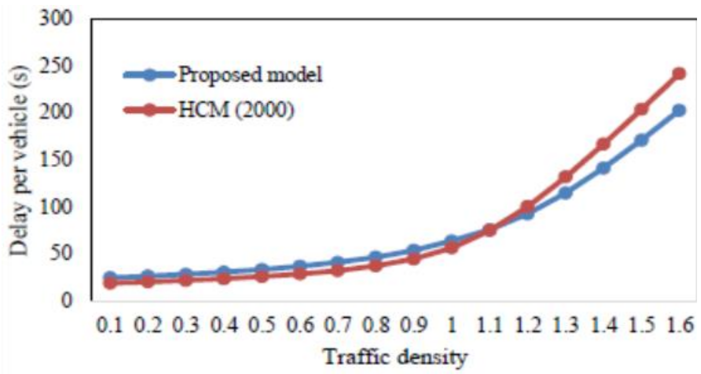

Fig. 7. Delay comparison between proposed model and HCM 2000 values
(*Source: Tang & Wagner, 2011*)

(*Prasetijo and Ahmad, 2012*) introduced the conflict technique for calculating occupation times for turning and through movements for two unsignalized three-legged intersections in the city of Perak, Malaysia. Occupation time is the time expensed in occupying the intersection conflict area while taking turns or in completing through movements. With reference to the occupation time values, the authors, extracted the values of control delay (service delay + stopped delay+ queue delay) in seconds per vehicle for all the possible conflicting movements. The field extracted control delay values obtained from the conflict technique was compared with the HCM 2010 (empirical values). It was observed that the HCM 2010 values underestimated the delay values for both the intersections. Average vehicular delay was analyzed under different traffic volumes for both stop-controlled and yield-controlled intersections through calibration and validation in VISSIM by (*Yun and Ji, 2013*). The authors compared both the intersection types with respect to vehicular delays and oncoming traffic volume in VISSIM. Delays to vehicles at urban uncontrolled intersections depend on several factors. (*Caliendo, 2014*) conducted a *statistical micro-simulation process* for providing a *point estimate of average traffic delay at urban unsignalized intersections* during peak hours for nine different types of intersections with varying geometric and traffic flow characteristics. The author found that measuring delay only through video-graphic surveys in the field was difficult and impossible and thus used **AIMSUN** to simulate performance measures like delay time, stop-time and maximum average queue length and compared them with the measured field values. The research was mainly motivated specifically by the need to develop *a micro-simulation approach for assessing the performance measures at unsignalized intersections when the real system appears to be much more complex than the measurements in the field.* A negative binomial regression model (NB model), jointly applied to *conflict traffic volume* and *traffic volume entering intersection from minor roads* was used to model the average delay at intersections. Additionally, *a stop-time and a maximum queue length model* was also developed by the author. During the micro-simulation, the author assumed:

1. No lane changing/passing is allowed when drivers are near intersections
2. All drivers maintain safe minimum headways
3. Drivers have past knowledge of the priority movements at these intersections

The most important among these being the *major road approach volume*, *type of turning movement,* and *vehicular composition* (*Praveen et al., 2016*). The extent of intersection of these factors and their collective effect on delay caused to vehicles need to be studied in detailed for better traffic management at these intersections. The authors modelled service delay at three uncontrolled T- intersections in the Kompally city of Telangana for priority movements using the HCM 2000 method and Kyte's delay estimation technique. A multiple linear regression model was created in IBM SPSS 17.0 with service delay as the dependent variable and conflicting traffic volume for three (minor left, major right and major left) as independent variables.

(*Guller and Menendez, 2016*) established a methodology to systematically evaluate the expected average delays at multi-modal uncontrolled intersections. The methodology considers the demand traffic volumes of different traffic streams along with priority and direction of each stream to determine the capacity available to each. The methodology was tested using data collected at five locations in Zurich, Switzerland. The results yield that the proposed methodology can predict the delay of different streams to an extent of 4 secs/veh and can also identify streams with larger delays. The methodology comprises of building a general capacity estimation equation using the type of interactions and calculating inputs for the capacity equation after analysing the conflicting streams; Calculation of the final effective capacity and using this to find out delays. The authors used AIMSUN for experimental validation of the proposed methodology.

(*Sahraei and Che Paun, 2018*) devised an Artificial Neural Network (ANN) model with two hidden layers and several sizes on neurons which was in turn used to form two mathematical models for estimation of control delay from minor road. The authors used video-graphic data of three unsignalized intersections from the region of Johor, Malaysia (*27 hours of data collection with 9 hours for each intersection*) to formulate the ANN model. A statistical hypothesis testing between the field estimated and the ANN outputs was done. The results of the hypothesis testing stated that the ANN model was able estimate control delay values more accurately with the influence of heavy vehicles being negligible in its determination criteria. There was about 30 to 40% increase in control delay by using the ANN technique. Such a model was developed by the authors in order to indoctrinate the inefficiency of the Malaysian Highway Capacity Manual (MHCM) to accurate estimation of control delay values under Malaysian field conditions.

2.3. *Former Literature on Unsignalized Intersection Level of Service (LOS)*

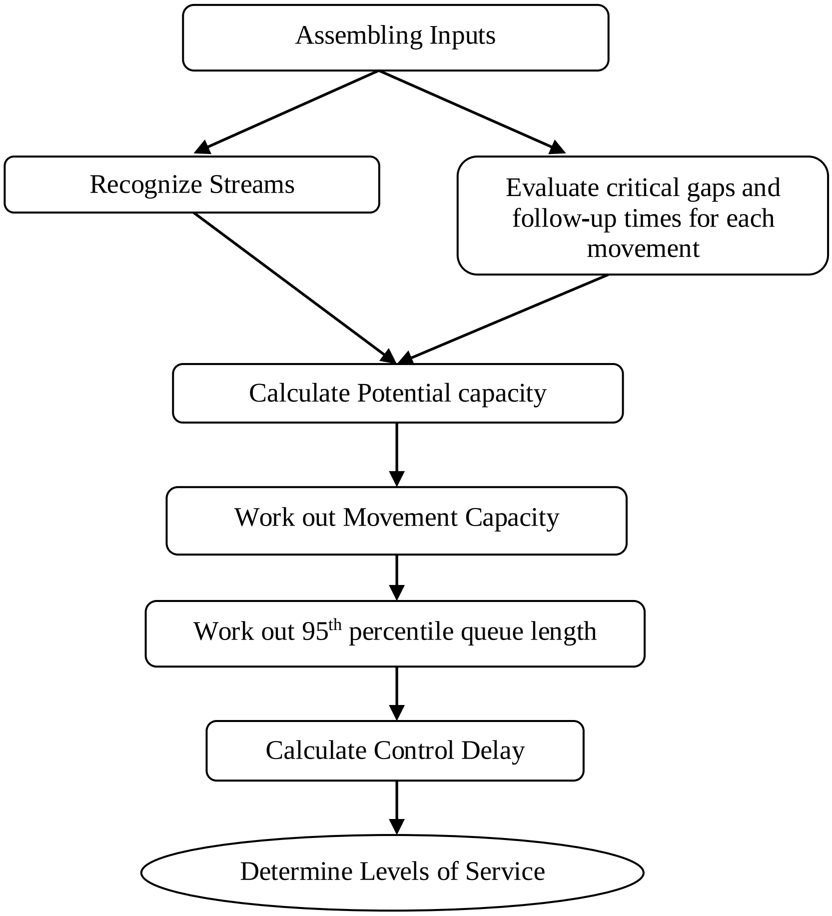

Fig. 8. U.S. Highway Capacity Manual Procedure for Unsignalized Intersection Analysis (*Source: HCM, 2010*)

The development of the notion for level of service (LOS) for traffic amenities goes back to the 1950s. LOS was officially presented in the Highway Capacity Manual (HCM) published in 1965 (*HCM, 1965*). It was defined as "a qualitative measure of the effect of a number of factors, which include speed and travel time, traffic interruptions, freedom to maneuver, safety, driving comfort and convenience, and operating costs." In HCM 1985, reserve capacity of lane was pointed out as a LOS measure for unsignalized intersections. In HCM 2000, average control delay supplanted reserve capacity. Be that as it may, these measures exclude the safety aspect, which digresses from the definition of LOS. The same concept has been translated to HCM, 2010. The US Highway capacity manual 2010 (chapter 17, 18) provides LOS determination techniques for Two-Way-STOP-Controlled (TWSC) intersections, All-Way-STOP-Controlled (AWSC) intersections. The procedures for finding out levels of service for unsignalized intersections are depicted in the figure 7.The manual also suggests with fitting variations in key factors an expert can apply the TWSC determination for yield-controlled conditions. The Swedish Capacity Analysis software *Capcal* gears the techniques of capacity manual (*Statens vägverk 1977*). Mean service times are utilized to determine degrees of saturation, which occur the significant parameters in the assessment of MOEs, such as, capacity, delay and length of queues. The performance measures which could be obtained by the technique are: capacity, delay, queue length, and the percentage of stopping vehicles. The Swedish system does not exhibit in the least level-of-service criteria which are elaborated in the following steps:

- Step 1: Fixation of Major Road Flow Rates
- Step 2: Evaluation of Critical Gaps based on the Major Road Flows
- Step 3: Determination of Mean Service Times: Mean service times are utilized to determine degrees of saturation, which occur the significant parameters in the assessment of MOEs, such as, capacity, delay and length of queues.
- Step 4: Modification of the Mean Service Times obtained from the previous step.
- Step 5: Modifications and Adjustments for the flared or shared lanes for the major road flow rate
- Step 6: Calibration of the MOEs for determination of LOS

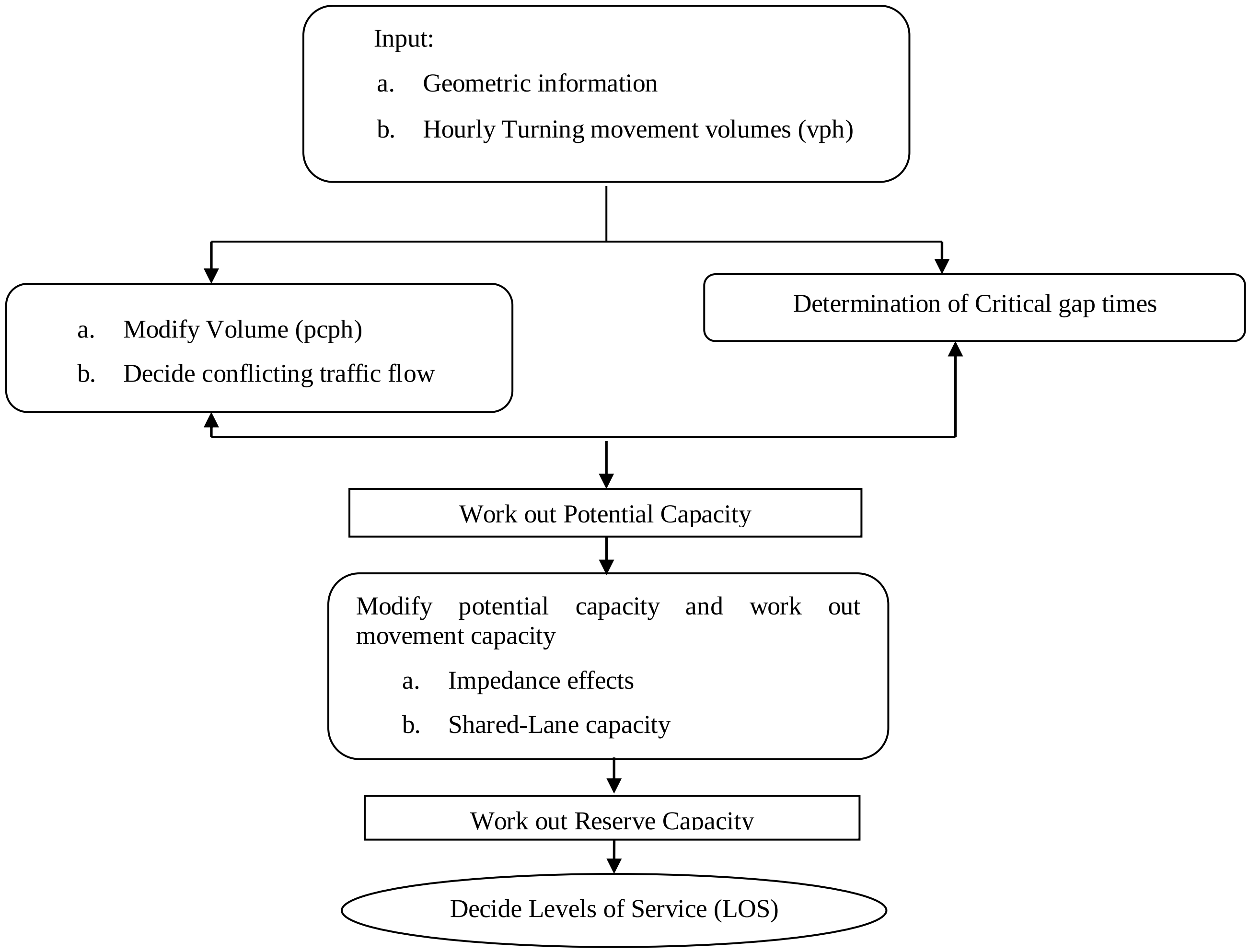

Fig.7. Flow chart depicting the Motorized LOS Analysis Procedure for Finnish and Malaysian Unsignalized Intersections (*Source: Finnra Reports: Finnish Road Administration, 2004; Binti Izzuddin, 2009*)

The Finnish Road Administration in their Finnra report 1/2004 published guidelines for analyzing capacity and level of service for Finnish Unsignalized Intersections. In this, the administration have suggested the term “Reserve Capacity” which is a modification over HCM 2000’s potential capacity with suitable adjustments for pedestrian or non-motorized vehicle impedance effects. Malaysian methodology of level of service analysis for urban unsignalized intersections is adopted from Finland Road Administration guidelines (*Arahan Teknik (Jalan) 11/87 formulated based upon Master’s thesis of Binti Izzuddin, 2009*).The assessment of capacity for unsignalized intersections as projected by Malaysia is based on the Finnish LOS analysis concept as depicted in fig.7. The

Indonesian Highway Capacity manual (*IHCM, 1997*) evaluates the performance of unsignalized intersections collectively using the set of rules for finding IHCM Capacity(which can be obtained based on a regression equation on base capacity considering other adjustment factors under heterogeneous traffic flow conditions in Indonesia) and the performance measures like Degree of saturation DS, Delay D (sec/pcu) and Queue probability QP % for pre-defined geometric, environmental and traffic conditions. The overview of the calculation procedure is as follows:

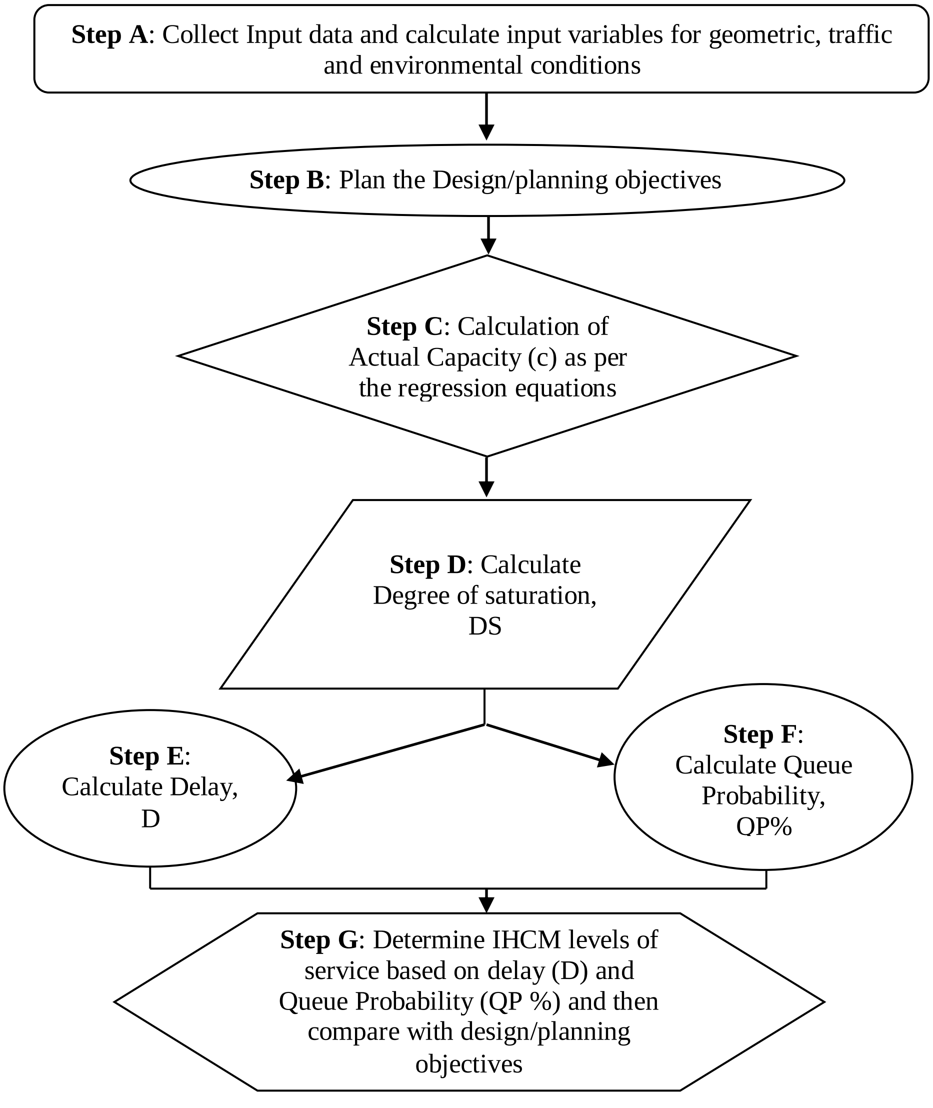

Fig. 8. Overview of the *IHCM 1997* LOS calculation procedure for Unsignalized Intersections

For calculation of queue probability (%) and Service delay (D), empirical charts have been designed based on single independent variable linear regression approach for varying geometrics and layouts of intersections. The overall heads considered for IHCM LOS analysis are Geometry, Traffic and Road side environment. Indonesia being a country with heterogeneous traffic mix have close resemblance with Indian traffic conditions and therefore, a modification of this concept can also be adopted for analyzing unsignalized LOS in countries like India. Levels of service is defined as the qualitative measure which most importantly reflects the user perceptions and depends upon the comfort and convenience of the road user. Delay has been identified as the most important service measure for determining intersection levels of service but there is a major deficiency in the behavioral justification. Web-based and motorist surveys reveal that road users judge the quality of comfort and convenience at an intersection based on a huge array of factors, few to be named are safety risk, usefulness of pavement markings, visibility and clarity of stop/yield signs, left-turn and right turn convenience and conflicts, road side aesthetics and other road-side activities, presence of upstream signals, driver's expectation of waiting time, etc. To get an overview of LOS, questionnaires and a wide variety of surveys are to be conducted with road users as the primary source/inputs. Previous methods for LOS determination include Potential Conflict Analysis Approach, Fuzzy Weighted and logic techniques, etc. According to previous studies, delay has been identified as the most efficient factor on the basis of which people grade the quality of service at an unsignalized intersection along with the above mentioned factors.

3. Summary and Conclusions

This paper summarizes and reviews someof the existing relevant literature on three different concepts, namely, Capacity, Control Delay and level of service which are essential measures of effectiveness in assessing the performance of urban unsignalized intersections. In the first section, the different capacity estimation procedures are discussed which broadly can be divided into five categories. The first one is the Gap acceptance approach (GAP) which is basically based upon stochastic distribution of critical gaps, follow-up-time and conflicting flow rates based on certain heuristic assumptions. Some of the global capacity estimation manuals for unsignalized intersections like the US-HCM, the Indo-HCM and the Finland Capacity Guide which follow GAP have also been summarized in this study. The second one is the Empirical regression approach which linear multiple linear regression equations yield capacity with independent attributes like geometry, traffic behaviour and composition and other roadside related environmental factors. The third one is the Additive Conflict Flow approach in which capacity of non-priority movements are mathematically formulated based upon occupation times, service times and conflicting flow rates of priority movements based on Glue's graph theory. The advantage of this approach over the previous two is that it considers the effect of flared lanes, presence of shared lanes, non-motorized traffic, pedestrians on motorized vehicle capacity in a sigle step. The fouth one is through microscopic simulation which is somewhat realistic any one or all of the above mentined approaches can be incorporated in predicting capacity. The fifth one is by using soft-computing techniques like Artificial Neural Networks (ANN), Cellular Automata (CA) and Fuzzy Logic (FL) for capacity and performance evaluation of unsignalized intersections. In the control delay section, critical reviews and summarization of the Tanner's, Brilon's and Akcelik's model has been done along with focus on Kyte's microscopic simulation procedure for service delay estimation. The Tanner's hypothesis which is widely followed by most of the developed countries determines minor road average control delay by considering continuous formation of blocks (queues) and gaps (in terms of time) whereas minor road vehicles are considered as discrete arrows which utilizes the major road gaps for acceptance. Further, delay analysis using soft-computing techniques like Artifical Neural Networks and Fuzzy Logic have also been displayed, of which ANN gives better results when compared with microscopic delay values and field extracted values. The US highway capacity manual 2010, Swedish Highway capacity manual, finnish road administration, Malaysian Highway Capacity Manual and the Indonesian Highway Capacity manual Level of service (LOS) guidelines are represented in this review. Both the Finnish and Malaysian guidelines have a common concept in which Reserve Capacity needs to be determined based on the potential capacity for all the priority movements. The US highway capacity manual technique evaluates LOS based on both control delay and volume to capacity ratio (v/c ratio) whereas the Indian Highway Capacity Manual (Indo-HCM) reccomends that unsignalized LOS should be estimated only on volume to capacity ratio values for all priority movements. The Swedish procedure for LOS estimation on the other hand, suggests calibration of the measures of effectiveness (need not be essentially delay and queue length) before their usage in the estimation technique. For automobile modes, both control delay and volume-to-capacity (v/c ratio) are generally calculated to characterize LOS for a certain lane group as per US HCM 2010. According to the US HCM 2010, questionnaire surveys should be conducted to understand a non-motorized traveler's perception when he/she is crossing the intersection. Non-motorized drivers can be asked to score their individual comfort and convenience alphabetically as A, B, C, D, E and F. HCM then allots certain scores ranging from (<2.00 to >5.00) for LOS conditions of "A" to "F". These so-called LOS SCORES were based on some of the basic descriptors of intersection character like speed, width of the cross-walk, headway in between the vehicles. Therefore, a constructive methodology should be formulated to ascertain and validate the currently used capacity, control delay and LOS procedures which are used for assesing usignalized intersections in both developed and developing countries.

References

Ashalatha, R., Chandra, S., 2011. Critical Gap through Clearing Behaviour of Drivers at Unsignalized Intersections. KSCE Journal of Civil Engineering 15(8), 1427-1434.

Ashalatha, R., Chandra, S., 2011. Service Delay Analysis at TWSC Intersections through Simulation. KSCE Journal of Civil Engineering 15(2), 413-425.

Al-Omari, B., Benekohal, R.F., 1999. Hybrid Delay Models for Unsaturated Two-way Stop Controlled Intersections. Journal of Transportation Engineering, 125(4), 291-296.

Akcelik, R., Christensen, R., Chung, E., 1998. A Comparison of Three Delay Models for Sign-controlled Intersections, 3rd International Symposium on Highway Capacity. Copenhagen, Denmark, 35-56.

Arahan Teknik (Jalan): Design Guide Report for 1997, A Guide to the Design of At-grade Intersections. Jabatan Kerja Raya, Nov. 1997.

Bakare, B.A., Jovanis, P.P, 1998. Analysis of Unsignalized Intersection Capacity. Transportation Research Record. Journal of Transportation Research Board, Washington D.C., USA, pp.1078-1082.

Brilon, W. 2008. Delay at Unsignalized Intersections. Delay at Unsignalized Intersections. Transportation Research Record: Journal of Transportation Research Board, Washington D.C., U.S.A., 98-108.

Binti, I. 2009. Sensitivity Analysis of Malaysian Highway Capacity Manual for Unsignalized Intersections. B.E. Thesis, University Malaysia Sarawak, Malaysia, 13-14.

Caliendo, C. 2014. Delay Time Model at Unsignalized Intersections. Journal of Transportation Engineering, 140 (9), pp. 1-13.

Chancey, T.B., Jackson, R.L. 2010. The Effects of Volume on Driver Critical Gap Acceptance at a Two-Way Stop Controlled Intersection. Florida Honour Thesis: University of Florida.

Chandra, S., Agarwal, A., Rajamma, A. 2009. Microscopic Analysis of Service Delay at Uncontrolled in Mixed Traffic Conditions. Journal of Transportation Engineering, 135 (6), 323-329.

Fellendorf, M., Vortisch, P. 2010. Microscopic Traffic Flow Simulator VISSIM. Fundamentals of Traffic Simulation, Edited Book in: International Series in Operations Research & Management Science, 145, pp. 71-73.

Finnra Reports No. 1. 2004. Capacity and Level of Service at Finnish Unsignalized Intersections. Finnish Road Administration, Helsinki, Finland.

Glue, J.D. 1972. Graph Theory: Principles and Practice. Journal of Soviet Mathematics, Springer, 2 (5), Switzerland.

Guller, S.I., Menendez, M. 2016. Methodology for estimating capacity and vehicle delays at unsignalized multimodal intersections. International Journal of Transportation Science and Technology, 5(4), 257-267.

Hemavathy, M., Kalaanidhi, S., Gunasekaran, K., Advani, M., Velmurugan, S. 2015.Assessment of critical gap at uncontrolled intersections under heterogeneous traffic conditions. Indian Journal of Transport Management, 39 (4), 242-254.

Holik, J., Dorda, M., Teichmann, D., Graf, V. 2016. Universal Simulation Model for Unsignalized Intersection Capacity Analysis, 17th International Carpathian Control Conference (ICCC). Kosice, Slovakia Republic, pp. 236-241.

Ministry of Public Works. Directorate General of Highways. 1997. Indonesian Highway Capacity Manual (IHCM). Part-IV. Jakarta, Indonesia.

CSIR-CRRI. Ministry of Road Transport and Highways. 2018. Indian Highway Capacity Manual (Indo-HCM). Work Package 6. New Delhi, India.

Khattak, A.J., Jovanis, P.P. 1990. Capacity and Delay Estimation for Priority Unsignalized Intersections: Conceptual and Empirical Issues. Transportation Research Record: Journal of Transportation Research Board, Washington D.C., U.S.A., 1287, 129-137.

Kimber R., 1980. The Capacity of Some Major/minor Priority Intersections. Laboratory report 735, Transport and Road Research Laboratory (TRRL), Crowthrone, Berkshire, U.K.

Kimber R., Coombe, R.D., 1980. The Traffic Capacity of Major/minor Priority Junctions. Supplementary Report no. 582, Transport and Road Research Laboratory (TRRL), Crowthrone, Berkshire, U.K.

Kimber, R., Hollis, E., 1980. Traffic Queues and Delays at Road Junctions. Laboratory Report 909, Transport and Road Research Laboratory (TRRL), Crowthrone, Berkshire, U.K.

Kyte, M., 1991. Estimating Capacity and Delay at an All-Way Stop Controlled Intersection. Special Report, Transnow, Idaho, Moscow.

Malaysian Highway Capacity Manual. 1993. MHCM. Malaysia.

Maurya, A. K., Amin, H. J., Kumar, A. 2016. Estimation of Critical Gap for through Movement at Four Leg Uncontrolled Intersection, Transportation Research Procedia, 17, 203–212.

Mohan, M., Chandra, S .2018. Critical Gap Estimation at Two-Way Stop-Controlled Intersections Based On Occupancy Time Data. *Transportmetrica A: Transport Science*. Taylor & Francis, 14(4), 316–329.

Nagel, K., Schreckenberg, M. 1997. Cellular Automata: Basic Principles. Journal of Physique. 2, 2221.

National Research Council. Transportation Research Board. 1965. Highway Capacity Manual. *Chapter 15 & 16*. Washington D.C.

National Research Council. Transportation Research Board. 2000. Highway Capacity Manual. *Chapter 17 & 18*. Washington D.C.

National Research Council. Transportation Research Board. 2010. Highway Capacity Manual. *Chapter 17 & 18*. Washington D.C.

Parameswaran, A. and Asaithambi, G. 2016. Capacity estimation of uncontrolled intersections in mixed traffic: comparison of gap acceptance procedure and additive conflict flow technique. *12th Transportation Planning and Methodologies for Developing Countries, TPMDC 2016*, Mumbai, Maharashtra [online]: Procedia: Social and Behavioral Sciences, pp.1-14.

Prasetijo, J. 2007. Capacity and Traffic Performance of Unsignalized Intersections under Mixed Traffic Conditions. Doctoral Dissertation. Ruhr University, Bochum, Germany.

Prasetijo. J., Pour Hossein, M., Reza Ghadiri, S.M. 2011. Capacity of Unsignalized Intersections under Mixed Traffic Conditions. 6th International Symposium on Highway Capacity and Quality of Service, Stockholm, Sweden, Procedia: Social and Behavioural Sciences, pp. 676-685.

Prasetijo, J., Ahmad, H. 2012. Capacity Analysis of Unsignalized Intersection under Mixed Traffic Conditions. 8th International Conference on Traffic and Transportation Studies, Changsha, China, Procedia: Social and Behavioural Sciences, paper# 43, pp. 135-147.

Praveen, D., Sai Baba, A.N., Rao, M.K. 2016. Delay Modelling at Urban Uncontrolled Intersections. International Journal of Advance Engineering and Research Development, 3(2), 112-118.

Rao, V.T., Rengaraju, V.R., 1998. Modelling Conflicts of Heterogeneous Traffic at Urban Uncontrolled Intersections. Journal of Transportation Engineering, 124, 23-34.

Rao, B., Rambabu, T. and Rao, G. 2017. Analysis of Capacity and level of Service at Uncontrolled Intersections under Heterogeneous Traffic Conditions. International Journal of Civil Engineering and Technology, 8(8), 181–190.

Ruskin, H.J., Wang, R. 2002. Modelling Traffic Flow at an Urban Unsignalized Intersection. Lecture Notes in Computer Systems (LNCS), Springer, 2329, 381-390.

Sahraei Ali, Md., Che Paun, O.B. 2018. Traffic Delay Estimation using Artificial Neural Network (ANN) at Unsignalized Intersections. 3rd International Conference on Civil, Structural and Transportation Engineering (ICCSTE 18), Niagara Falls, Canada, Paper # 106.

Shahpar, A.H., Aashtiani H.Z., Faghri, A. 2011. Development of a Delay Model for Unsignalized Intersections Applicable to Traffic Assignment. Transportation Planning and Technology, 34(5), 497-507.

Tang, Q. and Wagner, P. 1992. Delay Estimation of Low Priority Traffic Flows at Intersections, 23rd International Symposium on Transportation and Traffic Theory. pp. 1–5.

Tanner, J., 1962. A Theoretical Analysis of Delays at an Uncontrolled intersection. Biometrika. 49(1), 163-170

Troutbeck, R.J., Brilon, W. (1999). Unsignalized Intersection Theory. Chapter 8 in: Monograph on Traffic Flow Theory, Federal Highway Administration (FHWA), USA.

Wu, N. 2001. Universal Procedure for Capacity Determination at Unsignalized (Priority-controlled) Intersection. Transportation Research Part B: Methodological, 35(6), 593 – 623.

Wu, Q.S., Li, X.B., Hu, M.B., Jiang, R. 2005. Study of Traffic Flow at an Unsignalized T-shaped Intersection by Cellular Automata Model. European Physics Journal, B 48, 265-269.

Wu, N. 2012. ACF Procedure for TWSC Intersections – Extensions and Modifications. 10th International Conference of Chinese Transportation Professionals (ICCTP), Beijing, China, paper # 23.

Yun, M. and Ji, J. 2013. Delay Analysis of Stop Sign Intersection and Yield Sign Intersection Based on VISSIM. 13th COTA International Conference of Transportation Professionals (CICTP 2013). Singapore, China, pp.2024-2031.

Zhou, H., Ivan, J.N., Garder, P.E., Ravishanker, N. 2014. Gap Acceptance for Left turns from the Major Road at Unsignalized Intersections. Transport, 32(3), 252 – 261.