ANALYTICAL ANALYSIS OF PEDESTRIAN EFFECTS ON ROUNDABOUT EXIT CAPACITY

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ABSTRACT

The availability of pedestrian gaps and the queuing effects of pedestrian crossings have implications for roundabout design, particularly when considering the operations of roundabout exits and the potential for vehicle queues to spill back onto the circulatory roadway. In most jurisdictions, vehicles are required to yield to pedestrians. In practice, pedestrians often choose their crossings to coincide with gaps in the traffic stream, i.e., yielding to vehicles. This paper presents methods to analyze both conditions. In the case where pedestrians yield to vehicles, the minor-street movement capacity equations from the *Highway Capacity Manual*'s unsignalized intersection methodology can be adapted to determine the number of gaps in a traffic stream sufficient for a pedestrian to cross. In the case where vehicles yield to pedestrians, the effect of a vehicular queue extending into the roundabout while waiting for pedestrians to cross can be estimated, and the extent to which this queue will adversely affect capacity can be approximated. The paper concludes by discussing the implications of the interactions between pedestrians and vehicles on the design of the roundabout.

1. INTRODUCTION

This paper presents an analytical model for quantifying the effects of reductions in exit capacity due to an event that blocks the exit downstream of the circulating roadway. The blockage could be caused by pedestrian activity, transit bus blockage, or other causes; this paper focuses on the specific situation of a pedestrian crossing located near the roundabout. The blockage will result in a queue of vehicles that could reach the circulating roadway and degrade the performance of the entire roundabout. The remainder of this paper presents a methodology for predicting the queue duration and discusses implications for design of roundabouts.

The methodologies presented in this paper are intended to provide basic analytical tools that can be used to determine the interaction effects between vehicles and pedestrians. These tools have been developed to specifically assist in addressing the following questions:

- Under what conditions are gaps in vehicular traffic sufficient for pedestrians to cross without requiring any vehicular yielding, either voluntarily or via enforcement by a traffic control device?

- Assuming some kind of vehicular yielding, what queuing effect can be expected on the exiting leg of a roundabout due to a blocking event (e.g., pedestrian crossing, traffic control device, parking maneuver) across the exiting leg?

- What reduction in entry capacity might be expected for a given entry due to a downstream blocking event?

These tools are based on well-established traffic flow theoretical principles and are unique only in their specific application to roundabouts. They are also general and thus might be applicable for other uses besides those described herein.

2. LITERATURE REVIEW

The effect of pedestrians at roundabouts is of great interest to practitioners. Draft Guidelines for Accessible Public Rights-of-Way (U. S. Access Board, 2002) have suggested the need for some type of pedestrian signalization for pedestrian crossings at roundabouts to address the usability of pedestrian crossings at roundabouts for pedestrians with visual impairments. This has met some resistance from practitioners who have expressed concern regarding the effect of such devices on traffic flow, in addition to cost implications and equity with other unsignalized intersections. Part of this concern is related to its apparent universality to all roundabouts, regardless of vehicle or pedestrian volume. Recent comparisons of the perceived usability of gaps by pedestrians with and without visual impairments suggests that while some roundabouts under certain traffic levels create difficulties for pedestrians with visual impairments, others could still be considered usable. Therefore, there is a clear need to provide analysis tools to the practitioner to aid in deciding the degree to which additional pedestrian treatments are necessary and what effect those treatments may have on the overall operation of the roundabout.

The available literature assessing the interaction effects between pedestrians and vehicles is limited, thus contributing to the unease of the practitioner. FHWA's *Roundabouts: An Informational Guide* (Robinson, et al., 2000) presents entry capacity adjustment factors based on German research (Brilon, et al., 1993). These adjustment factors reduce the vehicular capacity of an entry based on the volume of pedestrians and volume of conflicting vehicular traffic across the entry. As vehicular volumes decrease, the effect of conflicting pedestrians increase, as the pedestrians create additional impedance for entering traffic that would not otherwise be realized when conflicting vehicular traffic is low. In any case, additional impedance of entering vehicles by pedestrians can cause reduced entry capacity and increased vehicular queuing on the subject approach, but this impedance does not adversely affect the operation of the other entries to the roundabout. To this end, the effect of pedestrians on a roundabout entry is not typically a factor that could eliminate a roundabout from consideration as an intersection type and traffic control treatment for a given location.

The effect of pedestrians on exiting traffic has a much more pronounced effect on the operation of a roundabout as a whole. This effect is more difficult to analyze, with few analytical tools available. FHWA's *Roundabouts: An Informational Guide* (Robinson, et al., 2000) suggests an exit capacity of 1,400 vehicles per hour per lane under ideal conditions, with a recommended exit capacity of 1,200 vehicles per hour per lane in normal urban conditions (i.e. with pedestrians and bicycles present). This exit capacity is most properly used to determine the required number of exit lanes from multi-lane roundabouts and does not consider the effects of near or at capacity exits on the overall capacity of the roundabout. These guidelines, however, are insensitive to pedestrian volumes and thus have limited value in helping a practitioner determine what effect a particular crosswalk may have on the operation of a roundabout as a whole.

Simulation is a tool that can be used to address these interaction effects. Models such as VISSIM have been used to explicitly model pedestrians and vehicles at roundabouts to determine the interaction effects (Hughes, et al., 2003). Simulation can address a wide variety of cases, including many that are too complex to be analyzed analytically. While such models are valuable and appropriate for assessing how various forms of control interact, there is a role that simple analytical models can play in estimating the first-order effects of such interactions. The methodologies in this paper propose a group of these analytical models.

3. METHODOLOGY

Two methodologies are presented here: the analysis of the availability of pedestrian gaps, and the analysis of the effect on vehicles exiting a roundabout of a blocking event, such as a pedestrian crossing.

3.1 Availability of Pedestrian Gaps

A basic formula for determining the duration of an adequate gap for a single pedestrian can be given in Equation 1. This value can be used to approximate the effective blocking time, T_B, by assuming that the pedestrian perception-reaction time is needed to ascertain whether a driver is going to yield.

$$T_B = G = R + \frac{w}{s} \tag{1}$$

where:
- T_B = Blocking time (s)
- G = Adequate gap time (s)
- R = Pedestrian perception-reaction time (s)
- w = Width of roadway to be crossed (m or ft)
- s = Assumed pedestrian walking speed (m/s or ft/s)

Commonly, values of walking speed, *s*, of 1.2 m/s (4.0 ft/s) and pedestrian perception-reaction time, *R*, of 3.0 s have been used in practice (ITE, 2000). A recent summary of research on pedestrian walking speeds suggests that lower values for walking speed of 1.1 m/s (3.5 ft/s) may be more appropriate to capture the 15^{th}-percentile speed for the general population (LaPlante and Kaesar, 2004); this value may need to be lower still (e.g., 0.9 m/s [3.0 ft/s]) if the pedestrian population contains a high proportion of elderly pedestrians or pedestrians with mobility impairments. In addition, research by Guth et al. suggests that blind pedestrians need additional time to assess a gap, with mean additional times on the order of 3 seconds (Guth, et al., 2002). To account for this, the value of *R* could be increased to a value of 6.0 s.

A simple example of this is as follows: Using this formula with an assumed R = 6.0 s, w = 14 ft, and s = 3.5 ft/s yields G = 10 s. Therefore, a typical required gap needed for a pedestrian to assess and cross a single-lane roundabout exit is approximately 10 s.

The assessment of the extent to which a gap G is available in the vehicular stream can be estimated using simple gap acceptance theory. Assuming that the headways of exiting vehicles are distributed exponentially, the number of gaps of duration G available within the exiting traffic stream can be given by Equation 2. Note that the assumption of exponentially distributed headways is not completely accurate, given the multiple processes within a roundabout, but it is sufficiently accurate for this approximation.

$$n = v_c \frac{e^{-v_c G/3600}}{1 - e^{-v_c G/3600}} \tag{2}$$

where: n = number of available gaps of size G (gaps/h)
v_c = conflicting vehicular flow rate (veh/h)
G = duration of adequate gap (s)

Figure 1 shows the application of Equation 2, displaying the expected number of available gaps per hour for a range of conflicting vehicular flow rates and durations of adequate gaps. When the expected number of pedestrian events exceeds the number of available gaps per hour, vehicle yielding will be necessary to provide enough capacity for pedestrians to cross. Note that the presence of a sufficient number of gaps during the hour does not necessarily mean that pedestrians will only cross when an adequate gap presents itself. If the delay to the pedestrian is too great, the pedestrian may choose to force yielding rather than wait for the expected available gap.

Fig. 1 - Available gaps per hour for a range of conflicting vehicular flow rates and durations of adequate gaps.

Conflicting vehicular flow	Gap duration, G (s)					
v_c (veh/h)	5	10	15	20	25	30
100	671	312	193	134	99	76
200	624	269	153	98	66	46
300	580	230	120	69	42	26
400	538	196	93	48	26	14
500	498	166	71	33	16	7
600	461	139	53	22	9	4
700	425	116	40	14	5	2
800	392	97	29	9	3	1
900	361	80	21	6	1	0
1000	332	66	15	3	0	0
1100	304	54	11	2	0	0
1200	279	44	8	1	0	0
1300	255	36	5	0	0	0
1400	233	29	4	0	0	0
1500	213	23	2	0	0	0
1600	194	19	2	0	0	0
1700	177	15	1	0	0	0
1800	160	12	0	0	0	0

Note that the above formulas assess only the availability of gaps in the vehicular stream *assuming no yielding for pedestrians by drivers*. Most States require that drivers yield to pedestrians once pedestrians are in the crosswalk, and some States require that drivers yield to pedestrians if they are about to commence crossing. Therefore, the use of this formula to assess the availability of gaps is quite conservative and should not be construed as the definitive measure of the usability of a crosswalk for pedestrians. It, however, could be used to demonstrate that sufficient gaps are available for pedestrians to the extent that no additional gap-enforcing measures are necessary.

3.2 Effect of Blocking Event on Roundabout Exit

The probability of a queue of length q can be estimated by assuming a Poisson arrival distribution and a blocking time equal to the length of the actual blocking event, T_B, plus the time needed to clear the average queue, Q_{avg}/S_E. The Poisson distribution assumption is consistent with the negative exponential distribution of headways assumed previously and is sufficient for approximation. The use of a constant T_B and an average queue Q_{avg} to estimate the overall blocking time is a simplifying assumption; in reality, this duration varies by pedestrian event and the actual queue experienced during the specific event. This probability is given in Equation 3.

$$P_{queue}(q) = \frac{e^{-V_E\left(T_B+\frac{3600Q_{avg}}{S_E}\right)}\left[V_E\left(T_B+\frac{3600Q_{avg}}{S_E}\right)\right]^q}{q!} \quad (3)$$

where:

$P_{queue}(q)$ = probability that a queue of length q will occur during a blocking event

Q_{avg} = average expected queue (see Equation 4)

V_E = vehicle flow rate on the exit being studied [veh/hr]

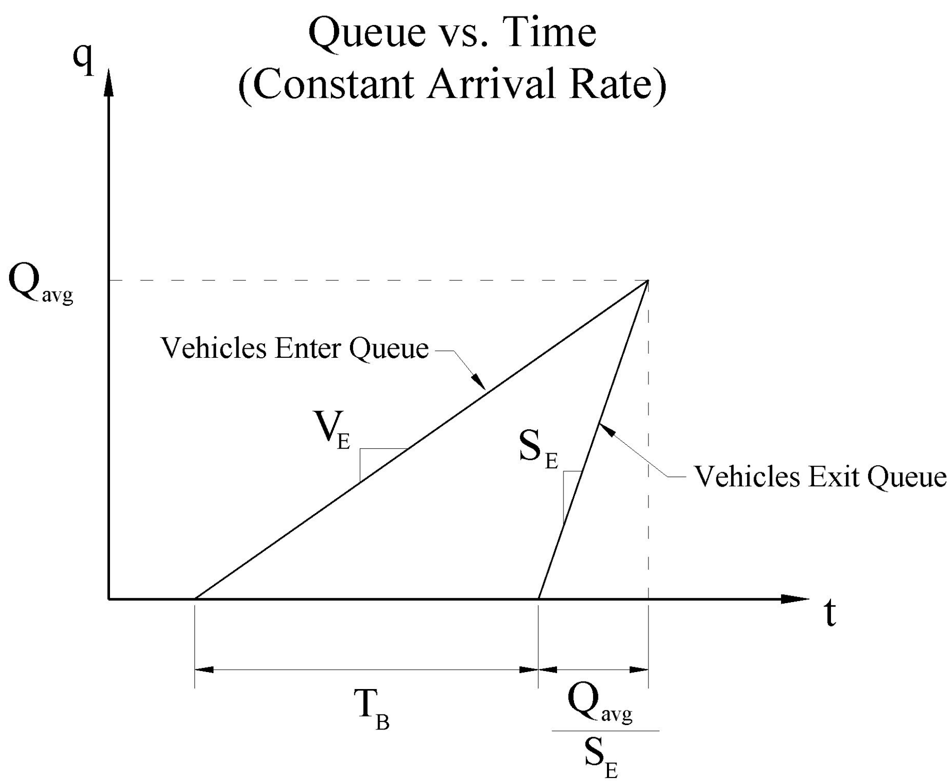
T_B = duration of blocking event [s]

S_E = saturation flow rate of exiting vehicles upon release from blocking event [veh/hr]

q = queue length (used in estimating probabilities of specific queue lengths)

The $3600Q_{avg}/S_E$ term in Equation 3 accounts for the additional effective blocking time caused by the departure of the queue after the end of the actual blocking event, defined by duration T_B. This relationship is illustrated in Figure 2. It should be noted that the actual queue duration varies based on the number of vehicles in the queue; however, using variable queue duration significantly complicates the computation of queue probability.

Fig. 2 - Queue Versus Time Assuming a Constant Arrival Rate



Based on the relationship shown in Figure 2, Q_{avg} can be calculated as follows:

$$Q_{avg} = \frac{V_E T_B}{3600\left(1 - \frac{V_E}{S_E}\right)} \text{, rounded up to the nearest vehicle} \tag{4}$$

where:

Q_{avg} = average expected queue
V_E = vehicle flow rate on the exit being studied [veh/hr]
T_B = duration of blocking event [s]
S_E = saturation flow rate of exiting vehicles upon release from blocking event [veh/hr]

Using Q_{avg} to define the queue duration will slightly underestimate the probabilities of longer queues. The authors expect that this underestimation will have a relatively small effect on the end results.

The duration of queue of interest, t_{queue}, is the time over which the queue exceeds the critical queue length Q_E; this is shown in Figure 3. This queue length Q_E represents the length of queue that can be accommodated within the exit roadway of the roundabout between the crosswalk and circulatory roadway without disrupting the operation of the roundabout itself. For queues less than Q_E, the duration of queue of interest is zero.

$$t_{queue}(q) = \left(1 - \frac{Q_E}{q}\right)\left(T_B + \frac{3600q}{S_E}\right) \quad \text{for } q > Q_E\text{, and} \tag{5}$$

$$t_{queue}(q) = 0 \text{ for } q \leq Q_E \tag{6}$$

$$Q_E = \frac{L_E}{L_V}\text{, rounded up to the nearest vehicle} \tag{7}$$

where:

$t_{queue}(q)$ = duration over which a queue of length q exceeds queue length Q_E

Q_E = size of queue that just blocks the circulatory roadway of the roundabout [veh]

T_B = duration of blocking event [s]

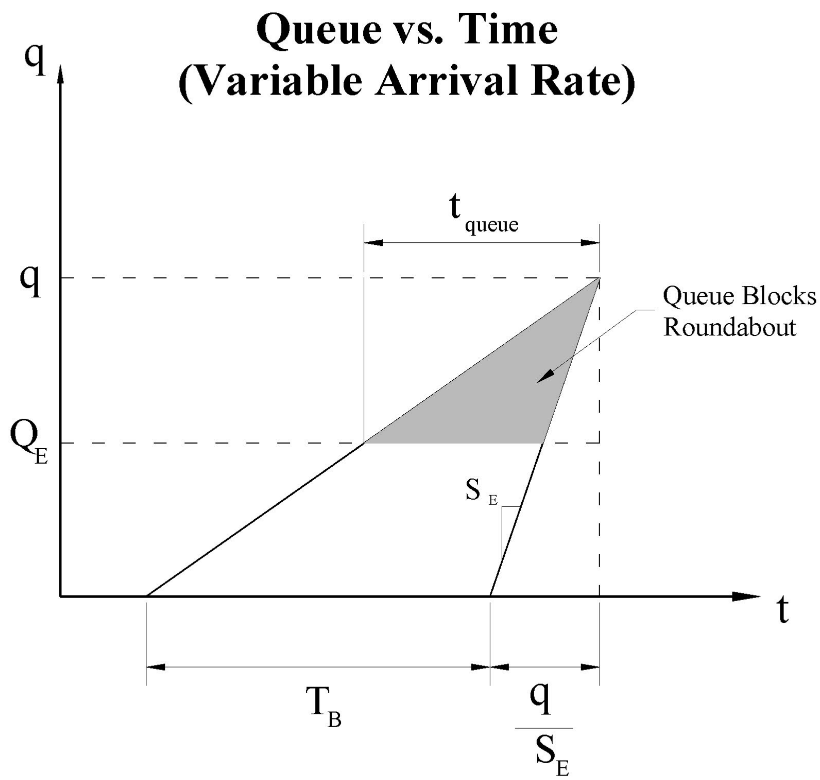
S_E = saturation flow rate of exiting vehicles upon release from blocking event [veh/hr]

q = queue length (used in estimating probabilities of specific queue lengths)

L_E = exit throat length between the blocking event and the circulating roadway [unit length]

L_V = assumed vehicle length [unit length] = 7.5 m = 25 ft

Fig. 3 - Queue Versus Time Assuming Variable Arrival Rate



Once the probabilities and durations of each queue length are known, one can estimate the average duration of queue blocking for each blocking event by determining the probability of a queue of length q and multiplying it by its duration. Short queues have a high probability but low duration, and long queues have a low probability but high duration. This is shown as follows:

$$t_{avg} = \sum_{q=0}^{q=\infty} P_{queue}(q) \cdot t_{queue}(q) \tag{8}$$

where:

t_{avg} = average duration of queue blocking on a per event basis.

$P_{queue}(q)$ = probability that a queue of length q will occur during a blocking event

$t_{queue}(q)$ = duration over which a queue of length q exceeds queue length Q_E

q = queue length (used in estimating probabilities of specific queue lengths)

The proposed model estimates the amount of time, t_{block}, during the study period during which an exit queue blocks the roundabout circulatory roadway. The model assumes that vehicles in the circulatory roadway are completely blocked by the exit queue once it extends to the circulatory roadway (i.e., they cannot maneuver around as might be possible with a wide circulatory roadway).

The value t_{block} is calculated by multiplying the number of blocking events by the average duration of each event, as follows:

$$t_{block} = n_{event} \cdot t_{avg} \qquad (9)$$

where: t_{block} = total time during the study time period that the circulatory roadway is blocked.
n_{event} = number of blocking events occurring during the study time period
t_{avg} = average duration of queue blocking on a per event basis.

Using this, one can approximate the overall reduction in capacity of an upstream roundabout entry by using the following equation:

$$c_{adj} = c_{base}(1 - \frac{t_{block}}{3600}) \qquad (10)$$

where: c_{adj} = adjusted capacity of a subject entry [veh/h]
c_{base} = base capacity of a subject entry [veh/h]
t_{block} = duration of circulatory roadway blocking over the analysis hour.

Using Equation 10, one can determine whether the reduction in capacity of an entry due to downstream events can be absorbed without causing unacceptable operations. The model conservatively assumes that the roundabout entry is considered blocked once a downstream exit has a queue filling the available exit throat length (i.e., just reached the circulatory roadway), regardless of the amount of additional distance between the entry and exit. This assumption is reasonable for most roundabouts where drivers at the entry can see the blocked exit before entering the roundabout. If drivers fill in the space between the subject entry and the blocked exit, the actual entry capacity is somewhat higher.

4. EXAMPLES AND IMPLICATIONS FOR DESIGN

To illustrate the use of these methodologies and their implications for design, two cases have been presented.

4.1 Case 1

This case is of a typical mid-volume single-lane roundabout with a moderate number of pedestrian crossings. The basic assumptions are as follows:

Q_E = 2 vehicles (a crosswalk is located 25 feet from the roundabout – the second vehicle will block the circulating roadway)
V_E = 500 vehicles per hour on the study exit
T_B = 10 seconds (vehicle stopped time required for a pedestrian to cross the exit))
S_E = 1800 veh/hr (i.e. 2 s headways)
n_{event}= 15 pedestrian crossings requiring vehicles to yield during the study hour.

The number of pedestrian crossing events represents only crossings that require a vehicle to yield. Based on Figure 1, there should be 166 10-second gaps in the exit traffic stream, or on average a gap will occur every 22 seconds. The majority of pedestrians will simply choose a gap and cross, but for the purposes of this calculation it is assumed that 15 pedestrians will cross in such a manner as to force the exiting vehicles to yield.

Based on these characteristics, the average queue can be calculated as follows:

$$Q_{avg} = \frac{V_E T_B}{3600\left(1-\frac{V_E}{S_E}\right)} = \frac{500 \cdot 10}{3600\left(1-\frac{500}{1800}\right)} = 2 \text{ veh}$$

This provides enough information to evaluate some of the terms of the infinite sum that defines t_{avg}. Figure 4 shows the calculations.

Fig. 4 - Calculation of t_{avg}

q	P(q)	t(q)	P(q)*t(q)	Sum of P(q) to t(q) from 0 to q	Comments
0	0.14	0.0	0.0	0.0	Queue does not exceed Q_E
1	0.28	0.0	0.0	0.0	Queue does not exceed Q_E
2	0.27	0.0	0.0	0.0	Queue matches Q_E
3	0.18	5.3	0.93	0.93	Queue exceeds Q_E
4	0.09	9.0	0.77	1.70	.
5	0.03	12.0	0.40	2.10	.
6	0.01	14.7	0.16	2.26	.
7	0.003	17.1	0.05	2.31	
8	0.0007	19.5	0.01	2.32	
9	0.0002	21.8	0.003	2.33	Sum has converged
10	0.00003	24.0	0.0007	2.33	
11	0.00001	26.2	0.0001	2.33	

As shown in Figure 4, the sum that defines t_{avg} reaches a value of 2.33. Computing the sum up to higher values of q does not significantly change the value of t_{avg}. The reduction in capacity as a result of this can be calculated as follows:

$$t_{block} = n_{event} \cdot t_{avg} = 15 \cdot 2.33 = 35 \text{ seconds}$$

$$c_{adj} = c_{base}(1 - \frac{t_{block}}{3600}) = c_{base}\left(1 - \frac{35}{3600}\right) = 0.99c_{base}$$

Therefore, in this case, the estimated loss of capacity of upstream entries due to exiting blockages is approximately 1 percent.

4.2 Example 2

Example 2 is a higher volume roundabout. The assumptions are as follows:

Q_E = 2 vehicles (a crosswalk is located 25 feet from the roundabout – the second vehicle will block the circulating roadway)
V_E = 1000 veh/hr on the study exit
T_B = 10 seconds (vehicle stopped time required for a pedestrian to cross the exit)
S_E = 1800 veh/hr (i.e., 2 second headways)
n_{event} = 25 pedestrian crossings requiring vehicles to stop during the study hour.

As in the first example, the number of pedestrian crossing events represents only crossings that require a vehicle to stop. Based on Figure 1, there should be 66 10-second gaps in the exit traffic stream, and on average a gap will occur every 55 seconds. In this case, it is expected that pedestrians are more likely to force vehicles to yield for them than in example 1.

Based on these characteristics, the average queue can be calculated as follows:

Q_{avg} = 6 vehicles

This provides enough information to evaluate some of the terms of the infinite sum that defines t_{avg}. Figure 4 shows the calculations.

Fig. 5 - Calculation of t_{avg}

Q	P(q)	t(q)	P(q)*t(q)	Sum of P(q) to t(q) from 0 to q	Comments
0	0.002	0.0	0.0	0.0	Queue does not exceed Q_E
1	0.01	0.0	0.0	0.0	Queue does not exceed Q_E
2	0.04	0.0	0.0	0.0	Queue matches Q_E
3	0.08	5.33	0.45	0.45	Queue exceeds Q_E
4	0.13	9.00	1.16	1.61	
5	0.16	12.00	1.19	3.50	
6	0.16	14.67	2.35	5.85	
7	0.14	17.14	2.40	8.25	
8	0.11	19.50	2.09	10.34	
9	0.07	21.78	1.58	11.92	
10	0.04	24.00	1.06	12.99	
11	0.02	26.18	0.65	13.64	
12	0.01	28.33	0.36	13.99	
13	0.006	30.46	0.18	14.17	
14	0.003	32.57	0.08	14.26	
15	0.001	34.67	0.04	14.29	
16	0.0004	36.75	0.01	14.31	
17	0.0001	38.82	0.006	14.31	
18	0.00005	40.89	0.002	14.31	
19	0.00002	42.95	0.0007	14.32	
20	0.000005	45.00	0.0002	14.32	Sum has converged
21	0.000001	47.05	0.00007	14.32	
22	0.0000004	49.09	0.00001	14.32	

As shown in the Figure, the sum that defines t_{avg} reaches a value of 14 s. Computing the sum up to q=100 does not significantly change the value of t_{avg}. The reduction in capacity as a result of this can be calculated as follows:

$$t_{block} = n_{event} \cdot t_{avg} = 25 \cdot 14 = 350 \text{ seconds}$$

$$c_{adj} = c_{base}(1 - \frac{t_{block}}{3600}) = c_{base}\left(1 - \frac{350}{3600}\right) = 0.90 c_{base}$$

So in this case, the loss of capacity due to downstream blockages can be estimated at approximately 10 percent.

If one moves the crosswalk one vehicle length farther away from the roundabout, such that $Q_E = 3$, one can calculate using the above procedure that $t_{avg} = 11$ s. Therefore,

$$t_{block} = n_{event} \cdot t_{avg} = 25 \cdot 11 = 275 \text{ seconds}$$

$$c_{adj} = c_{base}(1 - \frac{t_{block}}{3600}) = c_{base}\left(1 - \frac{268}{3600}\right) = 0.92 c_{base}$$

As can be seen, this geometric treatment increases capacity by approximately 2 percent as compared to the original proposed design; the queue blocking effects are reduced by approximately one quarter.

4.3 Implications for design

Given the two examples above, it can be seen that there are cases where significant reductions in capacity can result from blocking the exit of a roundabout (by pedestrians or by others). Based on the inputs to the model, the effects on pedestrian capacity can be decreased by changing the available queue storage (locate the crosswalk farther from the circulating roadway), decreasing the crossing time (narrow the exit), or by decreasing the number of blocking events (relocate the pedestrian flow away from exit). Alternately, additional entry capacity could be considered to offset the losses experienced due to exit blockage.

Another potential application for the methodology is to explore the effects of pedestrian crossing signalization on roundabout capacity. A pedestrian signal will have a defined blocking time that is likely to be longer than an unsignalized blocking time due to fixed walk and pedestrian clearance intervals. It will also change the number of blocking occurrences, either increasing them when pedestrians that would otherwise wait for a gap use the signal, or in the case of high pedestrian volumes, decreasing blocking by grouping the pedestrians into larger platoons.

CONCLUSION

The methodologies in this paper are intended to provide a set of analytical tools that can be used to assist the practitioner in quantifying the interaction effects between pedestrians and vehicles. While simple in nature and thus not applicable in complex cases, the models in this paper can provide a first-order estimate of the reductions in vehicular capacity that might be realized due to pedestrian events across roundabout exits. The practitioner can then size the roundabout appropriately to accommodate the projected capacity reductions, refine the design of the pedestrian crossing, or, in some cases, recommend an alternative form of intersection form and control if the impacts are too severe. Simulation remains a tool to analyze more complicated cases.

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