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Review and Assessment of Techniques for Estimating Critical Gap at Two-way Stop-controlled Intersections

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Abstract

Critical gap is a vital parameter in the analysis of two-way stop-controlled (TWSC) intersections. Due to the complex traffic operations at these intersections, different researchers have proposed different techniques for its accurate estimation. This paper reviews several of these popular techniques which were used in the analysis of TWSC intersections over the past 60 years. Application procedure of each of these methods, along with their advantages and limitations are also included. Most of these methods provide the mean value of critical gap, while a few gave the entire distribution of critical gap. The accuracy of these methods is checked through simulation. Through movement at a four-legged intersection formed by two single lane one-way streets were simulated in VISSIM software and critical gap values for this movement is compared against estimated critical gap from various methods. The study found that the estimates of many of these methods are dependent on the volume of conflicting traffic. Maximum Likelihood Method is found to give the closest and consistent estimate for critical gap followed by Probability Equilibrium Method and Raff's Method.

*Keywords:*Unsignalized Intersection; Critical Gap; Simulation; VISSIM; Maximum Likelihood Method.

1. Introduction

Two-way stop-controlled (TWSC) intersections are one of the most common type of intersections in a road network. It comprises of a minor street meeting or crossing a major street, with stop signs installed on minor roads. They operate based on relative priorities of the conflicting movement where a lower priority movement must yield to a higher priority movement. The interaction among the merging, diverging and crossing traffic is quite complex, making the study of such intersections a very challenging task. Capacity analysis of these intersection is quite significant due to their influence on the overall capacity of the road system, since a poorly performing intersection can hamper the overall efficiency of the road network. The capacity analysis of the intersection can be broadly divided into three approaches: empirical regression process, gap acceptance procedures and conflicting technique. Gap acceptance concept is predominantly used in the capacity manuals of several countries across the globe, including the US Highway Capacity Manual (HCM).

Gap acceptance process is based on the decision made by a minor street driver who on approaching an intersection has to decide whether to accept or reject the gap being offered. A driver might reject a number of gaps before finally accepting one. Two important

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parameters associated with the gap acceptance process are critical gap and follow-up time. HCM (2000) defined critical gap as the minimum time between successive major-stream vehicles in which a minor-street vehicle can make a manoeuvre. Critical gap of a driver lies between the largest rejected gap and the accepted gap. HCM (2000) also defined follow-up time as the time between the departures of two consecutive vehicles from the minor street using the same gap under a condition of continuous queuing. While follow-up time can be measured in the field, critical gap can only be estimated based on the gaps that were accepted and rejected by drivers.

Estimation of critical gap is quite intriguing owing to the fact that it cannot be deduced from field observations. Over the years, researchers have come up with several techniques for its estimation as it is a vital input in the calculation of movement capacities at a TWSC intersection. While some of them are quite simple to use, others involve complex computational procedures that could be accomplished only by the use of a computer. This paper presents a detailed review of popular methods for estimating critical gap. Each of these methods is laden with a set of advantages as well as limitations. Results of these methods were checked for their accuracy by using simulation.

2. Concept of Critical Gap

A minor street driver on approaching the intersection has to evaluate whether a gap in the conflicting traffic stream is large enough to safely execute the desired movement or not. A driver generally accepts all the gap that are more than his/her critical gap and rejects the rest. Thus critical gap specifies the least value of gap that is acceptable to a driver. One of the first attempts towards defining critical gap can be credited to Greenshields et al. (1947) when they introduced the concept of average minimum acceptable gap, which is the lag accepted by more than 50 per cent of the drivers. Later, Raff (1950) introduced the concept of critical lag which refers to the size of the lag that has the property that number of accepted lags shorter than it is equal to the number of rejected lags longer than it. A similar definition was given by Drew (1968) with critical gap being the gap for which equal percentages of drivers accept a shorter gap as well as reject a larger gap. The latest edition of Highway Capacity Manual (HCM, 2010) has replaced critical gap with critical headway. However, the universal applicability of this concept seems doubtful as it might not be applicable to heterogeneous traffic conditions where size of each vehicle is different.

Critical gap is not a constant but varies from drivers to driver and from time to time. Critical gap was found to also vary with subject vehicle type, intersection geometry, approach gradient, delay, weather conditions etc. (Kareem, 2002; MahmassaniandSheffi, 1981; Rakhaet al., 2011; Tian et al., 2000; Velanand Van Aerde, 1996), but independent of conflicting traffic volume (Brilonet al., 1999; Troutbeck, 2014).

Since critical gap cannot be measured in the field, researchers have put forward a number of techniques to estimate the mean critical gap based on the gaps rejected and accepted by drivers. Hewitt (1985) enumerated three main difficulties faced in finding exact value of critical gap. Firstly, it is impossible to measure critical gap exactly by observing a single driver. Secondly, the driver’s reaction to a lag may not be same as that to a gap and combining them might not yield the exact critical gap. Thirdly, since the major street gap follow negative exponential distribution, there will a predominance of drivers having short critical gap. These difficulties had thus, resulted in the development of several methods to estimate critical gap.

3. Methods of Estimating Critical Gap

Over the years, researchers have come up with a multitude of techniques for finding the value of critical gaps at unsignalized intersections. This section discusses some of the popular techniques among them.

3.1 Siegloch's Method

This method was proposed by Siegloch in 1973 for estimating critical gap and follow-up time for minor streets under saturated condition. The method requires recording the number of minor street vehicles that can enter into each major street gap under a case of continuous queuing. Average gap sizefor the entry of certain number of minor street vehicles is calculated. A linear regression line is fitted between the number of vehicles accepting a gap and the average accepted gap as given in Figure 1.

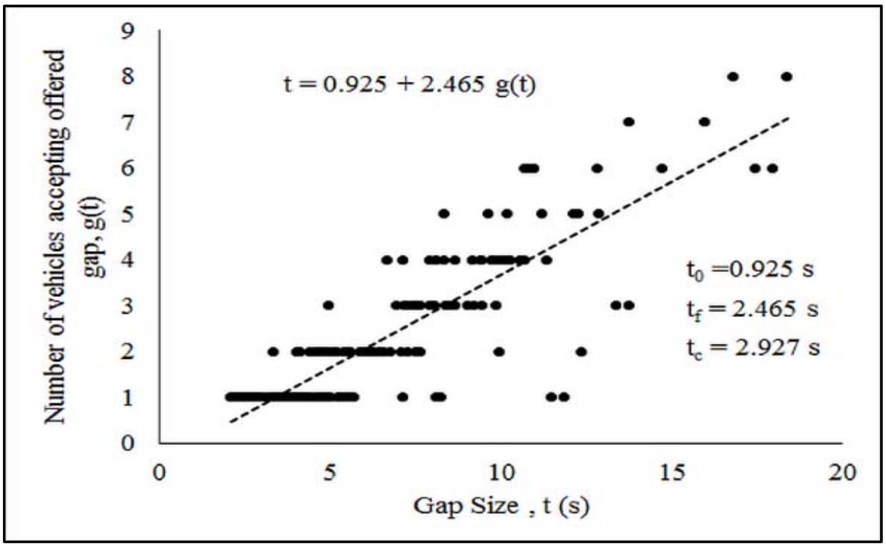

Figure 1. Illustration of Siegloch's method

Reciprocal of the slope of regression line gives the follow-up time (t_f). If the regression line intersect X-axis at t_0, then the critical gap (t_c) is given byEquation 1.

$$t_c = t_0 + \frac{t_f}{2} \quad (1)$$

This method is easy to apply and gives the value of critical gap as well as the follow-up time. It considers the stochastic nature of critical gap and the estimated values of critical gap and follow-up time bear a close relationship with Siegloch's formula for capacity of unsignalized intersections (Brilon et al., 1999). However the application of this method is limited to saturated conditions which might not occur practically. The simulation study conducted by Brilon et al. (1999) found that the result of this method is dependent on the distribution of major street headways. This technique was employed in the study by Vasconceloset al.(2013) for obtaining critical gap where the authors redefined continuous queuing as the situation where the move-up time on the minor street was less than 4s instead of usual 6s. The authors found that the result of this method is highly dependent on the value of move-up time and a move-up time of 6s yielded critical gaps that was close to the results of other methods.

3.2 Greenshields Method

This method is based on a histogram drawn between the number of acceptance and rejection with the range of gap size (usually 0.5 s). Number of acceptance is represented on the positive Y-axis and number of rejections is represented on negative Y-axis with gap size on X-axis as shown in Figure 2. The mean of gap range for which the number of accepted and rejected gaps are same represents the critical gap. If no such range exists, then the range with minimum difference between numbers of accepted and rejected gaps should be considered.

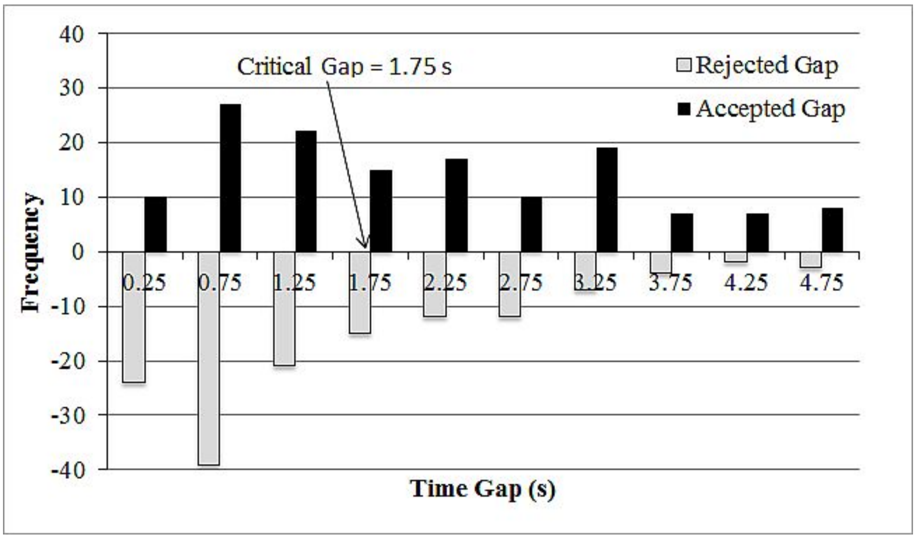

Figure 2. Critical gap from Greenshields method

Harwood et al. (1990) cautioned on the use of this method for small sample size as it may disrupt the analysis.

3.3 Acceptance Curve Method

This method is based on the cumulative distribution of accepted gap, which forms an S-shaped curve that is asymptotic at probability of 0 and 1. Greenshields et al. (1947) had defined critical gap as the gap accepted by 50 percent of the drivers. Thus, critical gap value can be obtained from theprobability distribution curve for accepted gaps corresponding to a probability of 0.5.

Radwan and Sinha (1980) andGattis and Low (1999) included this method in their study. But the distribution of gap acceptance curve is subjected to bias as the percentage of acceptance of a given gap size will be less than percentage of minor road vehicle prepared to accept the same gap (Ashworth 1970). Ashworth (1968) advocated the displacement of the original gap acceptance curve to the leftin order to remove this bias. This can be done only when gap acceptance followsa normal distribution and when major street traffic is randomly distributed.

3.4 Lag Method

This is one of the simplest methods to estimate critical gap only on the basis of lag data. The method assumes drivers to be consistent and arrivals on the minor street to be independent. The proportion of drivers accepting a lag of size *t* is similar to the probability of drivers ($F_c(t)$) having critical gap smaller than *t*. After dividing the time scale into time intervals (usually of 1 s interval), this probability for each time interval can be found using Equation 2.

$$F_c(t_i) = {}^{A_i}/_{N_i} \tag{2}$$

where, A_i and N_i are the number of lags accepted and observed during a time interval i. The mean critical gap by lag method can be obtained from Equation 3.

$$t_c = \sum_{i=1}^{n} t_i \times [F_c(t_i) - F_c(t_{i-1})] \tag{3}$$

where, n is the total number of time intervals and t_i is the time at the centre of interval i.

This method requires sufficient number of data in each of the time interval and since data of lag might not be easily available, longer observation period will be required. Since lag is the only parameter considered, this method is capable to address situations having no queue on the minor street. It should be recognized that gaps are not used in this procedure and hence a large amount of useful data gets discarded. Moreover, the critical lag value obtained might be symmetrically different from critical gap (Brilon et al. 1999). However, the method avoids the over-representation of cautious drivers. Brilon et al. (1999), Ashalathaet al. (2005), Ashalatha and Chandra (2011) and Patil and Sangole (2015) demonstrated the application of lag method in their studies.

3.5 Harder's Method

This method is quite similar to the Lag method. Instead of lag, itconsiders only accepted gaps. The method assumes that drivers reject all gaps that are less than 1s and accepts all gap more than 21 s and hence only gaps within these intervals are considered in the analysis. The probability of accepting gap in each time interval is calculated using equation2, with A_i and $N_i$being the number of gaps accepted and observed during a time interval i.

The analysis of unsignalized intersection in Germany is based on the critical gap value obtained by this method (Brilon et al. 1999). This method were employed in estimating critical gaps by Brilon et al. (1999), Ashalatha et al. (2005) and Ashalatha and Chandra (2011). Brilon et al. (1999) found this method to overestimate critical gap when gaps alone were used and results improved when lags were also included.

3.6 Ashworth's Method

In order to eliminate the bias in the estimated critical gap value, Ashworth (1968, 1970) provided a corrective measure which involves the shifting of probability distribution curve for accepted gap along the time scale. Assuming the major street gap is exponentially distributed, consecutive gaps being independent and critical gap is normally distributed, Ashworth showed that the cumulative distribution of accepted gaps will follow a normal distribution with same standard deviation (σ) as critical gap distribution, but with mean increased by qσ2. So the gap acceptance curve can be shifted to left by qσ2 to obtain the distribution of critical gap where q is the flow on major street (veh/s). Thus, mean critical (tc) can be obtained using Equation 4.

$$t_c = \mu_a - q\sigma^2 \tag{4}$$

where, μ_a is the mean accepted gap.Miller (1972) explained that the equation 4 gives fairly approximate result even when critical gap follow log-normal distribution. Further, the author also provided a modification to equation 4 when critical gap has gamma distribution.

This method is used in several studies including Hewitt (1985), Brilon et al.(1997), Brilon et al. (1999), Ruijun Guo (2010)and Patil and Pawar (2014). The comparative study on different methods for estimating critical gaps conducted by Miller (1972) concluded that Ashworth method gave small bias and is much simpler for practical application in comparison to maximum likelihood method (MLM). Hewitt (1985) also drew a similar conclusion. However, mean critical gap is dependent on the conflicting traffic volume and hence was ruled out by Brilon et al. (1999) in another study that compared methods of critical gap estimation.

3.7 Raff's Method

This method was first introduced by Raff (1950) and it still continues to be one of the most popular methods for unsaturated conditions owing to its simplicity. The original Raff's procedure estimated critical lags on the basis of lag accepted and rejected which has been considered statistically wasteful as it omitted the entire gap data (Miller 1974). Raff's method was extended to estimating critical gaps by either considering only gaps(Brilon et al., 1999) or by combining gaps and lags together (Ashalatha and Chandra, 2011; Devarasetty et al., 2012)

Based on Raff'sdefinition, critical gap is the size of gap for which the number of gaps shorter than it is equal to the number of gaps longer than it. This could be found from the intersection of F_a and 1-F_r curves, where F_a and F_r are the cumulative probabilities of accepted and rejected gaps.

This method still continues to be popular among researchers and forms the part of majority of studies on critical gap. Miller (1972) found this method to be reasonably satisfactory with very small bias when the traffic flow is fairly light while considering only lag data. When data pertaining to only lags were used, the study found significant error in prediction using this method. Since all the rejected gap were considered in this method, cautious drivers gets over represented. To remove this bias in the data, some researchers have considered only the maximum rejected gaps (Tupper et al., 2013). Another disadvantage of this method is the dependence of the result on volume of conflicting traffic (Brilon et al., 1999; Miller, 1974).

3.8 Logit Method

This method assumes that the gap acceptance behaviour of a driver can be presented by a binary logit model with the utility function being a trade-off between safety and reduction of delay. Logit method is a weighted linear regression model, which can be represented mathematically byEquation 5.

$$P = \frac{1}{1 + e^{-(\beta_0 + \beta_1 x)}} \quad (5)$$

where, P is the probability of accepting a gap; β_0 and β_1 are the regression coefficients and x is the gap length. Critical gap can be obtained by solving the above equation for x by assigning a value of 0.5 to P, i.e. the gap having 50 percent probability of being accepted.

Logit method were included in the research conducted by Gattis and Low (1999), Ashalatha and Chandra (2011), Vasconcelos et al. (2013), etc. for estimating critical gaps. Vasconcelos et al. (2013) reported that among the methods used for estimation of critical gaps, logit method gave the least value. The study by Brilon et al. (1999) found logit method to give good estimates of critical gap when only gap data were used and it underestimated when lag data were also included. However, they did not recommend this method due to its dependence on volume of conflicting traffic. Polus et al.(2005) used logit procedure to study the effect of waiting time on critical gaps.

3.9 Probit Method

This method involves fitting a weighted linear regression line to the gap data. After dividing the time interval suitably, the proportion of accepted gap is found out. Since the gap acceptance process is a binomial response that is dependent of gap size and assuming that critical gap follows normal distribution, the corresponding probit of the proportion accepting a gap is given by Equation 6.

$$Y = 5 + \frac{(X - \mu)}{\sigma} \quad (6)$$

where, X is the proportion of accepted gaps, μ and σ are the parameters of normal distribution and Y is the probit of X. Five is added in the expression to always keep probit value positive. The probit of proportion of gaps accepted is plotted against the logarithm of gap size and a straight line is fitted to the plotted points. From the equation of the fitted line, critical gap is obtained corresponding to a probit value of 5.

Solberg (1964), Daganzo (1981) and Mahmassani and Sheffi (1981) used probit analysis in modelling gap acceptance behaviour of drivers, while Hamed et al. (1997) used it for modelling critical gap. Probit method was used in estimating critical gap by Ashton (1971), Miller (1972), Hewitt (1985) and Ashalatha and Chandra (2011). Miller (1972) found result of Probit method had very less bias, but less reliable in comparison to MLM.

3.10 Hewitt's Method

Hewitt proposed an iterative method for estimating critical gap (t_c). The procedure involves the division of time scale into intervals of same duration (usually 1s). Initially, the gap acceptance function is developed using lag or probit method. This could be used to estimate the probability of critical gap *(G_i)* to lie within an interval *i*. The expected numbers of lags or gaps of duration t_j which are accepted and rejected is given in Table 1.Using these values of accepted and rejected gaps and lags, new probability of critical gap ($G_{i'}$) could be found and used in estimating t_c. The iterative process is repeated until subsequent

t_c values remains nearly unchanged in subsequent iterations. A detailed procedure of this method is included in publication by Hewitt (1985).

Table 1. Expected numbers of accepted and rejected lags and gaps

	Lags	Gaps
Accepted	$n_0 f_{0,j} G_j$	$n_0 f_j \sum_{i=1}^{j-1} g_i \frac{F_{0,i}}{1-F_i} + \frac{1}{2} n_0 f_j g_j \frac{F_{0,j}}{1-F_j}$
Rejected	$n_0 f_{0,j}(1-G_j)$	$n_0 f_j \sum_{i=j+1}^{m} g_i \frac{F_{0,i}}{1-F_j} + \frac{1}{2} n_0 f_j g_j \frac{F_{0,j}}{1-F_j}$

Note: n_0=*total number of sample;* f_j= *probability that a major stream gap;* G_j=*cumulative probability distribution of critical gap;* g_i= *probability distribution of critical gap;* F_i= *cumulative probability distribution of major stream gaps; m= number of class intervals; subscript 0 in the expressions refers to lags.*

Hewitt's method was one among the two methods which had satisfied all the criteria laid down by Brilon et al. (1999) for a reliable technique for critical gap estimation. This method was used by Ashalatha and Chandra (2011) but the critical gap obtained were unreasonably low thus casting doubts on its applicability to heterogeneous traffic conditions. The practical applicability of this method is however limited owing to the complex iterative process involved.

3.11 Maximum Likelihood Method

Maximum Likelihood Method (MLM) is one of the most popular methods for estimation of critical gaps (Brilon et al., 1999; Miller, 1972; Tian et al., 1999; Troutbeck, 1992; Weinert, 2000). Although this method was in use for more than two decades, the approach was well documented by Troutbeck (1992). This method assumes drivers to be homogeneous and consistent. Troutbeck's procedure assumes critical gap to follow log-normal distribution and this method tries to maximize the probability of critical gap to lie between the accepted gap (a_g) and the maximum rejected gap (r_g). The result of estimation is independent of the assumed distribution as long as it is a typical distribution (Weinert, 2000).

The likelihood for driver's critical gap to lie between a_g and r_g is given by Equation 7, where F_a and F_r are the distribution functions of accepted and rejected gaps.

$$L^* = \prod_{g=1}^{n} [F_a(a_g) - F_r(r_g)] \tag{7}$$

The log-likelihood of the above function is given in Equation 8.

$$L = \sum_{g=1}^{n} ln[F_a(a_g) - F_r(r_g)] \tag{8}$$

The mean and standard deviation of critical gap can be obtained by maximizing the likelihood function through an iterative procedure.

Unlike other methods, MLM does not use all the rejected gap and hence the bias associated with critical gap by considering all the rejected gaps that might lead to the over-representation of cautious drivers is avoided. Two of the popular studies that compared different critical gap estimation techniques (Brilon et al. 1999; Miller 1972) found MLM as the best. However, this method fails if the drivers are not homogeneous and consistent. It further requires accepted and maximum rejected gap in pairs and hence data regarding vehicles that had accepted a gap which is smaller than the maximum rejected gap or vehicle that accepts the first gap should be excluded in this method (Wu, 2012). Troutbeck (2014) provided a workaround to account for inconsistent drivers in which the largest rejected gap was to be reassigned a value just less than accepted gap. Also, the rejected gap was to be set to zero or some very small value if no gap was rejected. It also assumes a lognormal distribution for critical gap, but (Wu, 2012) found it to follow weibull distribution. Application of MLM to heterogeneous traffic conditions also failed to yield satisfactory results (Ashalatha and Chandra, 2011).

3.12 Probability Equilibrium Method

Probability Equilibrium Method (PEM) was introduced by Wu (2006) as an alternative to MLM without involving any complex calculation and can be carried out using a simple spreadsheet. Unlike MLM, this method is free from any inherent assumptions and is capable of including inconsistent drivers and also the drivers who have not rejected any gaps. The method can be applied even for smaller sample sizes.

The cumulative probabilities of the accepted (F_a) and rejected (F_r) gaps are calculated and these are then used to calculate the probability distribution function of critical gaps (F_{tc}) usingEquation 9. The probability density of critical gap for time interval is calculated and the sum of product of this probability density with the corresponding class mean for the entire data gives the mean value of critical gap.

$$F_{tc}(t) = \frac{F_a(t)}{F_a(t)+1- F_r(t)} = 1 - \frac{1-F_r(t)}{F_a(t)+1- F_r(t)} \quad (9)$$

Study conducted by Gavulová (2012) supported the claim that PEM performed similar to MLM with simpler calculation procedure. However, Troutbeck (2014) opined that weibull distribution is not appropriate for critical gaps and log-normal distribution should be preferred. Using results from simulation, he further showed that PEM is dependent on the volume of conflicting traffic and reinstated MLM as the best method for finding critical gap.

3.13 Clearing Time Method

Many of the assumptions pertaining to basic formulation of different methods very often remained unsatisfied when used to estimate critical gaps at intersections in developing countries. Priority rules are commonly violated as lower priority movements force their way into the intersection creating their own gaps. This, when coupled with the lack of lane discipline, renders most of the above discussed methods useless for heterogeneous traffic conditions. Ashalatha and Chandra (2011) came up with a solution to this problem with an alternate approach termed as clearing time method.

Similar to Raff's method, this method also estimates critical gap based on two cumulative distributions: accepted gap (F_a) and clearing time (F_{ct}). They defined clearing time as the time that a vehicle incurs in covering the conflict area of the intersection. The conflict area was considered to be a rectangular region starting from middle of the near lane and extending to the middle of the far lane while having a width equal to 1.5 times the width of the crossing vehicle. In order to ensure that the two distribution curves intersect, a plot was made for F_a and 1- F_{ct} against time on X-axis as shown in Figure 3. The point of intersection of the two curves was referred to the time when the gap accepted is just sufficient to clear the conflict area and it was taken as the critical gap.

The near edge of the influence area was kept at the middle of the near lane based on the assumption that under heterogeneous traffic conditions, vehicle do not halt at the stop line but stops near the middle of the near lane. This seems to be a very simplified assumption without due consideration being given to the actual behaviour of drivers.

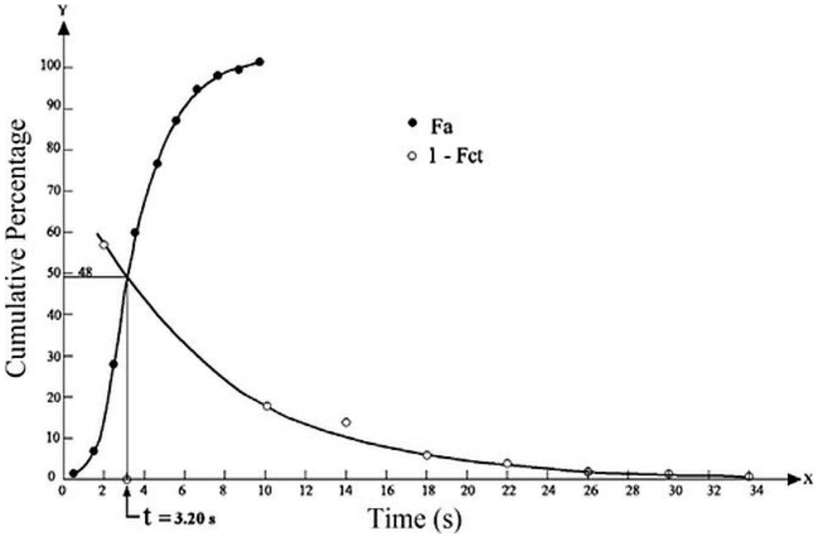

Figure 3. Critical gap based on clearing time method (*Source:*Ashalatha and Chandra, 2011)

3.14Occupancy Time Method

A modification to clearing time method was provided by Chandra et al.(2014) when they proposed a method for critical gap estimation based on the total time a vehicle spends within the conflict area of the intersection. The method delineate the conflict area as the rectangular region between the pavement edge and ends of the median opening where possible interaction occurs among different traffic streams. This method uses cumulative distributions of accepted gaps and occupancy time and is based on the condition that for a lower priority movement to safely execute a movement using the presented gap, the following inequality (Equation 10) should be satisfied.

$$P(t_a > t) \geq P(t_o \leq t) \tag{10}$$

where, t_a and t_o are respectively the accepted gap and occupancy time. They also showed that the method is equally applicable to homogeneous traffic as prevalent in US as well as heterogeneous traffic as found in India.

Occupancy time method eliminates any ambiguity associated with the conflict region and estimates the value of critical gap while considering the element of safety in executing the priority movement. The method has the specific advantage of being equally applicable for homogeneous and heterogeneous traffic.

4. Discussion

As critical gap could not be measured in the field, researchers have come up with different methodologies for its accurate estimation which were discussed in the previous section. Most of them were developed for homogeneous traffic and were found unsatisfactory for heterogeneous traffic conditions. Methods that yielded a single value of critical gaps are computationally simpler, while the methods which involved comparatively complex procedures gave the entire distribution of critical gap. Table 2 summarizes the advantages and limitations of each method discussed in the previous section.

Table 2. Summary of various techniques for critical gap estimation

Method	Data Required	Advantages	Limitations
Siegloch	Number of vehicles entering into each gap	Closely related to Siegloch's capacity formula Gives follow-up time also	Only suitable for saturated conditions Depends on headway distribution of major street
Greenshields	Accepted and rejected gaps	Based on histograms	Not suitable for small sets of data
Acceptance Curve	Accepted gaps	Simpler estimation process	Bias towards cautious drivers
Lag	Accepted and rejected lags	Lag data is free from any bias Simpler estimation process	Wastage of valuable gap data Longer observation periods required
Harder	Accepted and rejected gaps	Simpler estimation process	Require large data size for accurate estimation Depends on volume of conflicting traffic
Ashworth	Accepted gaps	No bias in the estimated result	Depends on volume of conflicting traffic Assumes critical gap to be normally distributed
Raff	Accepted and rejected gaps and/or lags	Simpler estimation process	Bias towards cautious drivers Depends on volume of conflicting traffic
Logit	Accepted gaps	Closely related to driver's gap acceptance decisions	Depends on volume of conflicting traffic
Probit	Accepted gaps	Closely related to driver's gap acceptance decisions	Assumes critical gap to be normally distributed
Hewitt	Accepted and rejected gaps and lags	Independent of conflicting traffic volume	Involves complex iterative procedure Difficult to accomplish without a computer
Maximum Likelihood	Accepted and maximum rejected gaps	Gives parameters of distribution Independent of conflicting traffic volume	Assume lognormal distribution for critical gap Cannot handle inconsistent drivers Difficult to accomplish without using a computer
Probability Equilibrium	Accepted and all/maximum rejected gaps	Capable of handling inconsistent drivers Gives parameters of distribution	Require least accepted gap to be smaller than largest rejected gap
Clearing Time	Accepted gaps and clearing time	Useful in heterogeneous traffic conditions	Ambiguity regarding the influence area
Occupancy Time	Accepted gaps and occupancy time	Useful in heterogeneous and homogeneous traffic conditions	Extraction of occupancy time data is time consuming

5. Performance of techniques in estimating critical gaps

The accuracy of the critical gap estimation procedures are checked in this section by using simulation. Simulation offers a wide range of control over the streams of intersecting traffic, especially in controlling the traffic composition as critical gap differs among vehicle types. It also helps in analysing traffic behaviour at intersections operating at capacity which might not be always available through field observations. The following analysis is carried out based on the researchers' finding that critical gaps of a priority stream are unaffected by the volume of conflicting traffic (Brilon et al., 1999; Troutbeck, 2014).

5.1 Simulation Network

A micro-simulation software, VISSIM, is used to simulate traffic interactions at an intersection formed by two one-way single lane roads. The traffic on major and minor streets were composed entirely of cars that travelled straight through the intersection and followed Wiedemann 74 driver behaviour model (PTV AG, 2015). Desired speed on major and minor streets were kept at 80 km/h and 60 km/h respectively. Right of way was assigned based on conflict rules with major street traffic having absolute priority. Simulation was carried out for 30 minutes after a 5 minute warm-up period. Data collection points were inserted into the network to count the passing vehicles and to retrieve time stamps corresponding to the arrival and departure of each vehicle, which can be used to deduce inputs (rejected gaps, accepted gap, follow-up time, etc.) to various critical gap estimation techniques.

5.2 Determination of Critical Gap

For a particular flow on the major street, the input volume on the minor street was varied until the minor street is fully saturated. This was done to ensure that the intersection operated at capacity during the entire duration of simulation process. Follow-up times were computed from the timestamps of vehicles that used the same gap under following conditions. However, VISSIM does not permit assigning critical gap values to each of the simulated drivers and it is not possible to measure it either. So an alternate approach is tried in this paper to estimate critical gap by assuming it to be independent of the volume of conflicting traffic. The capacity of the minor street is achieved through simulation runs at different levels of conflicting flows from 500 to 2500 veh/hr. The average value of follow-up times from the different simulation runs was found to be 2.33 s. The plot between conflicting flow and entry capacity is found to follow an exponential relation as shown in Figure 4 and the regression model thus obtained is used to find field capacity corresponding to a particular conflicting flow. The minor street capacity at a particular conflicting flow is also calculated using the equation suggested in HCM (2010) for an assumed value of critical gap. An optimization approach involving minimization of the absolute difference between the two capacity values was used to arrive at the actual critical gap. This approach yielded a critical gap value of 2.99 s for through movement on minor at the simulated intersection. This is taken as the true value of critical gap in the subsequent analysis and discussion.

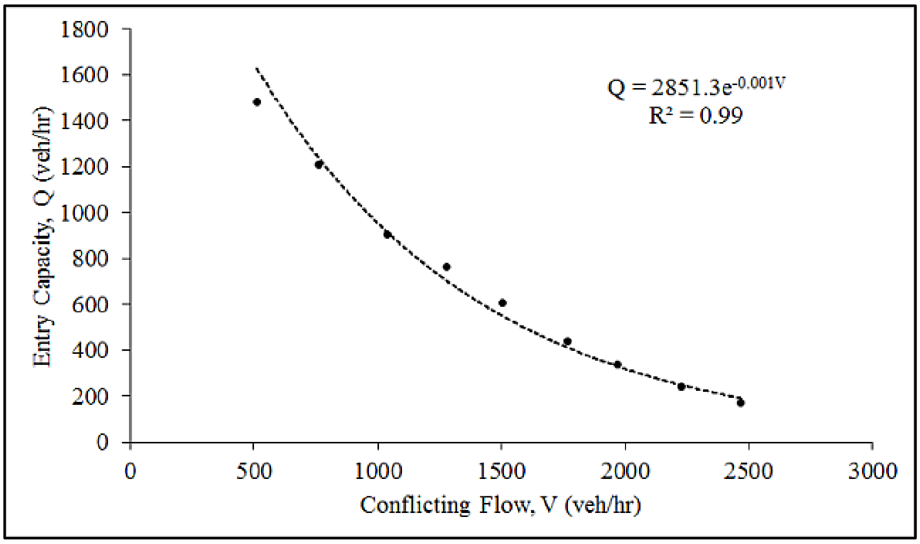

Figure 4.Plot between simulated conflicting flow and minor street capacity

5.3 Comparison of Critical Gaps Methods

Various techniques, as discussed earlier, were used to estimate critical gaps at the intersection based on the data collected from simulation runs. In order to check for the dependence of methods on volume of conflicting traffic, simulation runs were carried out at major street flows of 1000, 1500 and 2000 veh/h. For each of these runs, care was taken to ensure that minor street operates at capacity so that queuing occurs throughout the simulation. Accepted and rejected gaps were obtained from the outputs of the simulation runs which were then used to estimate the critical gap.

Critical gap estimated for through movement from the minor street at the simulated intersection using 11 different techniques are summarized in Table 3. The last column of the table gives the variation in the predicted critical gaps for each method under different volumes of conflicting traffic. This is an indicator of consistency of the method, means its dependence on conflicting traffic volume. As can be seen, MLM gives very consistent results followed by PEM (using only maximum rejected gaps) and Raff's method. The results also show that the estimates by Probit, Logit and Ashworth's methods are highly dependent on conflicting traffic volume.

The table also displays the accuracy in prediction of critical gap by different methods by comparing the estimated value with true critical gap (2.99 s) as obtained earlier. Among all the methods, MLM gave estimates which were closest to the actual critical gap for different volumes of conflicting traffic. Methods such as PEM (using only maximum rejected gaps), Raff's Method and Acceptance Curve Method also provided decent estimates of critical gap. Harder's, Ashworth's and Probit methods consistently over-estimated critical gap for all volumes of conflicting traffic. All other methods under-estimated the critical gap under low conflicting volume and over-estimated it at higher conflicting flows.

Table 3.Critical gaps estimated through various methods

Conflicting Flow (veh/hr)	1000	1500	2000	1000	1500	2000	Difference among critical gaps (%) $\frac{(Max - Min)}{Min}$	1000	1500	2000
Methods	Critical Gap (s)			Difference from actual critical gap of 2.99 s (%)				Difference from actual capacity calculated for critical gap of 2.99 s (veh/hr)		
Siegloch	2.93	2.98	3.19	2.01	0.33	6.69	8.87	15	3	55
Greenshields	2.88	3.13	3.13	3.68	4.68	4.68	8.68	28	39	39
Acceptance Curve	2.91	2.97	3.10	2.68	0.67	3.68	6.53	21	6	31
Harder	3.42	3.45	3.65	14.38	15.38	22.07	6.73	103	121	161
Ashworth	3.92	3.10	3.38	31.10	3.68	13.04	26.45	208	31	102
Raff	2.98	2.98	3.10	0.33	0.33	3.68	4.03	3	3	31
Logit	3.42	2.95	3.18	14.38	1.34	6.35	15.93	103	12	52
Probit	3.54	3.29	4.22	18.39	10.03	41.14	28.27	130	82	259
MLM	3.03	3.01	3.07	1.34	0.67	2.68	1.99	10	6	23
PEM (All rejected gaps)	2.65	2.63	2.70	11.37	12.04	9.70	2.66	91	112	91
PEM (Only max rejected gaps)	2.87	2.99	3.06	4.01	0.00	2.34	6.62	31	0	20

Among the methods compared in this simulation, MLM gave consistently accurate results for critical gaps over a regime of conflicting volumes. This is in accordance with the findings of previous research works (Brilon et al., 1999; Miller, 1972). PEM and Raff's method also gave good estimates for critical gap. PEM was found to be inferior when all rejected gaps were utilized in comparison to the case when only the maximum rejected gaps were utilized. The estimate in the latter case were close to those of MLM which is also stated by Wu (2006, 2012). In spite of being computationally simpler in comparison to MLM and PEM, Raff's method also gave good estimates for critical gaps. Thus, this study found that MLM, PEM and Raff's method are suitable for estimating critical gaps at TWSC intersections.

6. Concluding Remarks

Capacity analysis of TWSC intersection is primarily based on gap acceptance theory and estimation of critical gap constitutes the first step in the process. This paper discusses several techniques for estimation of critical gap at TWSC intersections. Most of the methods gave the mean critical gap values, while methods like MLM and PEM provide the complete distribution of critical gaps. Some of these methods are computationally simpler, while other can be solved only by the use of a computer. The conceptual differences among the methods provide different values for estimated critical gaps. MLM continues to be the most popular among these methods along with Raff's method, which had undergone modifications over the years.

Simulation was used to quantify accuracy of critical gap estimated by various methods. Critical gap was estimated for through movement from minor street at a simulated four-legged TWSC intersection and it was used to determine the accuracy of each method. The study found that MLM, PEM (using only maximum rejected gaps), Raff's and Acceptance Curve Methods gave consistent results while critical gap by Probit, Logit and Ashworth's methods varied with the volume of conflicting traffic. The study also found MLM to give the best estimate followed by PEM and Raff's method. In view of the consistency and accuracy in prediction, this paper suggests MLM, PEM (only considering maximum rejected gaps) and Raff's methods for the estimation of critical gaps at TWSC intersections.

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