Research on Capacity Model for Large Signalized Roundabouts

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Abstract

In order to calculate the capacity of signalized roundabout, this paper establishes the corresponding calculation model. Based on gap acceptance theory, the model defines that the maximum number of vehicles on the approach that can be imported into the island is the roundabout capacity. At the same time, some related parameters (such as cycle, green time) are considered to impact on the model. At first, the paper analyses the difference of traffic flow characteristics between signalized roundabout and non-signalized roundabout, and according to the vehicles conflict traits, the movement process is divided into two stages. Then the new capacity model of signalized roundabout is put forward. Moreover analysis of the influence on capacity caused by different follow-up time, critical gap and green time are made, too. Finally, taking Changchun’s signalized roundabout as an example, using the actual signal timing scheme and the data of the flow to verify the new capacity model. It turns out that the results match the actual situation properly. In summary, a method of calculating the capacity of signalized roundabout is put forward, and proved to be practical in this paper.

Keywords: signalized roundabout; gap acceptance; capacity model

1. Introduction

At the traditional roundabout, because of its strong self-organization characteristics, conflicts and delay of vehicles would be great decreased, and the safety and efficiency of vehicles are improved. Roundabout capacity, as an important index [1], is a hot spot in recent research at home and aboard.
Modern roundabout is a kind of non-signalized intersection. According to priority rules, vehicles enter the roundabout [2]. Capacity models of roundabouts are established mostly based on gap-acceptance theory, which has concerned the dynamic characteristics and priority rules. Critical gap and time headway [3] are its key parameters.


According to static characteristic of roundabout, Wardrop [12] presented ablending theoretical model, considered the capacity of weaving sections as the capacity of the roundabouts. In addition, some scholars used the means of linear regression and simulation method to establish roundabout capacity model. Britain, Germany and some other countries proposed to establish the regression capacity model between entrance capacity and the ring road traffic flow; Polus and Shmueli [13] took the diameter of roundabout into account in regression model, Al-Masaeid analysis the impacts of the ring road traffic volume, lane width, and diameter of roundabout to capacity and established capacity regression model. Bared used simulation software VISSIM and SIDRA to analysis capacities of single lane and double lane roundabout. Qiaojun Xiang [14] based on the gap acceptance theory established a capacity model under low traffic flow suitable for low canalization level roundabouts.

With the increasing of vehicles, traditional non-signalized control roundabout is difficult to ensure vehicle safety and efficiency. Therefore, when the traffic flow is heavy, signal control is necessary for a roundabout, which will improve the efficiency and safety of intersection by setting signal [15].

Currently, the mostly researches on roundabout capacity are based on non-signalized studies, the study on capacity of signalized roundabout is very few. Fengyuan Jia [16] and other scholars analysed the capacity of urban signalized roundabouts, concluded that geometrical conditions had impact on capacity under different control methods. However, due to signal control, traffic operation mode of roundabout has been changed. For example, during the initial green light time, queuing vehicles depart the stop line in saturation flow; during later green time, vehicles began to seek the gap acceptance to enter ring lanes. Except for the approach controlled by green light, the vehicles of other approaches won’t enter the roundabout, so they do not affected by other vehicles. And simply adding lane capacity is no longer applicable. This paper mainly studies the capacity of signalized roundabout by means of gap acceptance theory, builds the capacity model which is associated with the parameters such as the signal cycle and green time, etc. An example analysis of actual roundabout is also made.

1. Capacity model of signalized roundabout

2.1. Analysis on traffic process

In view of the conventional single-lane, symmetrical cross roundabouts, and signal lamp are set up in the four branches. Vehicles of opposite direction are released at the same time. Entering vehicles of this direction and opposite direction get the right of way synchronously. After taking signal control, there are some differences on operating characteristics compared with no-signal control roundabouts.

After setting signal control, vehicles at entrance are controlled. During the red time, vehicles cannot enter into the roundabout, and wait at the stop line in queue. Therefore, during the early green time, traffic is released into island with saturation flow rate, while vehicles of no-signal control roundabout only need to wait for the appropriate critical gap to enter all by their own. It can be said at this time, the entrance situation depends on vehicles arrival situation which is controlled by the signal timing program of upstream intersection. In the latter green time, because the vehicles have already run on the ring road, the entering vehicles need to wait for the appropriate gap to enter the roundabout.

During the green time, only this direction and opposite direction vehicles can enter into the island, vehicles of the other two entrances cannot enter, so traffic flow from the other two directions cannot impact the traffic flow on the
ring road, interweaving of vehicle will be reduced. As for non-signalized roundabouts, there are always this situation that vehicles from four directions enter the island, the car following situation will be changed.

2.2. Modeling principle

In this paper, based on the gap acceptance theory, considering the impact of changes to the capacity of the traffic operation characteristics and traffic conflict after setting the signal control, capacity model of signalized roundabout is put forward. In the model, the relationship among the signal cycle, green time, geometry and capacity is reflected in quantitative formula.

Capacity model based on gap acceptance principles of the theory [17] is as follows:

\[
C = q \int_{0}^{\infty} f(t) g(t) dt
\]  

(1)

Where, \(C\) is the capacity of minor stream; \(f(t)\) is distribution intensity of gaps \(t\) in the main stream; and \(g(t)\) is the function of the number of vehicles which can depart during \(t\); \(q\) is traffic intensity in the major stream (veh/s), HCM2000 requires to convert the intersection turning movements into circulating flows, namely with respect to this direction, the circulating flows is considered as the sum of several flows effected the entrance behavior. This model reflects the island's intertwined interludes feature, this paper based on the principle of the formula.

After signal control, the flows of ring road are still considered as the main flow, and there is no overtaking lane. Assuming that the distribution of headway is M3 distribution, namely

\[
f(t) = a \lambda e^{-\lambda(t-t_0)}, t > t_m
\]  

(2)

\[
\lambda = \frac{\alpha q}{1-t_m q}
\]  

(3)

Where, \(\lambda\) is the decay constant; \(\alpha\) is proportion of free vehicles; \(t_m\) is the main road vehicles minimum headway (s).

The flows on approaches are minor flows, the import vehicles queuing obtain the right of entering into the island continuously, \(g(t)\) is the number of vehicles entering into roundabout during time \(t\), namely

\[
g(t) = \begin{cases} 
\frac{t-t_0}{t_f}, & t > t_0 \\
0, & t < t_0 
\end{cases}
\]  

(4)

\[
t_0 = t_f - \frac{t_f}{2}
\]  

(5)

Where, \(t_0\) is the zero gap (s); \(t_f\) is the headway of approaches (s); \(t_c\) is a critical gap (s).

\[
g'(t) = \begin{cases} 
\frac{1}{t_f}, & t > t_0 \\
0, & t < t_0 
\end{cases}
\]  

(6)

2.3. Analysis of the operational stages and capacity
2.3.1 Early green time

During the early green time, vehicles of last phase have released completely or only few vehicles are running. And vehicles of opposite direction will travel some time to reach conflict point. As shown in Fig.1. Within the initial green time, left-turn vehicles from north approach haven’t reached conflict point of south approach, so the smaller affection is made to the entering vehicles. The queuing vehicles are free to enter the island during this period, the release rate of traffic flow is saturation flow rate.

As shown in Fig.1, the radius of island is R, the ring road width is w, stop line distance to the conflict point is d, vehicle start lost time is $t_d$, saturated headway of minor stream $t_h$, driving speed is $v_o$. The time of vehicles free to enter the island during early green time, which is the time vehicles of north approach driving to the conflict point of south approach, $t_i$.

According to the Geometric characteristics of the roundabout,

$$t_i = \frac{d + \pi(R + w/2)}{v_o}$$

(7)

Within $t_i$, the number of south import of vehicles entering is $n_i$,

$$n_i = \frac{(t_i - t_d)}{t_h}$$

(8)

2.3.2 Later green time

Within the later green time, the right-turn and straight vehicles of opposite direction won’t make a conflict to these direction vehicles entering the island, but the left-turn vehicles of opposite direction need to travel to the conflict point to exit the island. Meantime, entering vehicles of this direction need to pass through the left-turn vehicles. As shown in the Fig.2, after the green light for some time, left-turn vehicles from north import travel to the conflict point of south, making conflict to the entering vehicles of south approach, entering flow needs insert into the island.

After $t_i$ time, vehicles of north import have been traveling to the conflict point, the vehicles begin to make confliction. It can be divided into two types, namely, during the green time, due to higher imports of vehicles queuing, there are always vehicles on the approach entering, leading to the ring and the entering vehicle existing
confliction, this phenomenon is called the whole way conflict; in addition, due to the of two-way flow may exist asymmetry, it may cause the flow has not yet been completed released at this direction while the flow of opposite direction has already been released completely. Under this condition, entering flow and the circular flow conflict for some time, then the vehicle can enter the island freely, this phenomenon is defined as non-full conflict.

Fig. 2. The second operation of roundabouts.

Assuming the signal cycle is T, when the green time is g, conflict time within a cycle is \( t_g \), and \( t_g = g - t_i \). In both cases are calculated by the number of vehicles per hour.

For the whole way conflict situation, we calculate the capacity this way:

Suppose there is always a queue of vehicles entering from both directions around the roundabout, the number of vehicles entering the island at this time was better to represent the actual traffic capacity in larger traffic flow roundabouts.

Based on the conventional model of roundabout capacity, we assume that there will be a lower and upper limit of integration for vehicles driving into the roundabout, then we can get the capacity model of signalized roundabout during one cycle conflict phase, \( n_z \) (pcu / s):

\[
n_z = q\int_t^l f(t)g(t)dt
\]  
(9)

After substitution Equation (2) and Equation (4) the distribution is:

\[
n_z = q\int_t^l \alpha \lambda e^{-\lambda(t-t_i)} \frac{T-t_i}{t_f} dt
\]

\[
= \frac{q\alpha}{t_f} \int_t^l \alpha \lambda e^{-\lambda(t-t_i)} dt - \frac{q\alpha}{t_f} \int_t^l \alpha \lambda e^{-\lambda(t-t_i)} t_i dt
\]

\[
= \frac{q\alpha}{t_f} \left[ -e^{-\lambda(t-t_i)} \left| t_f - \left( \frac{1}{\lambda} e^{-\lambda(t-t_i)} \right) t_i + e^{-\lambda(t-t_i)} t_i \right| t_i \right]
\]  
(10)

At this point, roundabout capacity \( C \) (pcu / h) includes two parts, the formula is as follows:
The capacity model considered the influence of the island's geometry and signal control timing plans on signalized roundabout’s capability, such as the geometry parameters and green time as the main parameters.

For the non-full conflict situation, we calculate the capacity this way:

During the non-full conflict phase, the vehicles of this direction importing into the island can be divided into two types, one is a conflict with traffic on the stage a, the other is for the completion of the flow release in the late green time, vehicles can be free to enter the island again called phase b.

First, calculate the entry capacity in a phase $n_{con}$ (pcu / s):

$$n_{con} = q \int_{t_0}^{t_0 + \alpha \lambda} f(t) g(t) dt = q \int_{t_0}^{t_0 + \alpha \lambda} \alpha \lambda e^{-\lambda(t-t_0)} \frac{t-t_0}{t_f} dt$$

$$= \frac{q \alpha}{t_f} \left[ \alpha \lambda e^{-\lambda(t-t_0)} \frac{t-t_0}{t_f} \right]_{t_0}^{t_0 + \alpha \lambda}$$

Then, in b phase, calculated the number of vehicles entering the roundabout during one signal cycle. Without conflicts, vehicles with saturated headway release into the island, non-conflict time $t_{con} = g - t_1 - t_{con}$, $n_{non} = t_{non} / t_h$.

Finally, in the case of non-full conflict, capacity of the roundabouts is:

$$C = 3600 \left( \frac{n_1 + n_2}{T} \right)$$

$$= 3600 \left[ \frac{(t_1 - t_0)}{T} + \frac{q \alpha}{t_f} \left[ -e^{-\lambda(t-t_0)} \frac{t-t_0}{t_f} - \frac{1}{\lambda} e^{-\lambda(t-t_0)} \frac{t-t_0}{t_f} + e^{-\lambda(t-t_0)} t_0 \frac{1}{t_f} \right] \right]$$

$$= 3600 \left[ \frac{d + \pi(R + w/2)}{v_0 t_h T} + \frac{q \alpha}{t_f} \left[ -e^{-\lambda(t-t_0)} \frac{t-t_0}{t_f} - \frac{1}{\lambda} e^{-\lambda(t-t_0)} \frac{t-t_0}{t_f} + e^{-\lambda(t-t_0)} t_0 \frac{1}{t_f} \right] \right]$$

3. The example analysis

Taking Xi’an Square in Changchun as an example, the square is a symmetrical cross roundabout, and opposite two-way release at the same time. Signal cycle: $T=90s$, green time: $g=53s$, radius of island $R=73m$, ring road width $w = 16m$, distance from stop line to the conflict point $d = 48m$, saturated headway $h_t = 2.3s$, vehicle starting lost time $v_t = 2.3s$, free speed is 11.8m / s, and setting these parameters into Equation (7):

The time of vehicles entering the roundabout freely is $t_i = 25.6s$, at this time the number of vehicles entering is $n_i = 11$. 
As for late green time, this paper only considers the case of whole way conflict. Because when the whole way conflict condition occurs, it’s generally intersections with more vehicles, this situation can represent the peak period operation of the roundabout properly.

Letting the traffic circulation flow change within 100pcu/h ~ 1800pcu/h range, setting them into Equation (10) to calculate the relationship between the entry capacity with the circulating flow during full-conflict phase, as shown in Fig.3:

![Fig. 3. Entry capacity of full-conflict phase.](image)

Setting the calculation results into Equation (11), calculated capacity of roundabout is shown in Fig.4:

![Fig. 4. Entry capacity of signalized roundabout.](image)

In order to analysis the effect of different parameters on signalized roundabout, this paper analysis the effect of different critical gaps, headway and green time. The maximum and minimum ranges of critical gap and follow-up time is given in reference of HCM2000.

<table>
<thead>
<tr>
<th>Critical Gap (s)</th>
<th>Follow-up Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper bound</td>
<td>4.1</td>
</tr>
<tr>
<td>Lower bound</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Table 1. Critical gap and follow-up times for roundabouts in HCM2000.
Setting different values of parameters into the model to obtain the relationship between entry capacity and circulating flow are shown in Fig. 5, Fig. 6 and Fig. 7 below.

As can be seen, the range of critical gaps is small, and therefore less impact is made on capacity. But on the whole, the larger the critical gap selected, the smaller the capacity is. That is the larger critical gap vehicles need to be able to import the roundabout, the probability of its appearance is smaller. Therefore, the capacity curve tends to decline.

![Fig. 5. Capacity curves under different critical gaps.](image1)

The Fig. 6 shows that the follow-up time change in a small range, capacity will not change a lot. On the whole, the larger the follow-up time become, the smaller the entry capacity is.

As shown in the Fig. 7, the effect becomes relatively obvious when the growth of green time is 10s. The longer green time is, the greater the corresponding capacity is. But with the increase of traffic flow, the degree of influence began to decrease, that is to say, once flow exceeded a certain range, pure extension of green time can’t increase the capacity of roundabout intersection. At this time, other control measures is needed to take to ensure roundabout operates smoothly. For instance, by means of taking control of the arrival vehicles from upper entrance. Traffic managers can consider the effect of signal control appropriately by the changing the length of green time.

![Fig. 6. Capacity curves under different follow-up time.](image2)
4. Conclusion

This paper analyses the operation rules of signalized roundabout and gives a definition for the whole way conflict and non-full conflict during the whole green time, and calculates the entry capacity of above two situations respectively. The key parameters of the capacity model includes traffic flow, critical gap, follow-up time, length of green time and cycle time. In addition, it makes a case analysis according to the actual situation, and also analysis the influence of main parameters on the capacity, of which the result conform to be reality and can provide a reference for traffic designers.

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References


