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Estimation of critical gap at small roundabout

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Estimation of critical gap at small roundabout

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Abstract. The gap acceptance theory is basically implied to describe the driver's behavior in the minor stream at the entry of roundabout searching for a suitable gap at the major stream to merge. The critical gap is an important parameter in the gap acceptance theory. However, the critical gap cannot be measured directly on the field. One way to measure the critical gap is by measuring only the rejected and accepted gaps. This study attempts to determine the critical gap at small roundabout using three different methods namely Raff's Method, Wu's Method, and Simple Logit Method. The data is collected at a two-lane roundabout in Skudai – Johor Bahru at the morning and afternoon peak hour using video camera technology. Accepted and rejected gaps are then extracted from the recorded videotape. The accepted and rejected gaps obtained are analysed to determine the critical gap. The findings from the study reveal that the critical gap values from the three methods are almost similar, having a critical gap of 3.45s, 3.60s and 3.45s for Raff's Method, Wu's Method, and Simple Logit Method respectively.

1. Introduction

Highway Capacity Manual 2010 [1] defines a roundabout as a type of un-signalized intersection with a circular shape, characterized by the yield on entry and circulation around a central island. One of the greatest advantages of the roundabout is reducing the conflict points at the intersection, this leads to capacity improvement as well as intersection safety [2–4]. In addition, the total delay is also reduced [5,6].

To estimate roundabout capacity, the most used methods are the analytical method or the empirical method. The empirical method is based on a linear regression between entry flow and circulating flow, depending on field data [7]. On the other hand, the analytical method is based on gap acceptance theory which based on driver’s behaviour, the main concept of this theory is driver’s in the minor stream should yield at the entry and wait for the suitable gap at the major stream to merge. It simulates entering driver’s behaviour at the yield line, searching for a safe gap before entering the roundabout. The critical gap and follow up headway are the main elements for this theory. Highway Capacity Manual 2010 defines "critical gap as the minimum time interval in the major street traffic stream that allows intersection entry for a minor street vehicle”. Generally, critical gap hinges on the local conditions such as driver behaviour, geometric layout (entry lane width, circulating lane width, and size of roundabout diameter), and the traffic condition and vehicle characteristics [8–10]. However, the critical gap cannot be measured directly on the field, only rejected and accepted gaps can be measured. Therefore, this study aims to estimate the critical gap at roundabout using different statistical methods namely Raff's Method, Wu's Method, and the Simple Logit Method.

2. Literature review

Many factors influence critical gap value such as intersection geometry, vehicle type, approach grade, and traffic movements [10]. Dahl and Lee [11], and Kang and Nakamura [12] found that the critical gap value for trucks is higher than for cars. Also, it was found that a high percentage of trucks in the circulating flow leads in a significant reduction on roundabout entry capacity. Lee *et al*. [13] studied the effect of rain on gap acceptance behaviour. The results indicated that drivers need around 10 percent larger gap to enter the roundabout. Polus *et al.* [14] studied the effect of waiting time on gap acceptance at the roundabout and the results showed that the critical gaps are decreased with the increase of waiting times because drivers are becoming more aggressive waiting too long to enter the roundabout. Drivers tend to behave differently at the roundabout entry, some of them are more careful and patient waiting for sufficient gap to merge, while some of them are aggressive accepting smaller gaps [15, 16]. This differences in driver's behaviour influence the capacity significantly and this demonstrates why methods of capacity estimation cannot be transferred from country to country without modification and calibration [17, 18].

2.1. Estimation methods of critical gap

Estimation of gap acceptance parameters from traffic observation is a difficult task for traffic engineers. Statistical models or procedures are required to estimate the critical gap. Many models have been developed to estimate the critical gap such as Raff's method [19], Maximum Likelihood model [20], Macroscopic Probability Equilibrium Model [21] and logit method [22].

2.1.1. Raff method. This method is also known as the graphical method [23]. According to Gavulová [19], Raff's method is commonly used to estimate the critical gap in many countries because of its simplicity. This method is based on macroscopic models, the cumulative probability function is estimated empirically for accepted gap $F_a(t)$ and rejected gap $F_r(t)$ from field measurement. The critical gap (tc) falls in the cross point of $1 – F_r(t)$ and $F_a(t)$ value as shown in Equation 1.

$$F_a(t) = 1 - F_r(t) \tag{1}$$

Where

$F_a(t)$ and $F_r(t)$ are probability functions for the accepted gap and rejected gap respectively, t_c is the critical gap value.

2.1.2. Maximum Likelihood model. Based on Z. Tian *et al.* [24] maximum likelihood is the best method to estimate the critical gap. The method is based on the fact that the driver's critical gap falls between the range of his largest rejected gap and his accepted gap. The log-normal distribution was assumed for accepted and maximum rejected gap, it is assumed that all drivers behave homogeneity and consistency. Thus, the critical gap distribution falls between distributions of largest rejected and accepted gaps. The mean and variance of the critical gap are obtained by maximizing the likelihood function in Equation 2 [25]. This method is accurate but it needs an iterative procedure.

$$\prod_{i=1}^{n}[F(a_i) - F(r_i] \tag{2}$$

Where

a_i and r_i are the logarithm of the accepted and rejected gap respectively, $F(a_i)$ and $F(r_i)$ are cumulative distribution function for the normal distribution for accepted and rejected gap respectively

2.1.3. Wu Method (Model based on the macroscopic probability equilibrium). Wu [21] developed a new technique to estimate the critical gap value. This method is based on the equilibrium of probability between the accepted and rejected gaps. Wu's method does not need to assume any type of distribution for critical gaps and does not need any an iterative procedure.

The macroscopic probability equilibrium is constructed from the accepted and rejected gaps cumulative distribution, notice that the probability of accepted gap length (t) is $F_a(t)$ and that is not accepted is $1-F_a(t)$. Similarly, the probability of rejected gap length (t) is $F_r(t)$ and that is not rejected is $1-F_r(t)$. In general $F_r(t)$ is not equal to $1-F_a(t)$ and $1-F_r(t)$ is not equal to $F_a(t)$. The probability distribution function (PDF) of the critical gap is obtained by solving Equation 3. The PDF *Ftc* is always falling between $Fa(t)$ and $Fr(t)$. The critical gap value is determined by Equation 4. This model is simple and easy to be implemented in spreadsheet programs and the results are robust.

$$F_{tc}(t) = \frac{F_a(t)}{F_a(t)-[1-F_r(t)]} = 1 - \frac{1-F_r(t)}{F_a(t)-[1-F_r(t)]} \tag{3}$$

Where
$F_{tc}(t)$ is the probability distribution function of critical gap
$Fa(t)$ and $Fr(t)$ are the probability of accepted and rejected gap respectively

$$t_{c\ average} = \sum\left[p_{tc}(t_j) * t_{dj}^2\right] \tag{4}$$

Where
$P_{tc}(t_j)$ is frequencies of the estimated critical gaps
t_{dj} is the class mean for two consecutive time gaps in seconds

2.1.4. Simple logit method. The cumulative probability of both rejected and accepted gaps are modelled using simple logit analysis, the typical shape of this method is denoted in Equation 5.

$$P = \frac{e^{f(t)}}{1+e^{f(t)}} \tag{5}$$

Where P is the cumulative probability of accepting or rejecting a gap, t is time length of gap accepted or rejected in seconds, and $f(t)$ is a linear function of gap t.

Equation 6 represents the linear function, a and b are constant to be estimated from the intercept and slope of the probability function of accepting and rejecting gaps. Equation 7 and 8 shows the probability function of accepted and rejected gaps, where t_{cri} is the critical gap and a_{acc}, b_{acc}, a_{rej}, and b_{rej} are logit function parameters for the cumulative probability of accepted and rejected gaps respectively.

$$f(t) = a(t-b) \tag{6}$$

$$P = \frac{e^{a_{acc}(t_{cri}-b_{acc})}}{1+e^{a_{acc}(t_{cri}-b_{acc})}} \tag{7}$$

$$P = \frac{e^{a_{rej}(t_{cri}-b_{rej})}}{1+e^{a_{rej}(t_{cri}-b_{rej})}} \tag{8}$$

Equation 9 is a combination of Equation 5 and 6 together

$$ln\frac{P}{1-P} = a(t-b) \tag{9}$$

The critical gap falls at the cross point of the cumulative probability distributions of accepted gaps with the cumulative probability distributions of the rejected gaps as shown in Figure1. By solving Equation 10 the critical gap can be gained as shown in Equation 11.

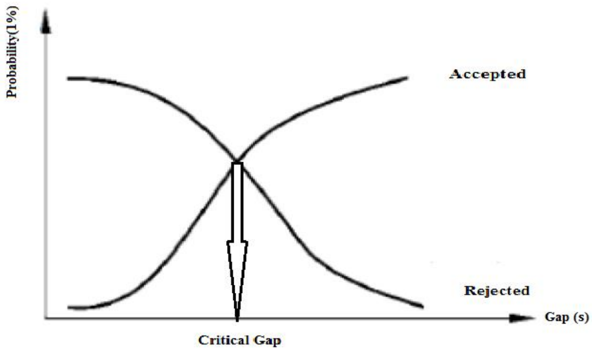

Figure 1. Critical gap.

$$\frac{e^{a_{acc}(t_{cri}-b_{acc})}}{1+e^{a_{acc}(t_{cri}-b_{acc})}} = \frac{e^{a_{rej}(t_{cri}-b_{rej})}}{1+e^{a_{rej}(t_{cri}-b_{rej})}} \quad (10)$$

$$t_{cri} = \frac{a_{acc}b_{acc}-a_{rej}b_{rej}}{a_{acc}-a_{rej}} \quad (11)$$

Where t_{cri} is the critical gap value in seconds

2.2. Previous studies on critical gap

Many researchers from different countries had been conducting research on critical gap for several types of roundabout. Table 1 shows the critical gap values obtained by different researchers from different countries.

Table 1. Critical gap values obtained by different researchers from different countries.

Reference	Country	Method	Critical gap (seconds)
Mathew *et al.* [7]	India	Maximum likelihood method	1.6
Cheng *et al.* [22]	China	Cumulative probability distributions function	– Peak hour 4.15 – Off-peak hour 4.38
Hagring *et al.* [26]	Denmark	Log-likelihood method	– Right lane (3.68 inner- 4.49 outer) – Left lane (4.64 inner -4.68 outer)
Xu and Tian [27]	California	Maximum likelihood method	Single lane 4.8 Multi-lane: – Left lane 4.7 – Right lane 4.4
Mwesige and Tindiwensi [28]	Uganda	Maximum likelihood method	3.18
Vasconcelos *et al.* [29]	Portugal	Siegloch, Raff, Wu, Maximum Likelihood and Logit	– Siegloch At move-up threshold 4s Critical gap ranges between (2.52-3.76) At move-up threshold 6s Critical gap ranges between (2.88-4.46) – Raff (2.97- 3.9) – Wu (3.22-3.9) – Maximum likelihood (3.19-3.98) – Logit (2.56-3.59)

Mathew *et al.* [7] estimated the critical gap value for the roundabout in India using (MLM), Root Mean Square (RMS) method and Probability Equilibrium Method (PEM) for different vehicle classes. And they found that vehicle dimensions and acceleration rate play an important role, as such the critical gap value increase with the increase in the vehicle dimensions, the critical gap value was found to be 1.6s in heterogeneous traffic condition. Cheng *et al.* [22] used Cumulative probability distributions function to measure the critical gap at a three-lane roundabout in China in peak hour and off-peak hour, they found that the critical gap value in peak hour is shorter than of peak hour.

Hagring, *et al*. [26] used Maximum Likelihood Method to estimate the critical gap value for a two-lane roundabout in Copenhagen, Denmark for both lanes (left and right) entries. They found that for drivers entering from the right approach the critical gap for the inner lane (3.68s) was smaller than the outer lane (4.49s), in contrast drivers entering from the left approach experience no differences in critical gap value (4.64 s for the inner lane and 4.68 s for the outer lane). Other work was done by Xu and Tian [27] investigating the critical gap at seven single-lane and three multilane roundabouts in California. They found that the critical gap values were consistent with that reported in the NCHRP 3-65 study, and there is no significant difference between California values and other states in the USA. In addition, Mwesige and Tindiwensi [28] also studied the driver's behaviour at Uganda roundabouts using maximum likelihood technique to estimate the critical gap, their results show that the critical values are 3.25s, 2.67s and 3.18s for vehicles, motorcycles, and a combination of the two respectively, the motorcycles have a shorter gap with a comparison to vehicles.

Vasconcelos *et al.* [29] estimated critical gap value at six roundabouts in Portugal using several estimation models (Siegloch, Raff, Wu, Maximum Likelihood and Logit). The results have shown that the critical gap value estimated from the different methods was consistent, moreover, the critical gap value from the right entries are slightly shorter and significantly shorter for the three-lane roundabouts.

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3. Methodology

3.1. Site description

The study was conducted at two-lane roundabout located within the Universiti Teknologi Malaysia Johor campus. The roundabout consists of two circulating lanes the average width of each lane is around 4.2m, the roundabout central circular island diameter is15.20m (inscribed diameter 32m). based on Arahan Teknik (Jalan) 11/87 [30] this roundabout categorized as small roundabout as the inscribed diameter is less than 50m and greater than 20m, as shown in Figure 2.

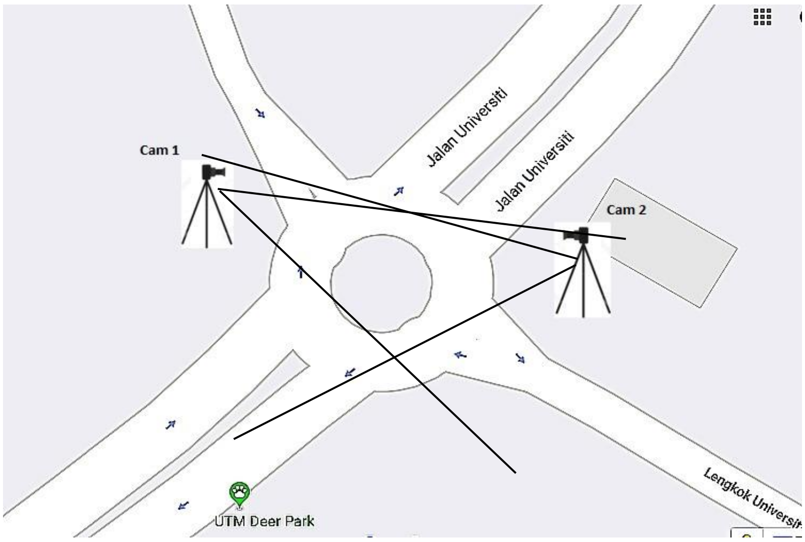

Figure 2. The roundabout inside Universiti Teknologi Malaysia, Johor campus.

3.2. Data collection and analysis

Two camcorders were used, the cameras were placed at a high ground point level to capture both entry traffic queue and circulating ones as shown in Figure 2. The traffic volumes were recorded for 3 days in a typical weekday, during the morning (8:00-10: 00 am) and afternoon (4:00-6:00) peak hours. The weather condition was mainly fair and the pavement surface was dry.

Later on, the recorded videos were played several times in the lab using Windows Movie Maker®. The stop line at each roundabout entry was selected as a reference line and the following were recorded:

1. The arrival and departure times of vehicles at the reference point
2. For each vehicle arrived the reference line, the time a conflicting vehicle arrived were recorded until the vehicle at the entry depart the reference line and the next vehicle at the circulating lane arrive the conflict point.

After extracting all the data, accepted and rejected gaps were estimated. The rejected gap was estimated by the time difference between vehicle arrival at the reference line and the conflicting vehicle arrival at the conflict point, as well as between two consecutive conflicting vehicles while the entry vehicle still at the reference line. The accepted gap was recorded by the time difference between the time of the last and first conflicting vehicles arrival the conflict points before and after the vehicle at the entry depart the reference line. Any gap greater than 13 s was excluded as it is regularly accepted by the drivers.

4. Results and discussion

After extracting the accepted and rejected gaps, it was found that the total number of accepted gaps were 710 and the total number of rejected gaps were 741 as shown in Table 2, any gap greater than 13 s was excluded as it is regularly accepted by the drivers. Then the critical gap value was obtained using three different methods namely Raff's Method, Wu's Method, and Simple Logit Method. The results were compared with the previous studies from different countries.

Table 2. Rejected and accepted gaps from field measurement.

Gap (s)	Number of accepted gaps (s)	Number of rejected gaps (s)
0	0	0
1	2	168
2	3	240
3	42	150
4	164	170
5	115	11
6	97	1
7	65	1
8	45	0
9	49	0
10	39	0
11	31	0
12	21	0
13	37	0
Total	710	741

4.1. The critical gap from Raff method

The cumulative probabilities for accepted gaps $F_a(t)$ and rejected gaps $F_r(t)$ were drawn in Figure 3. The critical gap was determined at the cross point of $F_a(t)$ with $F_r(t)$. Thus, the critical gap found to be 3.45s

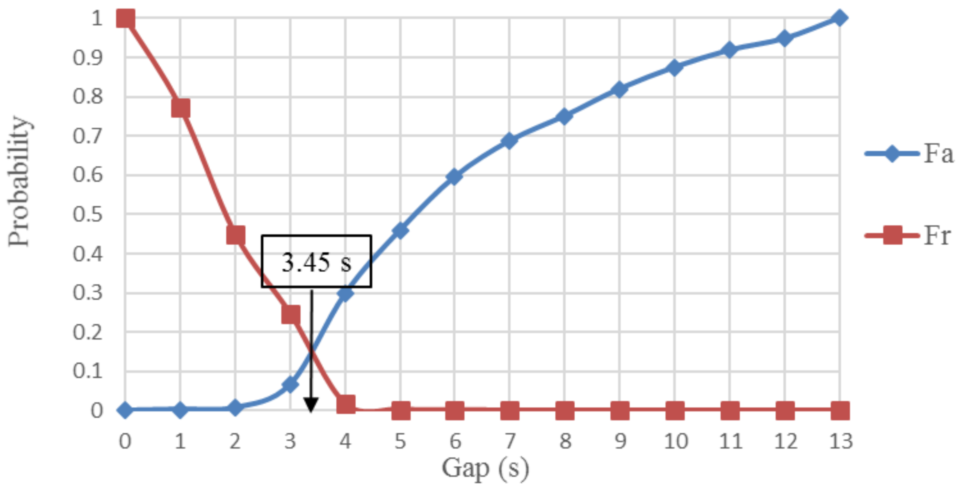

Figure 3. The estimated critical gap from Raff's method.

4.2. The critical gap from Wu method

Figure 4 shows the probability distribution functions (PDFs) for both accepted gaps $F_a(t)$ and rejected gaps $F_r(t)$, the probability distribution function (PDF) of the critical gap was found lies between $F_a(t)$ and $F_r(t)$. The critical gap value was estimated using Equation 3 and was found to be 3.6 s.

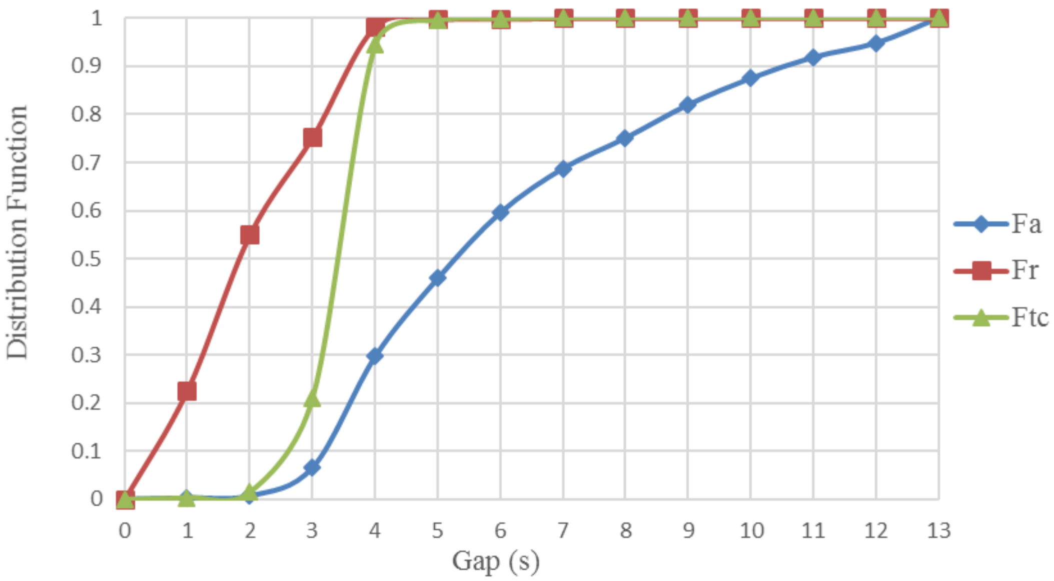

Figure 4. The PDF of the critical gap lies between PDFs of rejected gaps and accepted gaps.

4.3. The critical gap from simple logit method

Figure 5 and 6 show the linear regression for the cumulative probability of accepted and rejected gaps respectively, the values of a_{acc}, b_{acc}, $a_{rej,}$ and b_{rej} were found from the linear regression equation and summarized in Table 3. Using Equation 8 the critical gap was found to be 3.45s

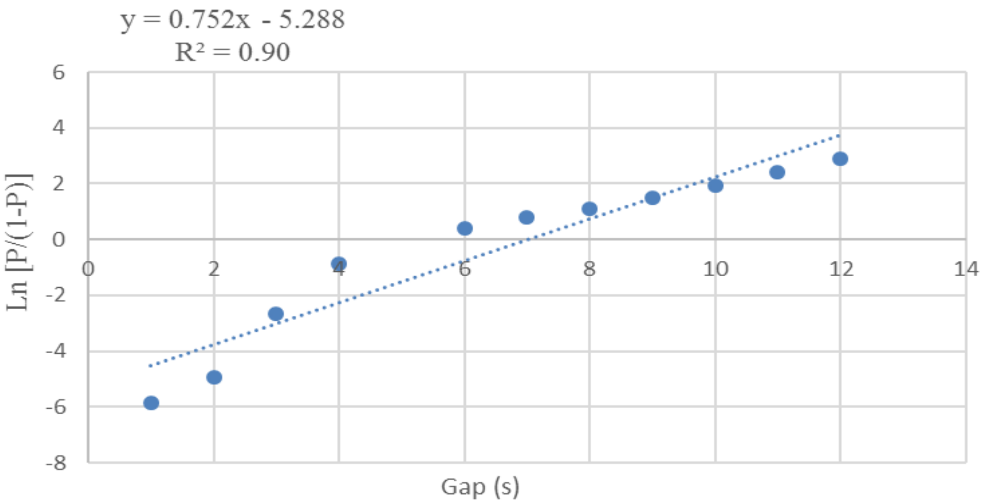

Figure 5. Linear regression for the cumulative probability of the accepted gaps.

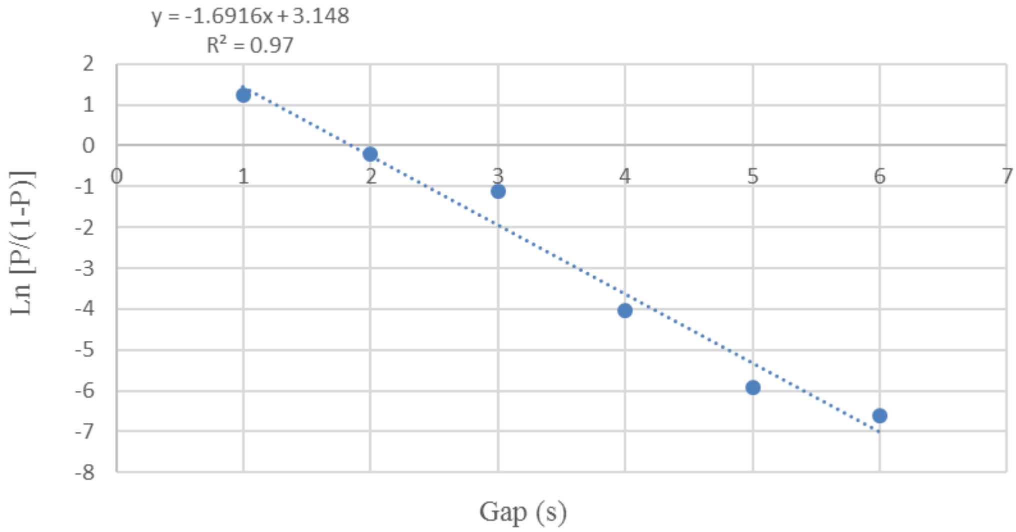

Figure 6. Linear regression for the cumulative probability of the rejected gaps.

Table 3. Logit function parameters for the cumulative probability of accepted and rejected gaps form the linear regression.

Parameter	Acceptance	Rejection
a	0.752	-1.6916
b	7.03	1.86096
R^2	0.9	0.97
Critical gap (s)	3.45	

4.4. Comparing the critical gap obtained with previous studies

Comparing the critical gap value obtained in this study with previous studies in other countries, the following could be concluded:

1. The critical gap value obtained by Mathew *et al*. [7] in India is significantly smaller than that value obtained in this study, this due to heterogeneous traffic condition in India
2. The estimated critical gap by Cheng *et al.* [22] in China and Xu and Tian [27] in California are almost the same but larger than the obtained value in this study, it shows that the drivers in this study behave aggressively, the drivers are accepting smaller gaps.
3. The critical gap value estimated by Vasconcelos *et al.* [29] in Portugal is consistent with the obtained value in this study, it shows that drivers behavior are comparable.
4. The critical gap value determined by Mwesige & Tindiwensi [28] in Uganda is slightly different from the obtained value in this study, it means that the drivers tended to accept almost the same gap.

5. Conclusion

This paper presented an exploratory approach to determine critical gap at small roundabout using three different methods namely Raff's Method, Wu's Method and Simple Logit Method. Raff's method and simple logit analysis give same results 3.45s. While Wu gives critical gap value 3.6s. Raff's method is extremely simple and no complicated calculation is needed. Wu's method is easy and can be carried out straightforward in a spreadsheet. The cumulative distribution of accepted and rejected gaps was perfectly adapted by logit function. The value of the critical gap from the three methods for the selected study area is smaller than the values recommended by Highway Capacity Manual 2010 (4.29s left and 4.11 s right lane).

This variation in the value of the critical gap indicates that using the Highway Capacity Manual 2010 equation to estimate the roundabout entry capacity will generate different capacity values if it is compared with real values in the field. This differences in driver's behaviour influence the capacity significantly and this demonstrates why methods of capacity estimation cannot be transferred from country to country without modification and calibration.

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