Gap Acceptance Cycles for Modelling Roundabout Capacity and Performance

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Reference

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Abstract

Gap-acceptance theory has been used widely for estimation of capacity at unsignalised roundabouts and two-way sign-controlled intersections. This paper discusses the use of the gap-acceptance method beyond modelling capacity. The author has developed gap acceptance capacity and performance models by signal analogy, including the estimation of delay, queue length and stop rates for roundabouts and other unsignalised intersections. These models have been implemented in the SIDRA INTERSECTION software which has been in extensive use in traffic engineering practice. This paper will describe the basic method that uses gap acceptance cycles for modelling performance measures with a focus on the modelling of queue length at roundabouts. A simple single-lane roundabout example is given to explain important aspects of modelling the queue length.

1 Introduction

Gap-acceptance theory has been used widely for estimation of capacity at unsignalised intersections including roundabouts and sign-controlled intersections that operate by the give-way (yield) rule. There are numerous capacity models in the literature based on this approach [1]. This paper discusses the use of gap-acceptance theory beyond modelling capacity. The author has developed gap acceptance capacity and performance models for unsignalised intersections by signal analogy, including the estimation of delay, queue length and stop rates, which in turn helps with the estimation of fuel consumption and emissions for unsignalised intersections. These models have been implemented in the SIDRA INTERSECTION software which has been in extensive use in traffic engineering practice. Detailed information about these models is available in a large number of papers and reports [2].

This paper will describe the basic method that uses gap acceptance cycles with a focus on the modelling of queue length at roundabouts with some reference to capacity and delay modelling as well. The method is applicable to two-way sign (give-way and stop) control as well. A simple single-lane roundabout example is given to explain important aspects of modelling the queue length.

2 Modelling Roundabout Capacity by Gap Acceptance Cycles

The main purpose of this paper is to the discuss modelling of two types of queue length that can be observed at roundabouts, namely the *back of queue* and the *cycle-average queue*, demonstrate the significant difference between these two queue types, and emphasise the importance of using the back of queue rather than the cycle-average queue in single intersection and network modelling.

Figure 1 depicts the modelling of gap acceptance cycles and its application to the modelling of capacity, delay, queue length, and other performance measures at unsignalised intersections.

A gap acceptance cycle consists of a *blocked period* and an *unblocked period*, i.e. vehicles waiting due to lack of an acceptable gap and then departing when an acceptable gap occurs, similar to a signal cycle that consists of a red period and a green period.

The capacity determined by this method can be expressed in a simple general form as follows [1], [3,4]:

$$Q = s\,u \tag{1}$$

where Q = capacity (veh/h), u = the proportion of time when the vehicles can depart from the queue and s = saturation flow rate (veh/h).

Equation (1) is the same as the capacity equation for signalised intersections where u is the green time ratio. For gap-acceptance processes at roundabouts and sign-controlled intersections, u is the *unblocked time ratio*, i.e. the ratio of the *unblocked time* (when gaps in the opposing stream are acceptable) to the *gap acceptance cycle time* (sum of *blocked time* and *unblocked time*).

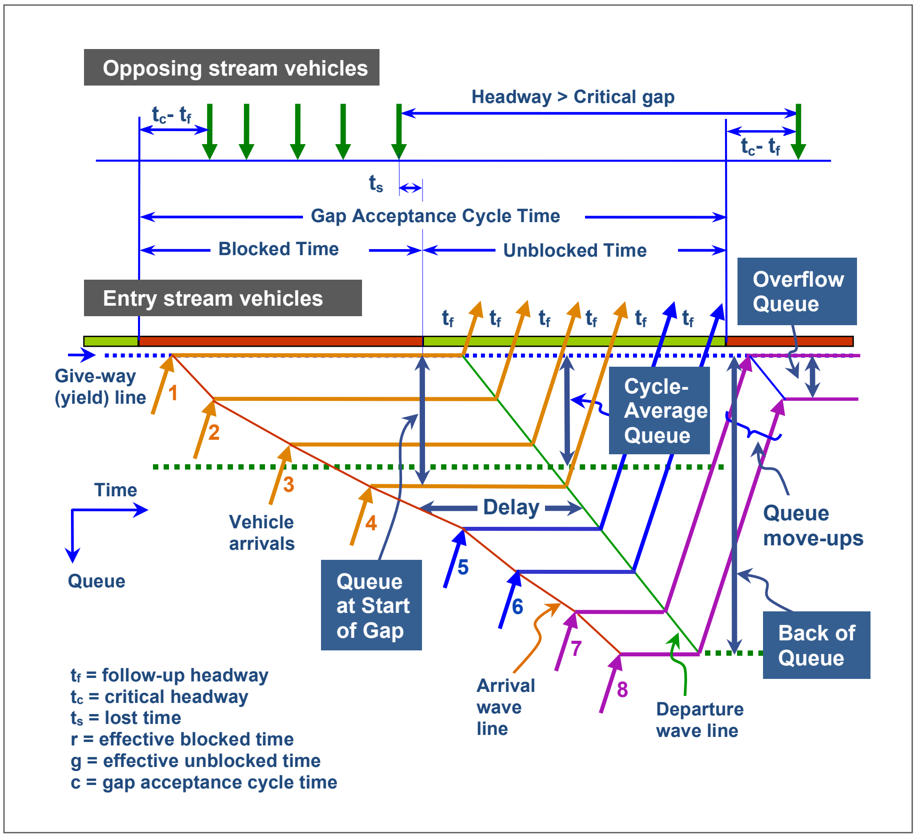


Figure 1 - An oversaturated gap acceptance cycle showing different queue length types

Saturation flow rate (s) corresponds to a *queue discharge headway* representing the minimum headway between vehicles that is achieved while they are departing from the queue:

$$h_s = 3600 / s \qquad (2)$$

where h_s = queue discharge (saturation) headway (seconds) and s = saturation flow rate (veh/h).

The gap-acceptance method uses the *follow-up headway* (t_f) as the queue discharge (saturation) headway, $t_f = h_s$. Therefore:

$$s = 3600 / t_f \qquad (3)$$

where s = saturation flow rate (veh/h) and t_f = follow-up headway as a queue discharge (saturation) headway (seconds).

As seen in *Figure 2*, the follow-up headway corresponds to a saturation flow rate which is the maximum gap-acceptance capacity that can be achieved when the opposing flow is close to zero.

Thus, the saturation flow rate for a gap-acceptance process is the maximum gap-acceptance capacity that can be achieved when the opposing flow is close to zero. In *Figure 2*, this is seen as the *y intercept* of the capacity curve. The capacity is reduced from this value with increased opposing flow rates due to the decreased values of *unblocked time ratio.*

In capacity models based on gap-acceptance modelling, while the follow-up headway determines the capacity value at low opposing flow rates directly, the critical gap parameter affects the *unblocked time ratio* (u) with lower values of u resulting from larger values of critical gap (hence lower capacity) for a given opposing flow rate (circulating flow rate for roundabouts). This is also depicted in *Figure 2*.

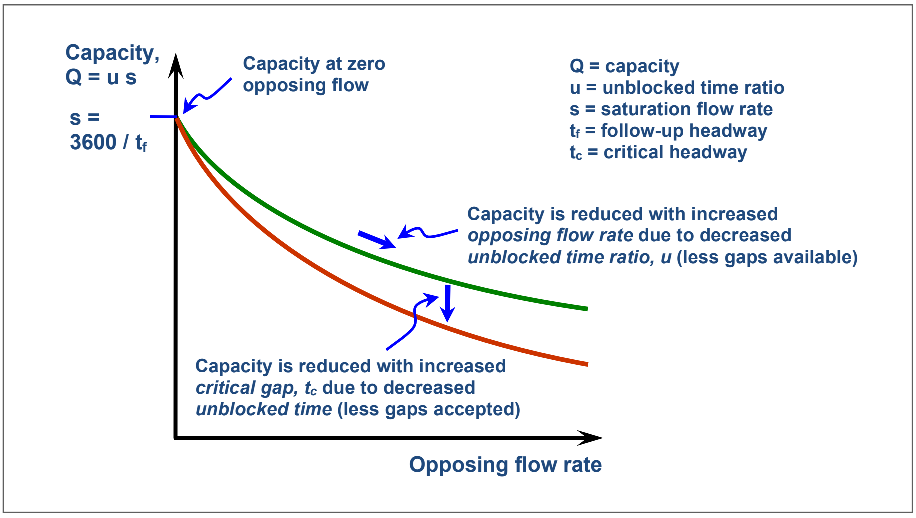


Figure 2 - The gap acceptance capacity

3 Back of Queue and Cycle Average Queue

The *back of queue* has been used commonly for modelling signalised intersection performance. On the other hand, the general literature and various guidelines as well as traffic theory text books present only the *cycle-average queue* based on traditional gap acceptance and queuing theory models as relevant to unsignalised intersections. This discrepancy continues to exist in the signalised and unsignalised intersection chapters of US Highway Capacity Manual Edition 6 [5].

Figure 1 shows an oversaturated gap acceptance cycle with various queue length types. These are the *back of queue, cycle-average queue, queue at start of gap* and *overflow queue*. *Figure 1* also indicates the relationship between *queue move-ups* (multiple stops) and the *overflow queue*.

In *Figure 1*, idealised vehicle trajectories are shown. Vehicles 1 to 4 arrive during a blocked interval (no acceptable gaps). Thus, *queue at start of gap* (at start of the unblocked interval) is 4 vehicles. Vehicles 5 to 8 arrive during the unblocked interval, slowing down to join the back of queue. Thus, the *back of queue* in this gap acceptance cycle is 8 vehicles. Vehicles 1 to 6 accept the available gap and depart from the queue (enter the roundabout circulating road). Vehicles 7 and 8 cannot accept the available gap and stop. Thus, they form an *overflow queue* (the gap acceptance cycle is oversaturated).

The *cycle-average queue* is the average value of the number of vehicles in the queue during each cycle. The cycle-average queue length incorporates all queue states including zero queues observed towards the end of the cycle in undersaturated cycles.

In *Figure 1*, delay experienced by each vehicle is represented by the horizontal line between the arrival and departure wave lines. Total delay is the area formed by these horizontal lines. A well-known delay survey method counts the number of vehicles in the queue in frequent intervals, e.g. every 5-10 seconds [5] to measure the total delay, and uses this for estimating the average delay. The corollary to this is the estimation of the *cycle-average queue* as average delay times the arrival flow rate. The delay used for this purpose is the *stopline delay*, i.e. the geometric delay component is not included.

The traditional queuing theory method of calculating the *cycle-average queue* using the average delay value is based on the assumption of steady-state conditions. This may not be reliable when the delay estimates are based on time-dependent queuing theory. In particular, this may result in a mismatch between delay and the *cycle-average queue* for oversaturated conditions if the delay estimate includes the delay experienced by vehicles beyond the analysis period, i.e. the delay experienced until the vehicles (arriving during the analysis period) depart from the queue. This may result in an estimate of the *cycle-average queue* that is larger than the *back of queue*.

The *back of queue* is maximum extent of the queue that occurs once each cycle, usually during the green time at signalised intersections or unblocked time in gap acceptance processes. Zero queue states are not relevant to the back of queue.

The *back of queue* is a more useful performance measure since it is relevant to the design of appropriate queuing space, e.g. for short lane design to avoid queue spillback into adjacent lanes, for phasing design to avoid blockage of upstream intersection lanes in networks situations, and for signal coordination offset design to prevent interruption of platoons by downstream queues. The *back of queue* is used for the prediction of such statistics as the saturated portion of the green period and for modelling short lane capacities.

An interesting aspect of the relation between delay and the *back of queue* is that these performance measures are not necessarily consistent in terms of magnitude. This is reflected in the comparison of the *cycle-average queue* and the *back of queue*. *Low delay* associated with a *long back of queue* as seen in *Figure 3* is a result of a high arrival flow rate, large green time ratio (relatively short red) at signalised intersections or large *unblocked time ratio* (relatively short blocked time) in gap acceptance processes.

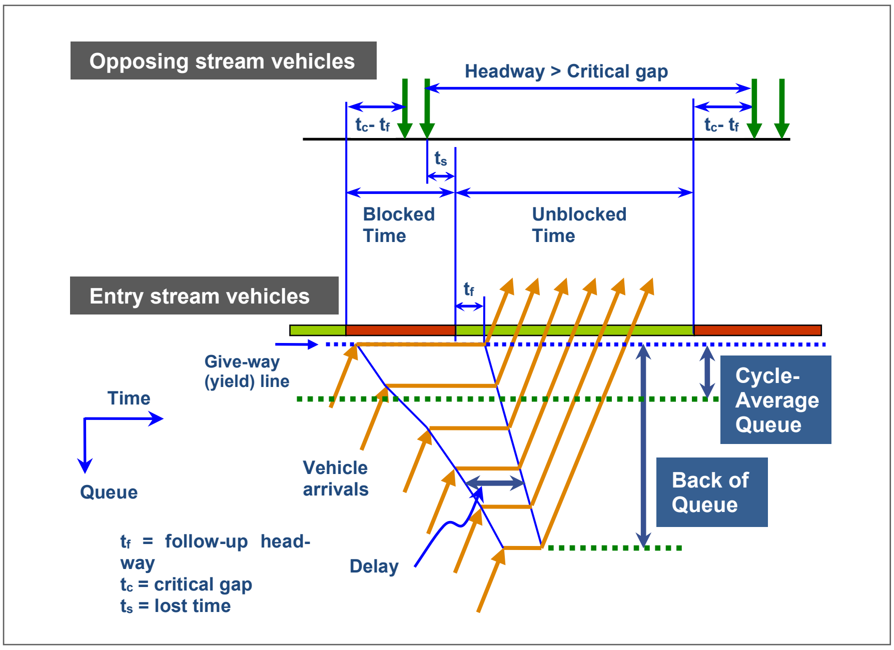


Figure 3 - The case of long back of queue associated with a low average delay at roundabouts: this case occurs under low circulating flow and high entry flow conditions

The case shown in *Figure 3* corresponds to high capacity and low degree of saturation conditions. For roundabouts and two-way sign control, this case occurs under low circulating / opposing flow and high entry demand flow conditions. In such cases, delay consists of acceleration and deceleration (slow down) delays only, and very small or zero idling (stopped) delays occur. While the large back of queue represents a moving queue formed by a heavy arrival flow, there may be a large proportion of vehicles that are undelayed, and therefore the *cycle-average queue* is usually small in this case.

This case helps to understand why the *back of queue* rather than the *cycle-average queue* should be used for modelling short lanes in intersection modelling and blockage of upstream intersection lanes (queue spillback) in network modelling. This case also has an important role in unbalanced roundabout conditions since the majority of departures with follow-up headways at this entry result in a uniform headway distribution at the next (downstream) entry which leads to low capacity for that approach.

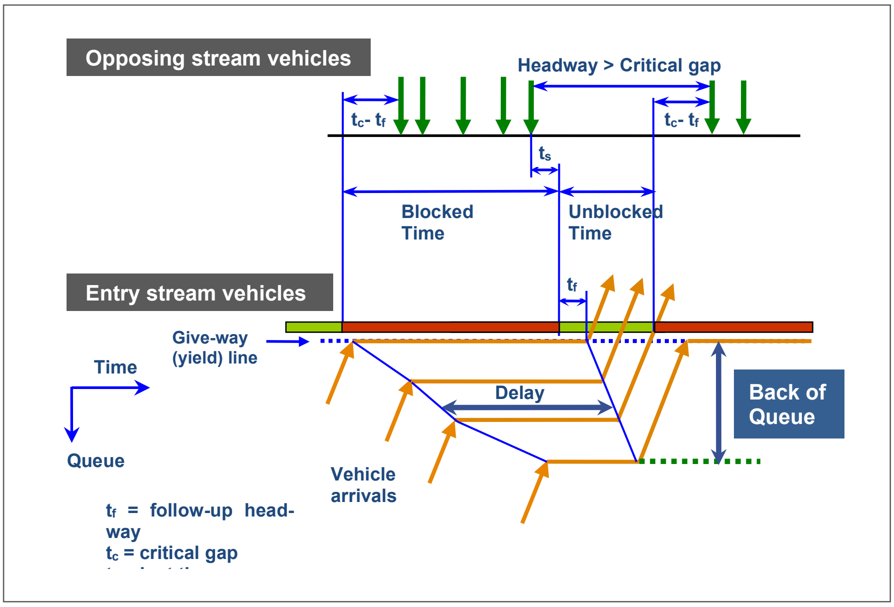


Figure 4 - The case of short back of queue associated with a large average delay at roundabouts: this occurs under high circulating flow and low entry flow conditions

On the other hand, the case of *short back of queue* associated with a *large average delay* as seen in *Figure 4* is a result of a low arrival flow rate and a small green time ratio (relatively long red) at signalised intersections or small *unblocked time ratio* (relatively long blocked time) in gap acceptance processes. This case corresponds to low capacity and high degree of saturation conditions. For roundabouts and two-way sign control, this case occurs under high circulating / opposing flow and low entry flow conditions.

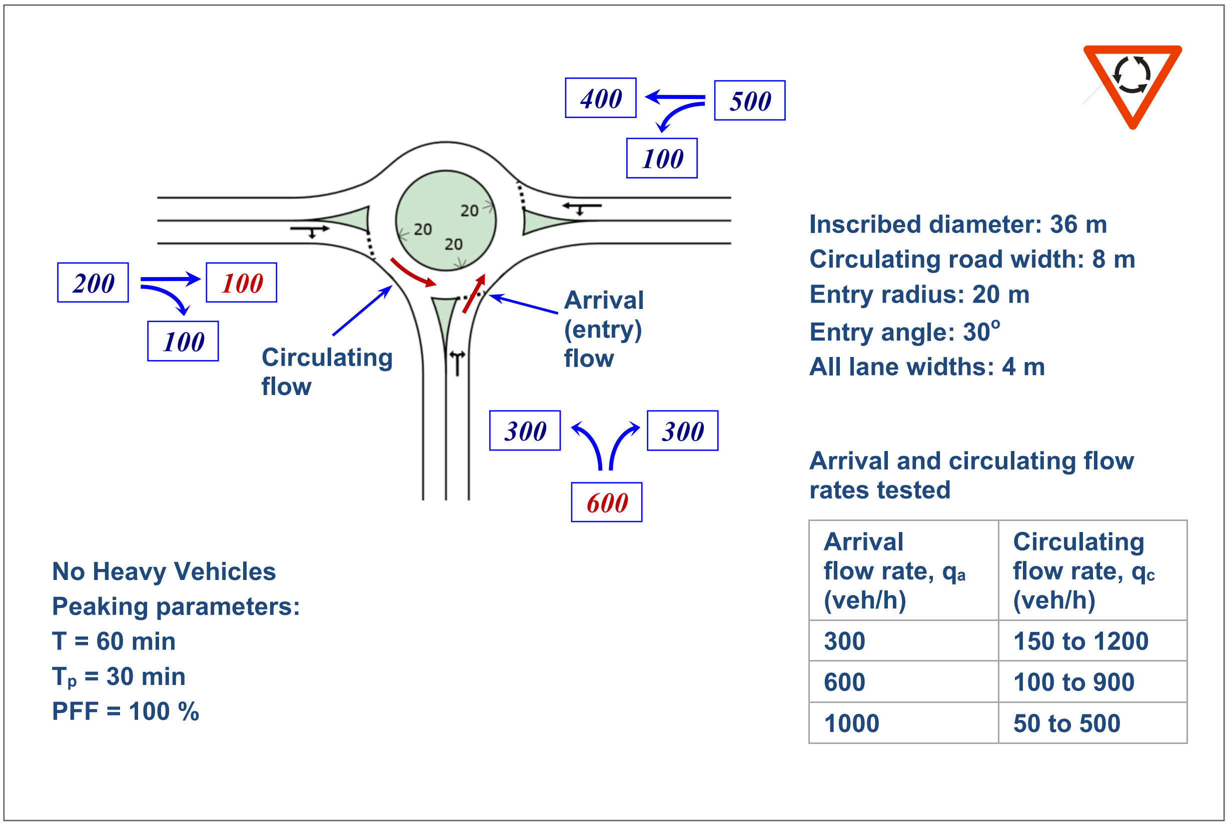
4 A Simple Roundabout Example

The single-lane T-intersection roundabout example shown in *Figure 5* is used to demonstrate the relationship between *back of queue* and *cycle-average queue* and present the related aspects of modelling using gap acceptance cycles for varying entry and circulating flow rates. The results are given for the South approach lane. The circulating flow rate for this approach is formed by the through movement from the West approach.

The volumes are set with the constraint that the sum of the entry flow and the circulating flow does not exceed approximately 1500 veh/h. This gives a reasonable range of degrees of saturation for all cases used.

The example is presented using the SIDRA INTERSECTION standard software setup for driving on the right-hand side of the road. To keep the discussion at a basic level, only the average queue length results are given and the percentile queue lengths are not discussed. Using a single-lane roundabout example, complications related to multi-lane roundabouts, e.g. calculation of lane flow rates, effect of unequal circulating flow rates, and so on are excluded.

The analysis results are presented in *Figures 6 to 10*. *Figure 6* shows the entry capacity as a function of the circulating flow rate for arrival flow rates of q_a = 300, 600 and 1000 veh/h. It is seen that capacities for the three arrival flow rates differ for low circulating flow rates. This is due to the effect of the ratio of entry flow rate to the circulating flow rate (higher values of this ratio give higher capacities in the model). This is an important feature in modelling unbalanced flow conditions.



Arrival flow rate, q_a (veh/h)	Circulating flow rate, q_c (veh/h)
300	150 to 1200
600	100 to 900
1000	50 to 500

Figure 5 - A single-lane roundabout example to demonstrate the relationship between back of queue and cycle-average queue and the related aspects of modelling

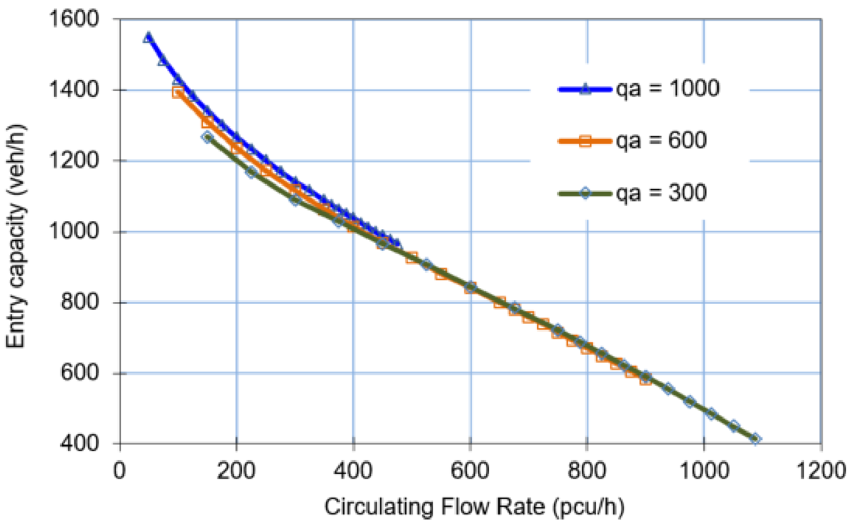


Figure 6 - Entry capacity as a function of the circulating flow rate for arrival flow rates of qa = 300, 600 and 1000 veh/h

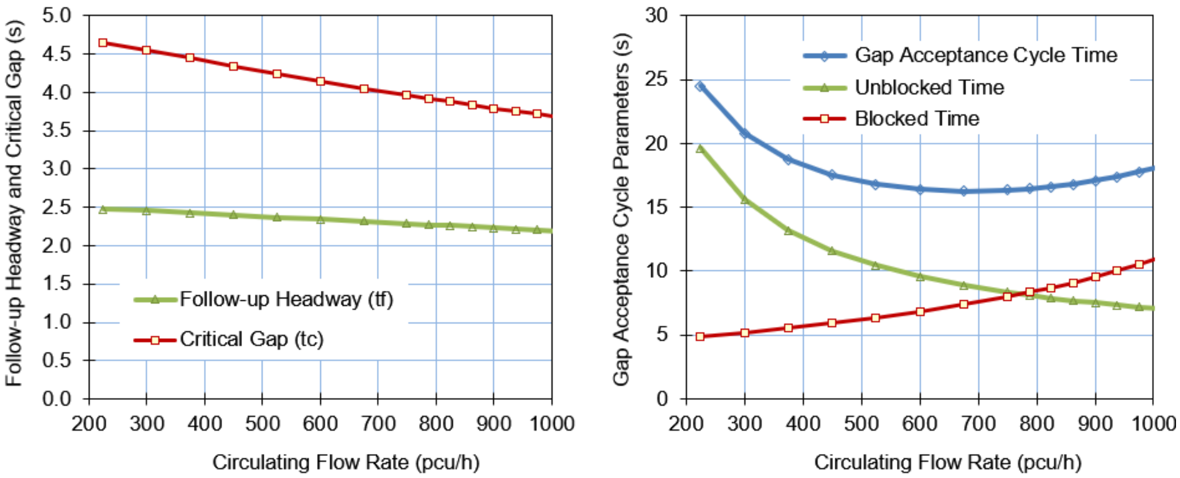


Figure 7 - Gap acceptance parameters, the blocked and unblocked times and the gap acceptance cycle time as a function of the circulating flow rate for the case of arrival flow rate qa = 300 veh/h

Figure 7 shows the gap acceptance parameters (critical gap and follow-up headway), the blocked and unblocked times and the gap acceptance cycle time as a function of the circulating flow rate for the case of arrival flow rate q_a = 300 veh/h. It is seen that the critical gap and follow-up headway values are reduced with increased circulating flow rates. This is based on the research at Australian roundabouts [6]. The slight increase in values of these parameters for very low circulating flow rates is related to the model used for the effect of the ratio of the entry flow rate to the circulating flow rate (Medium level of this effect was specified for this example).

Figure 8 shows the *average back of queue* and *cycle-average queue* as a function of the degree of saturation for arrival flow rates of q_a = 300 and 1000 veh/h. The correlation of the *average back of queue* and *cycle-average queue* for arrival flow rates of q_a = 300, 600 and 1000 veh/h is given in *Figure 9*. The linear trendline for these data points gives the relationship $N_b = 1.22\ N_c + 1.82$ ($R^2 = 0.94$) where N_b = average back of queue and N_c = cycle average queue.

It is seen from *Figures 8 and 9* that the difference between the values of *average back of queue* and *cycle-average queue* increase with increasing arrival flow rate. This is related to the case depicted in *Figure 3*.

Average back of queue and stopline delay values used in calculating the cycle-average queue values are given *Figure 10* as a function of the circulating flow rate for arrival flow rates of q_a = 300, 600 and 1000 veh/h.

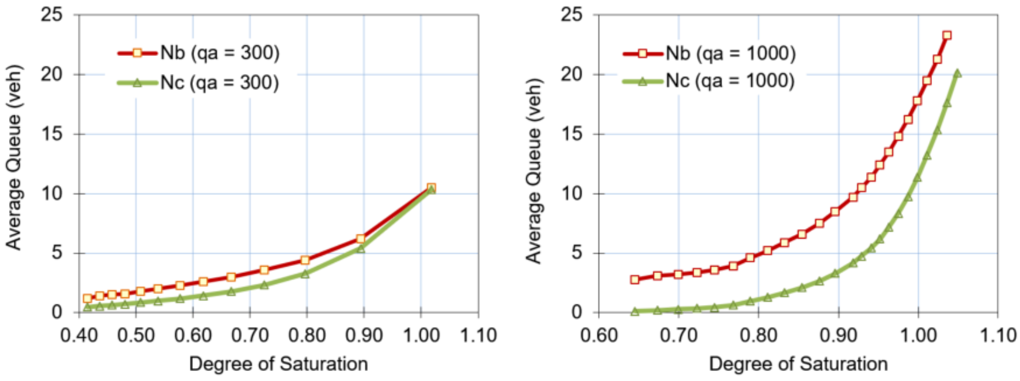


Figure 8 - Average back of queue (Nb) and cycle average queue (Nc) as a function of the degree of saturation for arrival flow rates of qa = 300, 600 and 1000 veh/h

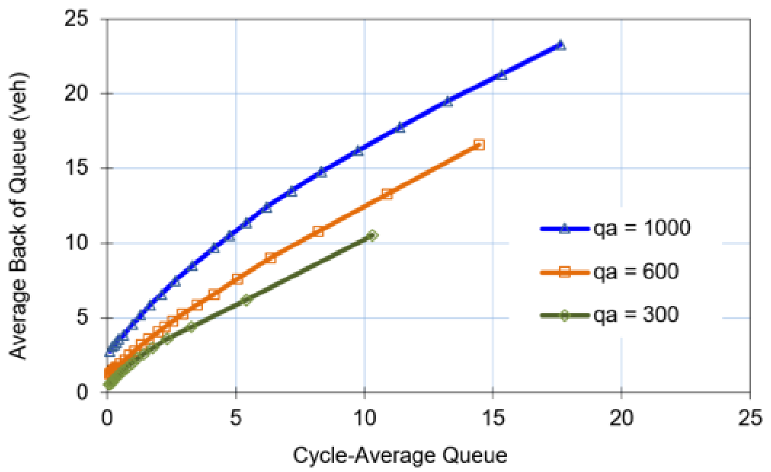


Figure 9 - Comparison of the back of queue and cycle-average queue

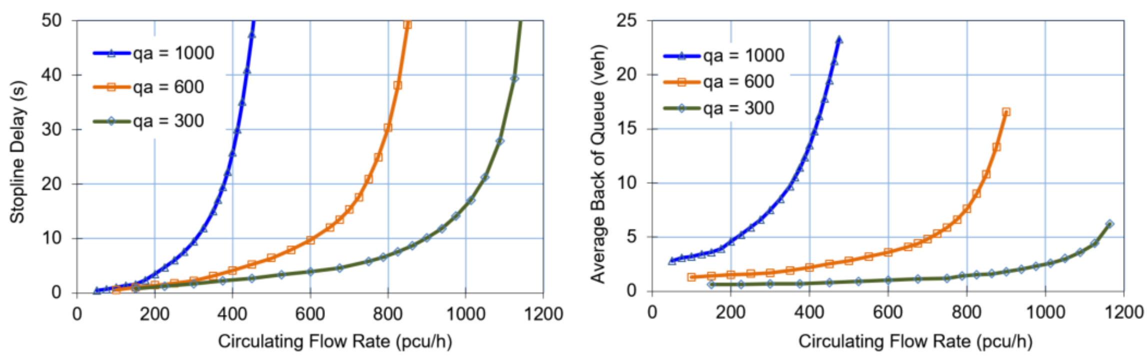


Figure 10 - Stopline delay and average back of queue as a function of the circulating flow rate for arrival flow rates of qa = 300, 600 and 1000 veh/h

5 Concluding Remarks

Further research is recommended to examine the results given in this paper by means of microsimulation analysis and real-life surveys. The results given here are for a simple case of single-lane roundabout used for the purpose of this paper. The research should consider complications that arise in real-life situations, e.g. the effect of short lanes, variations in various geometric and driver behavior parameters, slip lanes, effect of upstream signals, effect of pedestrians, and so on.

6 References

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