

Determining the Capacity Model of Urban Roundabouts, Considering the Drivers' Behaviour in Accepting and Rejecting of Gaps

Iraj Bargegol ¹, Seyyed Hamze Hosseini ², Mehdi Jahangir Samet ³

¹ Dept. of Civil Engineering, Faculty of Engineering University of Guilan, P.O.Box 3756, Rasht, Iran

² Faculty of Engineering University of Guilan, P.O.Box 3756, Rasht, Iran

³ School of Civil Engineering, Iran University of Science & Technology, P.O.Box 16765-163, Tehran, Iran

h.hosseini.1367@gmail.com

Abstract. Nowadays, urban roundabouts are one of the most popular types of intersections that have grown highly all over the world. Thus, the accurate and engineering design of these types of intersections has a significant effect on improving their traffic performance. The capacity is one of the important traffic parameters in different intersections, which represents the maximum volume of vehicles entering the roundabouts. There are two general methods for determining the capacity of intersections including the use of analytical models such as gap acceptance model and the use of empirical methods (regression model). In the present paper, using the collected data such as entry and circulating volume, both accepted and rejected gaps were studied for three urban roundabouts and the capacity model have been determined by the use of analytical method. After implementation of the data, they became consistent and homogeneous in four different groups and the most optimized range of critical gaps as well as the follow up time were separately determined for each of these groups by using conventional methods such as Sigloch, Raff, Wu, and Harder and according to statistical analyses with a confidence level of 95%. From the obtained results, a range of 3.03 – 3.32 s for critical gap of the studied roundabouts and the range of 1.3 – 1.7 s for follow up time could be mentioned. It was used from the theory of gap acceptance in order to determine urban roundabouts capacity model, in which these gaps have a random nature and follow negative exponential distribution and by conducting this analysis (also has been used by Sigloch), some relations were obtained for determining the capacity of the roundabouts according to the impact of circulating volume and drivers' behaviour. The results indicate that the maximum capacity of the roundabouts in the microscopic models is equal to 2400 veh/h, when the circulating flow rate is reached zero. Moreover, according to the obtained capacity model, the circulating flow never falls down to zero in the case that it reaches its peak value.

1. Introduction

Determining the performance features of each intersection are among the most important parts of designing them; factors such as capacity and delay are the most important examples of them. Monitoring and evaluation of capacity values in the roundabouts is a difficult matter due to the high dependence of



these parameters on the drivers' behaviour. In other words, capacity indicates the service rate (queue clear rate) in performance (delay, queue length, stop rate), therefore, it is associated with both saturated and unsaturated cases [1]. Several capacity model determination are developed in the world that can be classified based on the Experimental and Analytical methods: [2, 3] 1. Experimental models: They are measured based on the relationship between geometric and actual capacity, 2. Gap acceptance models: Based on the understanding driver's behaviour and 3. Microscopic simulation models: Based on kinesiology modelling and the interaction between vehicles. The acceptance gap model is an alternative method for modelling the capacity of roundabouts based on the gap parameters between vehicles, the circulating flow and the entry flow. The collected data in this method are on the heavy entries with continuous queue is much lower than the experimental models [4]. This model depends on three parameters of critical gap (t_c), follow up time (t_f) and gap distribution. Using these variables, the entry capacity can be calculated through appropriate models.

A variety of factors affect the entry capacity of a roundabout, the most important of which include the rate of traffic flow in each entry and circulating path and the combination of vehicles during the analysis period, the pedestrian, driver's behaviour and the roundabout's geometry [5]. Factors that are discussed in this article are: circulating traffic volume, driver's behaviour on the acceptance or rejection of the gap, entry slope and the vehicle characteristics. Critical gap is reduced under the saturated conditions which has a high impact on the capacity, [6].

In this paper, to determine the capacity of the roundabouts under study, the microscopic method and analytical models (gap acceptance) is used. These models are based on gaps; the critical gap (t_c) is the least gap a driver passing a side street accepts to enter the roundabout, [7].

In this paper, using valid methods described in several sources, the critical gap is determined for several roundabouts. These methods include: Siegloch, Raff, Wu and Harder that using the values the best range of critical gap and the follow up time are determined and finally using the obtained parameters as well as the circulating flow rate. Siegloch capacity model, calibrated model for the urban roundabouts' capacity that can be used in future design of the urban roundabouts within the geographic area under study as well as the modification of the existing roundabouts.

Since 1970, a series of models have been developed to determine the roundabouts' capacity throughout the world almost all of these models are based on extensive empirical data. The first models include Tanner (1962), Armitage and McDonald (1974) and Ashworth and Laurance (1978) also the first models are Germany (Stow, 1991) and French Jirabis (Setrto, 2006). Also, Siegloch model is the basis for HCM2000, HCM2010, Stroud Australian model and the German model Brilon-Wu based on the negative exponential distribution in which the gap time parameters are measured in terms of saturation.

Determining the critical gap by the traffic flow observation is one of the most difficult issues in Traffic Engineering Sciences and due to the impact of this parameter on the capacity of roundabouts, many studies have been conducted on determining the critical gap among which Siegloch (1973), Raff et al (1950) and Harder (1968) are among the most important methods to determine critical gap among which Siegloch (1973) and Raff (1950) are common for saturated conditions [8]. Among people who have compared different methods to determine critical gap are Miller (1972) and Brilon et al (1997) [9]. Miller (1972) proposed 9 different methods to determine critical gap that did not include all methods to determine critical gap [7]. Brilon et al (1999) conducted a comprehensive review on the different methods and developed them over time [5]. Using the microscopic simulation, evaluated the models [8]. Today more than 20 or 30 methods to determine critical gap are found that are used around the world [7].

2. Data Collection

In this paper, the gaps related to the entry and circulating paths of three roundabouts that are saturated at least in one line are studied. The specifications of these roundabouts are presented in Table 1.

Table 1. The specifications of the roundabouts

Roundabout	Location	Land Use	Entry Width (m)	Circulating Width (m)	Inscribed circle diameter (m)	Number of Entry	Controlled Intersection	Longitude (m)	Latitude (m)
1	Ciry Center	Commerical , Training	8.5	10	64	4	2	4126970.09	375227.29
2	Ciry Center	Commerical, Official	8	10	61	4	1	4125524.06	375449.35
3	Ciry Center	Commerical, Official	8.6	10	74	3	0	4122776.85	377561.88

Due to the existence of roundabouts around the educational, office and commercial centres, two peak times of the morning and afternoon are selected as the times to collect observations. Observations related to the gaps and vehicle traffic at peak hours are recorded by imaging and then the office was implemented. Table 2 presents the number of observations for each roundabout.

Table 2. observations recorded for each roundabout

Roundabout	Entry Volume (Veh/h)	Circulating Volume (Veh/h)	PHF (circulating/entry)	Number of Gap
1	1835	979	0.99/0.93	421
2	1199	1063	0.98/0.98	402
3	1434	1362	0.92/0.96	532

3. Analysis

In this paper, in order to determine the most optimal capacity model for the urban roundabouts and calibrate it with the geographical area conditions after data collection, first, with using the above methods, the upper and lower limit of the critical gap and the optimal follow up time were determined and by using Siegloch global relation, the optimal and calibrated model the capacity of roundabouts is determined.

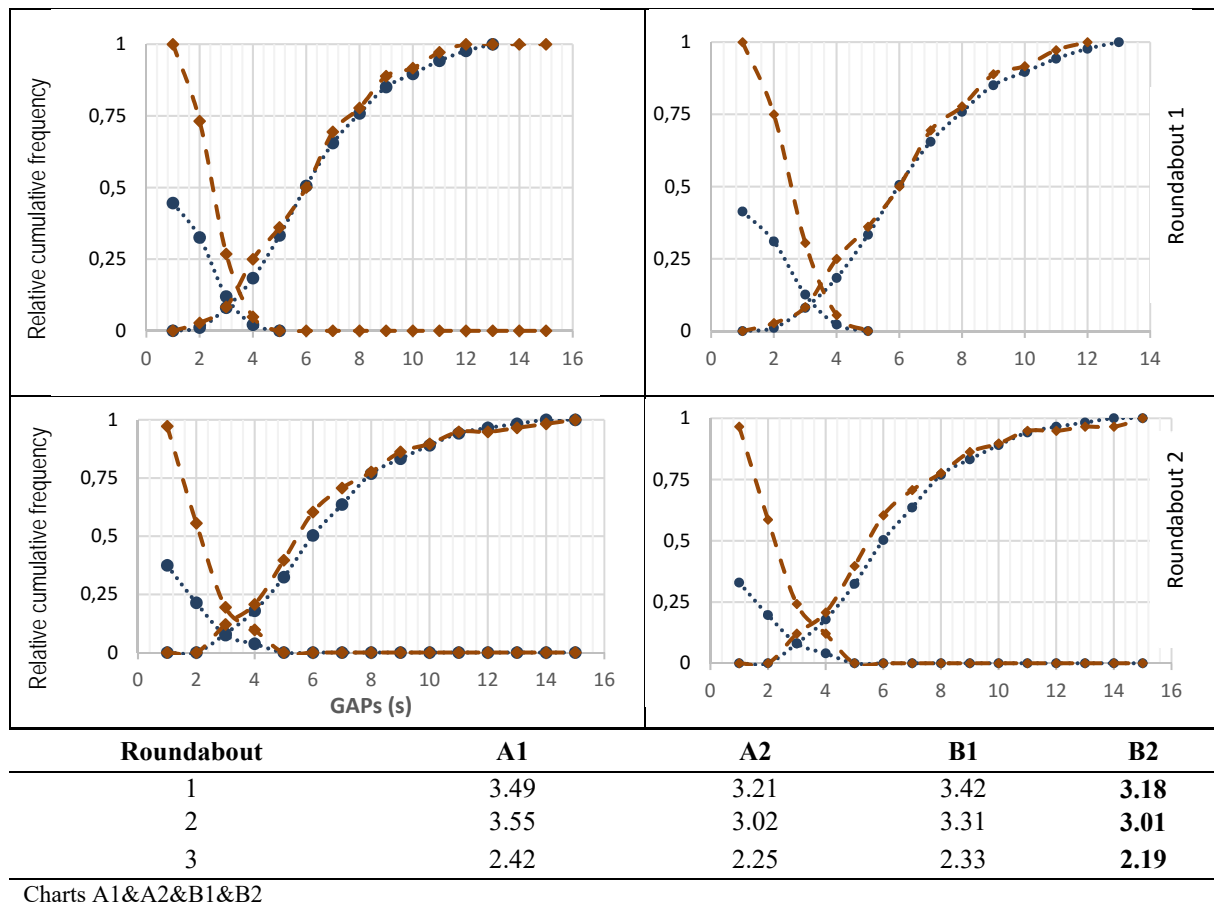
3.1. Determining the critical gap in urban roundabouts

By observing a series of accept and reject gaps, it is possible to present them by statistical distribution functions; thus, it is possible to present the gap acceptance by cumulative distribution function $F_a(t)$ and present the unacceptable gap times as $F_r(t)$. To create the function $F_r(t)$, 2 different modes can be considered for the gap samples: in the first mode for the drivers have passed several gaps before accepting the gap, only the greatest gap is considered and included in the calculations, This is in the case if a driver has not passed any gap, the output calculation ($A1$) or the passed gap 0 is considered for it ($A2$). In the second case, all gaps are included in the study and in this case if the driver does not pass any gap, the output calculations ($B1$) or the gap value of zero is considered for it ($B2$) [7].

3.1.1. Raff method

Raff method [10] is the most common method to estimate the gap. It is based on the cumulative distribution functions of the acceptable and unacceptable gaps. Raff in this method introduced the intersection of the two graphs $F_a(t)$ and $1 - F_r(t)$ as the critical gap (t_c). Accordingly, the critical gap in different states ($A1$, $A2$, $B1$ and $B2$) for each of the roundabouts was determined, the values and charts of which is presented in Table 3

Table 3. Critical gap value estimated by Raff method (in seconds)



3.1.2. Wu method

Wu method [11] is based on the balance of the acceptable and unacceptable critical gap probability. Wu, similar to Raff, used the gap cumulative distribution functions to determine the critical gap. First by arranging data incrementally and assuming the distance between any two data as a category and showing the type of each of them (acceptance (A) and unacceptance (R)), determined the cumulative frequency values ($N_a(t)$ and $N_r(t)$) and the relative cumulative frequency ($F_a(t)$ and $F_r(t)$) of each data and then obtained the cumulative distribution function of the critical gap $F_c(t)$ using the acceptable and unacceptable cumulative distribution functions. Finally, he determined the critical gap with regard to the frequency value between any two gaps using Equation (1). In Table 4, the values of critical gap obtained by Wu are presented.

$$t_c = \sum(f_{cj} \times t_{dj}) \quad (1)$$

f_{cj} : frequency between two consecutive gaps, t_{dj} : representative of each class (average of two consecutive gaps)

Table 4. Estimated critical gap by Wu method

Roundabout	A1	A2	B1	B2
1	3.19	3.00	3.16	2.99
2	3.49	3.16	3.41	3.14
3	2.48	2.28	2.33	2.23

In this method, the critical gap values obtained in cases A1 and B1 and the critical gap values obtained in cases A2 and B2, are almost equal.

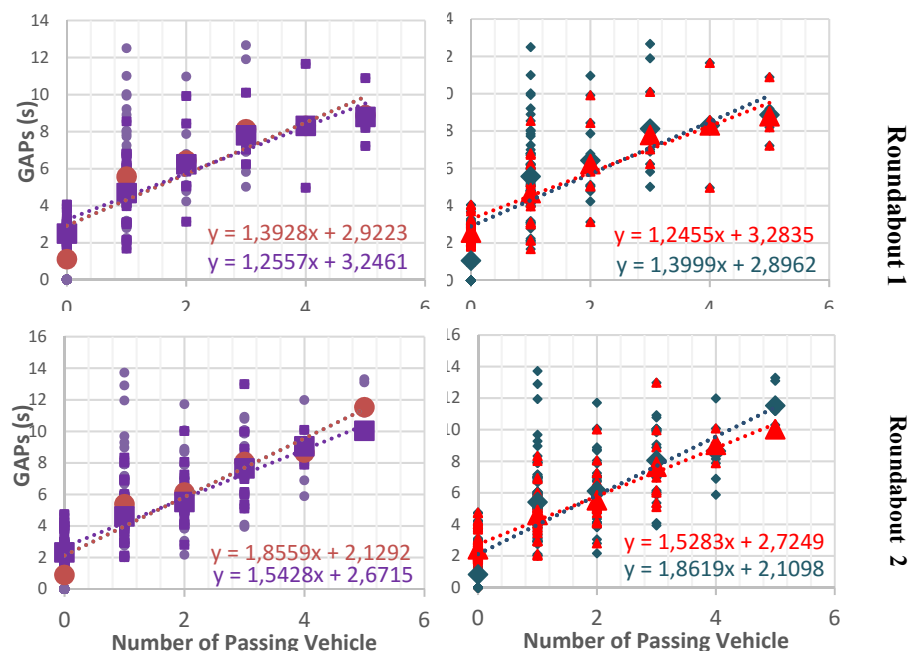
3.1.3. Siegloch method

Siegloch method is one of the only methods that is directly related to the capacity. In this method, the number of vehicles passing through each gap in the main flow (circulating flow of the roundabout) is considered which can be presented as the “gap-the number of passing vehicles”. It should be noted that for unacceptable gaps, the number of passing vehicles is considered as 0. In order that the fitted line with the associated data have higher reliability and less dispersion of data, the average gap for any number of data is used and the related line is fitted with the average values. If the fitted line equation is as $y=ax+b$, the critical gap and the follow up time are determined by the values of slope and intercept the fitted lines equation.

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

Based on the described method in Table 5 of the corresponding graphs as well as the obtained values, the critical gap and follow up time are determined.

Table 5. Values of critical gap and follow up time estimated by Siegloch method



Roundabout		Equation	Follow Up Time		Critical Gap
1	A1	$y = 1.2455x + 3.2835$	1.2455	3.2835	3.91
	A2	$y = 1.3928x + 2.9223$	1.3928	2.9223	3.62
	B1	$y = 1.2557x + 3.2461$	1.2557	3.2461	3.87
	B2	$y = 1.3999x + 2.8962$	1.3999	2.8962	3.6
2	A1	$y = 1.5283x + 2.7249$	1.5283	2.7249	3.49
	A2	$y = 1.8619x + 2.1098$	1.8619	2.1098	3.04
	B1	$y = 1.5428x + 2.6715$	1.5428	2.6715	3.43
	B2	$y = 1.8559x + 2.1292$	1.8559	2.1292	3.06
3	A1	$y = 1.4418x + 1.9405$	1.4418	2.9405	3.66
	A2	$y = 1.4408x + 2.0056$	1.4408	2.0056	2.72
	B1	$y = 1.4591x + 1.9142$	1.4591	2.9142	3.64
	A1	$y = 1.4521x + 2.1286$	1.4521	2.1286	2.85

Charts A1&A2&B1&B2

One of the advantages of this method is to determine the critical gap with follow up time simultaneously. The best way to determine the critical gap is to use all data obtained by the field observations. Based on the obtained logic by the previous methods, the critical gap in different states is very close together and it can be considered as almost equal. Another advantage of this method is that the presence of the outliers will have no significant effect on the results due to the average amounts of data which leads to the use of all data.

3.1.4. Harder method

Harder [12] presented a method for estimating the critical gap that is very popular in Germany. Almost all the functions of the intersections without traffic lights in Germany are based on the values of critical gap and follow up time values in this method. Using equation (3), Harder presented an acceptable cumulative distribution function for gaps. In this method, he divided the interval between the smallest unacceptable gap and the greatest acceptable gap into small time intervals (0.5 sec) and specified the centre of each time interval i as t_i .

$$a_i = A_i \cdot N_i \quad (3)$$

N_i : the frequency or number of intervals in interval i , A_i : the frequency or number of acceptable intervals in interval i

In this method, it is assumed that the values under 1 sec are considered as the unacceptable gap and the values above 21 secs are considered as the acceptable values. According to curve a_i , it is possible to consider function a_i equal to the cumulative distribution function of the critical gap $F_c(t)$. In Harder method, as in the Wu method, of the product the representative of each class and its frequency is used to determine the critical gap (equation (4)). Critical gap values for the urban roundabouts under study are given in Table 6.

$$t_c = \sum t_i \cdot [a_i - a_{i-1}] = \sum t_i [F_c(t_i) - F_c(t_{i-1})] \quad (4)$$

Table 6. Critical gap values estimated by Harder method

Roundabout	A1	A2	B1	B2
1	3.85	3.45	3.90	3.50
2	3.97	3.44	4.03	3.49
3	2.83	2.52	2.97	2.66

3.1.5. Determining the optimal critical gap interval

In this paper, In this paper, the best critical gap interval was determined using statistical analysis and 95% confidence level. Table 7 presents the statistical specifications of the critical gap intervals of each roundabout and the lower and upper limit of the confidence level 95% with respect to the values obtained by Raff, Siegloch, Harder and Wu methods for each of the roundabouts in all four cases of unacceptable gap time.

Table 7. Statistical values of the roundabouts' critical gaps (in seconds)

Satatistics Specifications		Roundabout 1	Roundabout 2	Roundabout 3	Average
Average		3.46	3.46	2.69	3.18
Middle		3.47	3.47	2.59	3.19
SD		0.32	0.32	0.44	0.49
Variance		0.1	0.1	0.196	0.25
Min-Max		2.99-3.91	3.01-4.03	2.19-3.66	2.19-4.03
Skewness		0.076	0.785	1.252	- 0.306
Strain		- 1.243	0.292	1.084	- 0.724
Confidence level 95%	Min	3.29	3.21	2.46	3.03
	Max	3.63	3.54	2.93	3.32

As can be seen in Table 7, the level of critical gap for the studied roundabout is between 3.03 and 3.32.

3.1.6. Follow up time

Siegloch method is the only method that can determine the critical gap and follow up time. According to the data collected from the studis roundabouts, it is possible to obtain the follow up time values by Siegloch method for each of the studis roundabouts based on different modes of data and follow up time that In this paper, the mean value of all states is used. These values are presented in Table 8.

Table 8. Values of follow up time estimated by Siegloch method

Roundabout	A1	A2	B1	B2	Average
1	1.4	1.25	1.4	1.25	1.33
2	1.86	1.54	1.86	1.53	1.70
3	1.45	1.44	1.45	1.44	1.45
All	1.5				

3.2. Determining the capacity of urban roundabouts

As mentioned earlier, Siegloch (1973) proposed a logical framework to determine the capacity of the intersections without traffic lights. This framework has emphasized on the use of critical gap in mathematical modelling. In this modelling, $g(t)$ is the number of vehicles in a side street that can enter the roundabout interference area in the main flow gap time. The number of gap times expected in the main flow is equal with $q_p \cdot h(t)$ where q_p is the rate of circulating flow and $h(t)$ is the statistical density distribution of all time gaps in the main flow. So, the amount of capacity obtained by the time gaps (t) over and hour is equal to $g(t) \cdot q_p \cdot h(t)$. To calculate the ultimate capacity of the intersection, the above equation should be integrated in the total main flow time gap interval. As a result, the capacity of intersections without traffic lights is obtained by Equation (5).

$$c = q_p \cdot \int_{t=0}^{\infty} g(t) \cdot h(t) \cdot dt \quad (5)$$

The equation for the intersections without traffic lights is a kind of acceptable gap time theory. Almost all intersections without traffic lights' estimation methods are discovered and formulated in the international literature based on this concept even when some authors are not aware of this method.

To calculate capacity using this method, it is necessary to identify the type of distribution of gap time intervals $h(t)$ and the function $g(t)$. Siegloch uses the method stated in determining the critical gap by field observations to determine $g(t)$. Observations should be conducted under saturation and the amount of $g(t)$ is always an integer. Equation t which is a function of g , is absolutely true when t_c and t_f are constant values. So, in this case, the equation $g(t)$ can be considered as equation (6).

$$t_0 = t_c - \frac{t_f}{2} \quad g(t) = \begin{cases} 0 & t < t_0 \\ \frac{t-t_0}{t_f} & t \geq t_0 \end{cases} \quad (6)$$

As a result, by combining the equations 5 and 6, and assuming that the gap times follow negative exponential distribution, using Siegloch model, the roundabouts' capacity model can be written as equation (7).

$$c = \frac{3600}{t_f} \times e^{-q_p \left(\frac{t_c - \frac{t_f}{2}}{3600} \right)} \quad (7)$$

Now according to the model obtained by equation 7, critical gap values and the circulating flow rate of each roundabout under study, the capacity of each roundabout can be determined. To determine the

total capacity model for studis roundabouts, it is assumed that the drivers in each roundabout have consistent behaviour and thus it can be assumed that drivers in all roundabouts have consistency. Thus, using the critical gap intervals, follow-up time and equation 7, the general model for urban roundabouts is determined. Now, according to the obtained models and diagrams of each field under study, it is possible to compare the models of each roundabout with each other and the overall model. The advantage of this comparison is that the roundabout with the highest capacity can be determined and specify which roundabout is closer to the overall model of roundabouts' capacity. As a result, by comparing the capacity and other features of the roundabouts such as geometric features, it is possible to understand the reason for higher or lower roundabout capacity. In Figure 1, the lower and upper limit of the capacity of all roundabouts is presented.

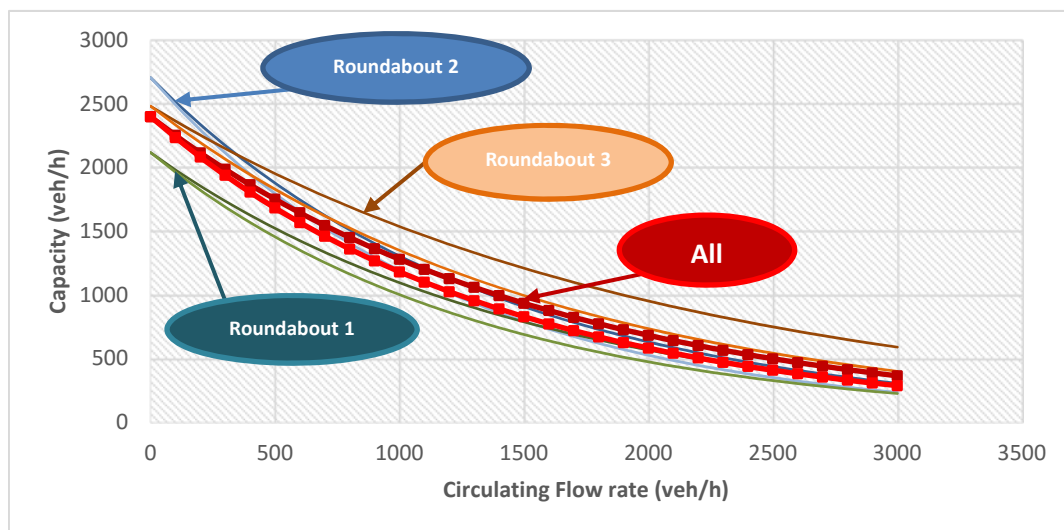


Figure 1. The lower and upper limit of the capacity of all roundabouts individually and in general

As it can be observed in Fig 1, the highest capacity is in roundabout 3 and the lowest one is observed in roundabout 2. Table 9 presents the lower and upper limit of the capacity of all roundabouts individually and in general.

Table 9. Capacity of urban roundabouts' model

Roundabout	Limit	Capacity Model
1	Upper Limit	$2706 \times e^{-0/00073 \times q_c}$
	Lower Limit	$2706 \times e^{-0/00082 \times q_c}$
2	Upper Limit	$2118 \times e^{-0/00065 \times q_c}$
	Lower Limit	$2118 \times e^{-0/00074 \times q_c}$
3	Upper Limit	$2482 \times e^{-0/00048 \times q_c}$
	Lower Limit	$2482 \times e^{-0/00061 \times q_c}$
All	Upper Limit	$2400 \times e^{-0/00063 \times q_c}$
	Lower Limit	$2400 \times e^{-0/00071 \times q_c}$

4. Results

- Sieglach method has the highest flexibility to determine the critical gap of roundabouts in Rasht city. Simpler calculations, higher coverage of the variables and simultaneous determination of the follow up time are among the reasons for the better performance of this method compared to other methods. The next method is Raff method.
- The values of the critical gap are always in close proximity to states A1 and B1 as well as A2 and B2. Therefore, due to more balance in acceptable and unacceptable gaps, it is proposed to use the case A1.

- According to the methods considered in this thesis (Raff, Siegloch, Harder and Wu), the drivers' behaviour in acceptable and unacceptable cases showed that the critical gap of the urban roundabouts is between 3.03 and 3.32 s.
- According to the method described for determining the follow up time (Siegloch method), the value of this interval in Rasht roundabouts is between 1.3 and 1.7 s.
- According to the models for roundabouts under study when $q_c=0$, the capacity is equal with 2400 vehicles per hour. In addition, it can be claimed that in the worst condition i.e. when rate of circulating value is maximum, the Entry capacity will not reach 0.

References

- [1] Transportation Research Board, "Highway Capacity Manual", 2010, Washington DC.
- [2] R. J. Troutbeck, "Evaluating the Performance of a Roundabout", Vermont South: Australian Road Research Board, 1989.
- [3] RM. Kimber, "THE TRAFFIC CAPACITY OF Roundabouts", in Trrl 942 REPORT LABORATORY, 1980.
- [4] Rodegerdts, M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter, "NCHRP Report 572: Roundabouts in the United States", 2007, Transportation Research Board of the National Academies: Washington DC.
- [5] Kusuma and Koutsopoulos, "Critical Gap Analysis of Dual Lane Roundabouts", Procedia - Social and Behavioral Sciences, 2011.
- [6] S. Mensah, S. Eshragh, and A. Faghri, "A Critical Gap Analysis for Modern Roundabouts", in Transportation Research Board 89th Annual Meeting, 2010.
- [7] Werner Brilon, Rjtark, "Useful Estimation Procedures for Critical Gaps", in the 3rd International Symposium on Intersections without Traffic Signals, 1997.
- [8] N. Wu, "A NEW MODEL FOR CRITICAL GAP AND ITS DISTRIBUTION AT Estimating Equilibrium OF THE Unsignalized Intersections BASED ON Probabilities", in the 5th International Symposium on Highway Capacity and Quality of Service, 2006.
- [9] Hagring, "Estimation of critical gaps in two major streams", Transportation Research Part B, 2000.
- [10] Raff, J. MaH, "volume Warrant to urban stop signs, Eno Foundation for Highway Traffic Control", 1950.
- [11] N. Wu, "Estimating Distribution Function of Critical Gaps Unsignalized at Intersections Based on Equilibrium of Probabilities", 2012.
- [12] J., H., "Capacity of Urban Intersections Unsignalized" Series Strassenbau und Strassenverkehrstechnik, 1968.