AN EXAMINATION OF PEDESTRIAN CROSSWALK DESIGN AT ROUNDABOUTS

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1.0 ABSTRACT

This study uses a rational approach to examine three elements of pedestrian design at roundabouts – crosswalk location, crosswalk angle, and exit design – and attempts to recommend how they could be implemented to achieve the best possible balance of pedestrian safety and convenience. This was done using the following objectives:

- Maximize visibility (of approaching vehicles to pedestrians, and of pedestrians to drivers).
- Minimize impacts of vehicle queues (on pedestrians and on other drivers).
- Minimize walking distances.
- Minimize pedestrian exposure in the crosswalk.
- Minimize vehicle speeds through the crosswalk.
- Maximize pedestrian refuge width.

The evaluation shows that the only clear preference in terms of pedestrian design at a roundabout is that a crosswalk be located one passenger car length from the roundabout on the exit side as opposed to two. This was because it was shown to minimize walking distances, minimize vehicle speeds through the crosswalk, and maximize pedestrian refuge width in the splitter island.

There was determined to be no overall preference between straight and angled crosswalks, and no overall difference between a curved and a more tangential exit design.

The evaluation was undertaken for an example two-lane roundabout. It is possible that different results may be obtained with different geometric designs. This could include exits much more curved than for the example roundabout, as well as single-lane roundabouts, three-lane roundabouts, flared entries and tapered exits, and crosswalk locations of three car lengths from the roundabout. It is also possible that different results may be obtained with a different evaluation procedure that assigns weights to the study objectives based on their level of pedestrian safety or convenience.

Regardless of the specifics of the evaluation results, it can be seen that the objectives associated with pedestrian crosswalks at roundabouts compete with each other. Weighting the objectives may be appropriate to account for site context. A more human factors approach may allow a better understanding of the driver and pedestrian tasks associated with using a roundabout, and therefore a better means of evaluating various pedestrian design elements.

2.0 STUDY BACKGROUND

2.1 STUDY DESIGN

The goal of this study is to examine three elements of pedestrian design at roundabouts and recommend guidelines for how they could be implemented to maximize pedestrian safety and convenience. The three elements are:

- Crosswalk location. Crosswalks at roundabouts are usually installed one passenger car length from the yield line at the entry, and similarly on the exit. Is this the best location, or should crosswalks be further from the roundabout?
- Crosswalk angle. Sometimes crosswalks run straight across the roundabout entry and exit, and sometimes they are angled perpendicular to the roadway. Is there a difference?
- Exit design. Some roundabouts have approximately equal curvature in the entries and exits. Others are of an "offset left" design that makes the exits less curved or more tangential (or flat) to the roundabout. Which exit design is preferred in terms of pedestrian safety?

The design elements are depicted for a typical two-lane roundabout in Figures 2.1 to 2.3.

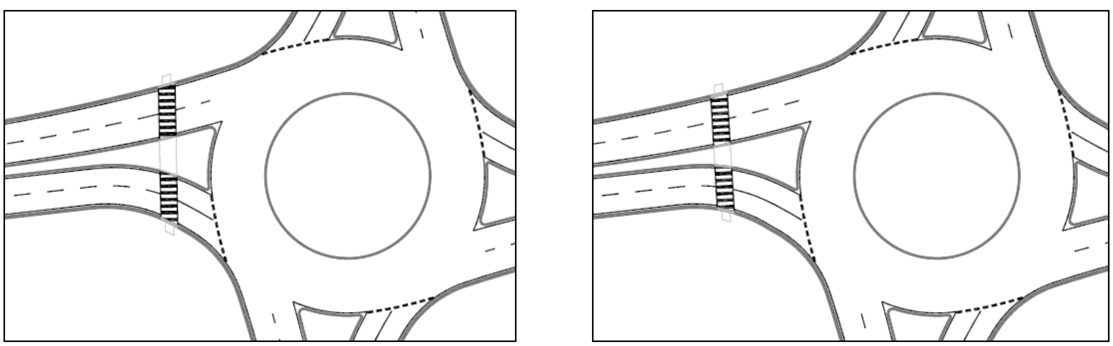

Figure 2.1 Varying Crosswalk Location. The figure on the left shows a location of one passenger car length from the roundabout. The figure on the right shows a location of two car lengths back.

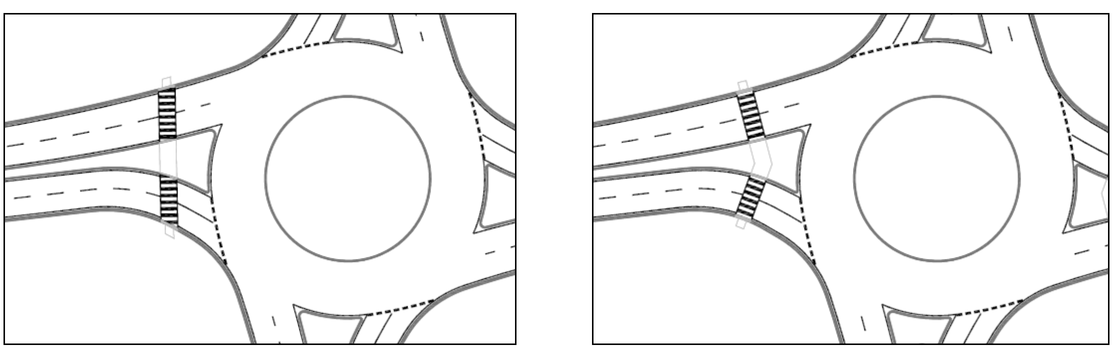

Figure 2.2 Varying Crosswalk Angle. The figure on the left illustrates a straight crosswalk, while the one on the right illustrates an angled crosswalk.

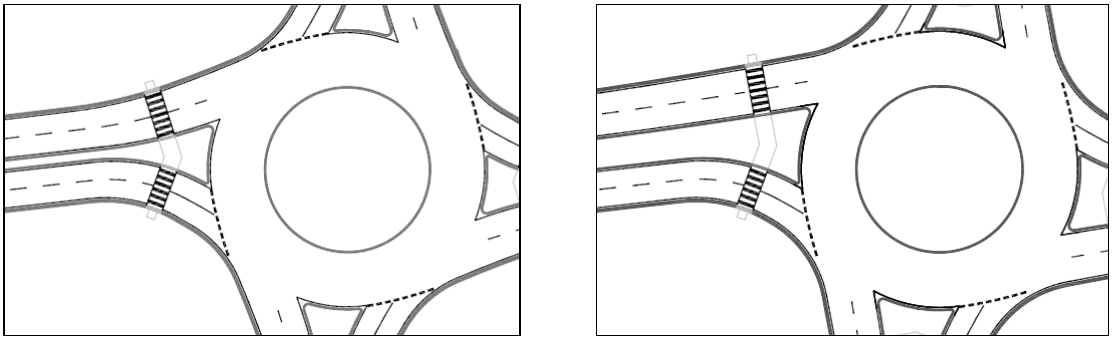

Figure 2.3 Different Exit Designs. The figure on the left shows a roundabout with a curved exit, while the one on the right shows a roundabout with a tangential or flat exit.

The elements should be designed in such a way as to achieve the best possible balance between the following objectives:

- Maximize visibility (of approaching vehicles to pedestrians, and of pedestrians to drivers).
- Minimize impacts of vehicle queues (on pedestrians and on other drivers).
- Minimize walking distances.
- Minimize pedestrian exposure in the crosswalk.
- Minimize vehicle speeds through the crosswalk.
- Maximize pedestrian refuge width.

For example, a crosswalk close to the roundabout on the exit side may minimize pedestrian walking distances, but result in a higher probability of vehicles that are stopped at the crosswalk queuing back into the roundabout.

2.2 PEDESTRIANS AT ROUNDABOUTS

Pedestrians travel through a roundabout by using crosswalks located one passenger car length from the yield line on the entry side of a leg, and at an equivalent location on the exit side. Sometimes crosswalks are located two or three car lengths from the roundabout. The underlying principle is to separate the driver tasks of looking for a pedestrian within or beside the crosswalk and looking for circulating traffic in the roundabout.

Splitter islands separate entering and exiting traffic, and create a two-stage crossing for pedestrians. This requires them to only look for oncoming traffic in one direction at a time, usually travelling at relatively slow speeds.

In most provinces and at most roundabouts the crosswalk is marked, usually with zebra markings, and is controlled by an RA-4 Pedestrian Crosswalk sign (or equivalent) so that drivers are required to give way to pedestrians. In Ontario, where such a sign does not exist, roundabout crosswalks are currently considered uncontrolled locations where there is no formal priority for pedestrians.

3.0 STUDY EVALUATION

3.1 EVALUATION OF DRIVER OBJECTIVES

Of the study objectives, the following apply for drivers:

- Maximize visibility of pedestrians to drivers.
- Minimize impacts of vehicle queues on drivers.

3.1.1 Maximize Visibility of Pedestrians on Entry

The task of looking for pedestrians within or beside a crosswalk on the entry side of a roundabout leg is dependent upon achieving good sightlines on the approach. Drivers typically glance to the left for oncoming traffic well upstream of a roundabout entry, and then again when they are at a point just before the entry starts to rapidly curve to the right. Otherwise drivers tend to fixate on the road ahead (as they do when approaching other intersections). This involves a naturally steady head position with eye movements. Thus it can be inferred that the further a pedestrian is located away from straight-ahead, the less visible that person will be to an approaching driver.

From an examination of Figure 3.1, it can be seen that a crosswalk location more distant from the roundabout (i.e. two passenger car lengths as opposed to one) will result in a smaller angle from straight-ahead. The difference in angle is small until the approaching driver comes close to the crosswalk. For the example roundabout, at between 10 and 15 metres from the crosswalk the difference reaches its maximum at about 10 degrees. Therefore a more distant location on the entry is preferred. The effect of crosswalk angle seems to be negligible.

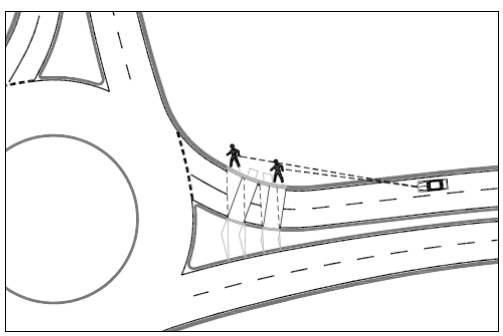

Figure 3.1 Effect of Entry Crosswalk Design on Visibility. A pedestrian should be more visible to an approaching driver when the right side of the crosswalk is further upstream.

3.1.2 Maximize Visibility of Pedestrians on Exit

The task of looking for pedestrians within or beside a crosswalk on the exit side is dependent upon achieving good sightlines approaching the exit from the circulatory road or from the preceding entry (when making a right turn). For this task an appropriate point of measurement is where minimum stopping sight distance (SSD) is achieved of a pedestrian standing beside the exit crosswalk on the right side of the road. Procedures for establishing circulatory road and exit stopping sight distances at roundabouts can be found in various sources.[1]

Figure 3.2 shows a vehicle located in the circulatory road and on the preceding entry at minimum SSD to the exit crosswalk.[2] A straight crosswalk one passenger car length from the roundabout and an angled crosswalk two passenger car lengths from the roundabout are shown, as are curved and tangential entry designs. For the example roundabout, it can be seen that there is little difference in visibility of a pedestrian to a driver for the various crosswalks and exit designs. There likely will not be a significant difference unless the exit is much more curved.

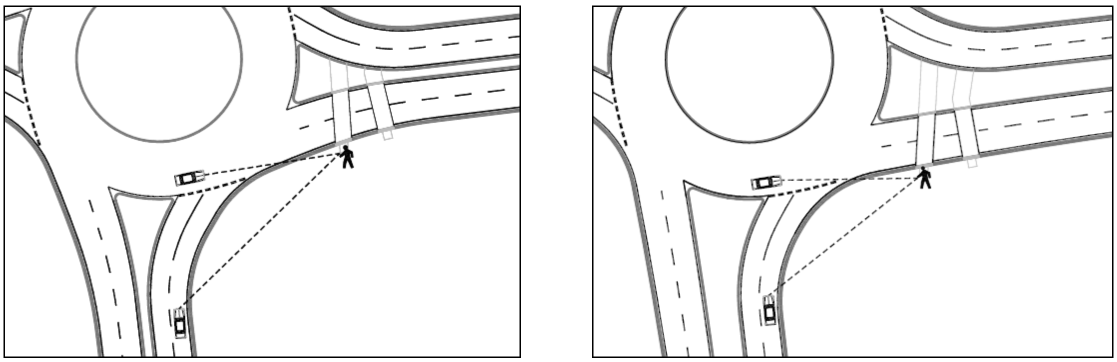

Figure 3.2 Effect of Exit Crosswalk Design on Visibility. A pedestrian should be more visible when the right side of the crosswalk is further from the roundabout and the exit is more tangential.

3.1.3 Minimize Impacts of Vehicle Queues

For a driver, to minimize the impacts of vehicle queues spilling back to the roundabout the crosswalk on the exit side should be located as far from the roundabout as possible. Therefore a crosswalk located two passenger car lengths from the roundabout as opposed to one will be preferred.

3.2 EVALUATION OF PEDESTRIAN OBJECTIVES

Of the study objectives, the following apply for pedestrians:

- Maximize visibility of approaching vehicles to pedestrians.
- Minimize impacts of vehicle queues on pedestrians.
- Minimize walking distances.
- Minimize pedestrian exposure in the crosswalk.
- Minimize vehicle speeds through the crosswalk.
- Maximize pedestrian refuge width.

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[1] The source used here was NCHRP Report 672 *Roundabouts: An Informational Guide, Second Edition*, National Cooperative Highway Research Program, 2010, pages 6-61 to 6-62.

[2] For this roundabout the circulatory road SSD is 25 metres and the right-turn SSD is 45 metres.

3.2.1 Maximize Visibility of Approaching Vehicles

Generally a crosswalk on the entry side of a roundabout leg is subject to the same visibility requirements for pedestrians as for drivers. Therefore a crosswalk located two passenger car lengths from the roundabout will be preferred on the entry.

The same generally holds with a crosswalk on the exit side, but an additional consideration is the exit design. A pedestrian needs to determine whether a circulating vehicle will exit or continue circulating before deciding when to cross. How early and with what certainty this happens is primarily achieved by observing the angle of the vehicle (and to a lesser extent on whether the driver uses the right-turn signal to indicate intent to exit). Figure 3.3 illustrates that the point at which the vehicle trajectory becomes apparent will be further from the crosswalk with a tangential exit than a curved exit.

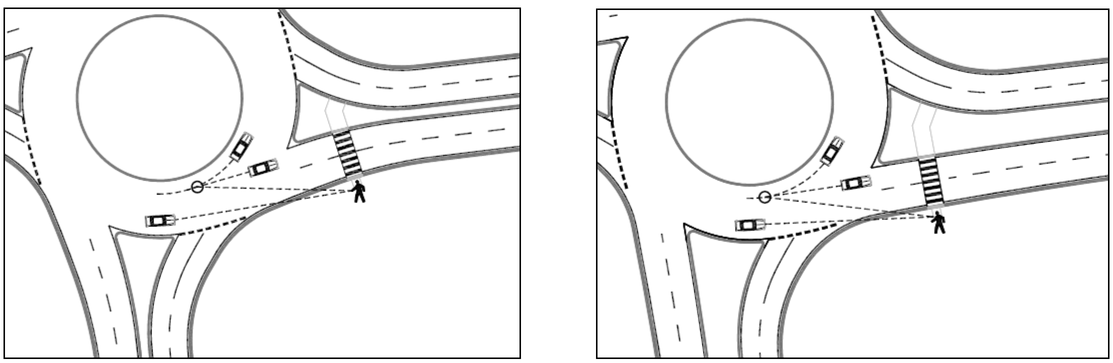

Figure 3.3 Effect of Exit Design on Visibility. A pedestrian should be able to make an earlier determination of whether a circulating vehicle will exit or continue circulating with an exit that is more tangential.

For the example roundabout, the difference between the two exit designs amounts to a distance of 2.0 metres from the point at which the vehicle trajectory becomes apparent and the standing pedestrian. This equates to a difference in pedestrian perception-reaction time of 0.15 seconds.[3] This is not a significant difference given that typical perception-reaction times for other tasks in the roadway environment are greater than 1 second.[4] Again, there likely will not be a much of a difference unless the roundabout exit is much more curved.

3.2.2 Minimize Impacts of Vehicle Queues

For a pedestrian, to minimize the impacts of vehicle queues it is necessary to consider the crosswalk on the entry side. Depending on location a straight crosswalk will allow space for one or two queued passenger cars downstream of the crosswalk in both entry lanes. An angled crosswalk will allow for one or two queued cars in the left lane, but somewhat more than that in the right lane and thus a higher chance of the crosswalk being blocked. This is shown in Figure 3.4.

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3 Calculation based on a speed of 49 km/h, midway between a circulating speed of 40 km/h and an exit speed of 58 km/h.

4 Dewar, R. and P. Olson, *Human Factors and Traffic Safety, Second Edition*, pages 43 and 47.

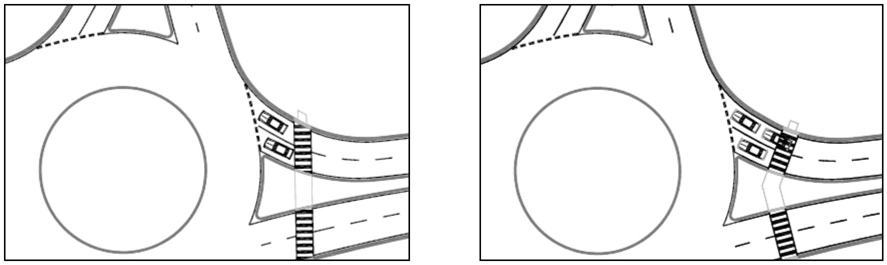

Figure 3.4 Effect of Entry Crosswalk Angle on Queuing. A straight crosswalk will accommodate queued vehicles with less chance of blocking the crosswalk.

The effect will be more exaggerated with a three-lane entry than a two-lane entry, and will not be an issue with a single-lane entry. An additional consideration is the percentage of vehicles longer than passenger cars, such as trucks and buses.

3.2.3 Minimize Walking Distances

It is generally accepted that pedestrians will not use a facility if it takes them too far from their intended path of travel. In the case of a roundabout a crosswalk three or more passenger car lengths away may qualify as such a facility.

For the example roundabout, the maximum difference in walking distances is between a straight crosswalk one passenger car length from the roundabout and an angled crosswalk two passenger car lengths from the roundabout. For a through pedestrian movement the total walking distance is 12 metres less for straight crosswalk closer to the roundabout. For a pedestrian turning left or right the total walking distance is 9 metres less for an angled crosswalk more distant from the roundabout. This assumes straight sidewalk connections between crosswalks, and of course that a pedestrian will remain in the crosswalk during an entire crossing.

There is likely no difference between straight and angled crosswalks, as pedestrians will typically cut across an angled crosswalk to minimize total walking distance.

3.2.4 Minimize Pedestrian Exposure

Pedestrian exposure refers to the amount of time a pedestrian is in the crosswalk, and thus vulnerable to being struck by motor vehicles. For the example roundabout the maximum difference in pedestrian exposure is between a straight crosswalk one car length from the roundabout and an angled crosswalk two car lengths from the roundabout. The difference amounts to a distance of 1.0 metre across the entry and 0.5 metres across the exit. Assuming a pedestrian walking speed of 1.0 metre per second, this equates to a difference in exposure time of 1.5 seconds in total across the entire leg of the roundabout.[5] Given that some pedestrians will not maintain a strict alignment in the crosswalk, the only difference that was considered significant was one of 1.0 seconds, which is the difference between a straight and an angled crosswalk on the entry side.

5 Walking speed from *A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Transportation Officials (AASHTO), 2011, page 2-79.

3.2.5 Minimize Vehicle Speeds Through Crosswalk

In addition to minimizing pedestrian exposure, it is important to minimize vehicle speeds approaching and travelling through a crosswalk. This allows a pedestrian to better judge the actions of an approaching driver, and lessens the chance of injury should the person be struck by a motor vehicle.

On a roundabout entry the worst-case assumption of vehicle speed through the crosswalk can be made by using the fastest-path speed. This is the speed achievable if a driver takes a racing path through the roundabout, in the absence of other traffic and ignoring all lane markings. It can be approximated by drawing a spline from the entry through to the exit and offsetting it from the right curb on entry, the central island, and the right curb on exit. See Figure 3.5. The smallest radius along the spline at the entry is called the entry path radius, which can be related to speed using equations.[6]

On an exit the worst-case assumption is either the exit path radius, or the circulating path radius plus vehicle acceleration from there to the crosswalk, whichever is less.[7]

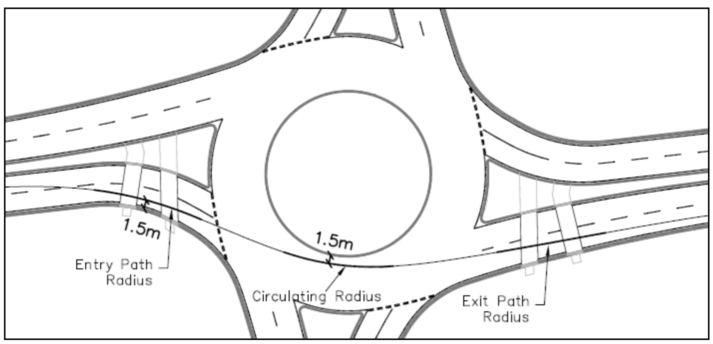

Figure 4.5 Effect of Crosswalk Location on Vehicle Speeds. A crosswalk further from the roundabout will allow higher speeds through it on entry and exit.

For the example roundabout, the fastest-path speed through the entry crosswalk is 42 km/h for both crosswalk locations. The fastest-path speed through the exit crosswalk is 56 km/h for the closer crosswalk and 60 km/h for the more distant crosswalk. This is because of vehicle acceleration out of the roundabout.

Figure 3.6 shows that a more tangential exit will also allow higher speeds through the exit crosswalk. For the example roundabout, for a crosswalk location one car length from the roundabout the fastest-path speeds through the exit are 56 km/h for the curved exit and 59 km/h for the more tangential exit.

Therefore on the exit side a crosswalk closer to the roundabout is preferred, as is a more curved exit design.

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6 This is documented in TD 16/07, *Geometric Design of Roundabouts*, United Kingdom, 2007. The speed can be calculated from $V = 8.7602R^{0.3861}$ as per AASHTO.

7 Here an acceleration rate of 2.1 m/s^2 is used, from NCHRP Report 572 *Roundabouts in the United States,* National Cooperative Highway Research Program, 2007, page 71.

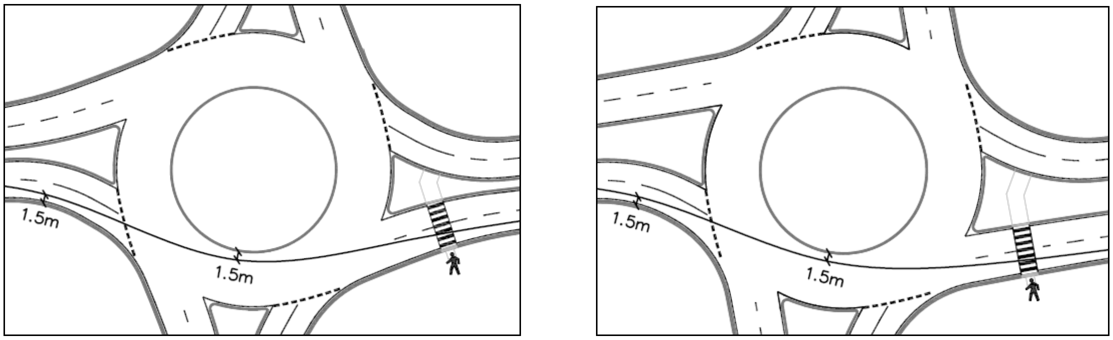

Figure 3.6 Effect of Exit Design on Vehicle Speeds. A more tangential exit will allow higher speeds through the exit crosswalk.

It has been hypothesized that a more tangential exit may encourage drivers to speed up, and therefore result in a greater speed differential with a curved exit than would be the case with just utilizing speed and acceleration rates.

3.2.6 Maximize Pedestrian Refuge Width

It can be seen from Figure 2.3 (or Figures 3.2, 3.3 or 3.6) that all design elements being equal, a crosswalk closer to the roundabout or a more tangential exit will both result in a wider area on the splitter island for pedestrians. A splitter island width at the back of the crosswalk of 1.8 metres is considered a minimum for a person walking a bicycle or pushing a stroller, but pedestrians will feel more comfortable with a wider refuge area. Where pedestrian volumes are significant or where vehicle speeds can be high a refuge area width of at least 3 metres is recommended.

4.0 STUDY RESULTS

4.1 EVALUATION OF CROSSWALK DESIGNS

The following evaluation is based on crosswalks as per the example two-lane roundabout shown in the previous figures. It is possible results will differ with single-lane or three-lane roundabouts, or with different roundabout designs.

Crosswalks on the entry and exit side of a roundabout leg were evaluated separately, mainly to allow for the possibility of staggered crosswalks.

4.1.1 Crosswalks on Roundabout Entries

The evaluation results for a crosswalk on the entry side of a roundabout leg are listed in Table 4.1. The two possibilities within each design element were ranked from 1 to 2, with 2 being the better score. Certain objectives, such as minimizing vehicle queues back to the roundabout, did not apply for the entry crosswalk, while with others there was determined to be no significant different between possibilities.

Table 4.1 – Evaluation for Crosswalks on Roundabout Entries

Objective	Location		Angle	
	1 Car Length	2 Car Lengths	Straight	Angled
Max. visibility of pedestrians to drivers	1	2		
Min. impacts of vehicle queues on drivers				
Max. visibility of approaching vehicles to pedestrians	1	2		
Min. impacts of vehicle queues on pedestrians			2	1
Min. walking distances	2	1		
Min. pedestrian exposure in the crosswalk			1	2
Min. vehicle speeds through the crosswalk				
Max. pedestrian refuge width	2	1		
Total	**6**	**6**	**3**	**3**

Note: Blank cells in the table indicate no significant difference between possibilities.

From this simple evaluation there is no distinct preference between a straight versus an angled crosswalk, or that it be one versus two passenger car lengths from the yield line at the entry.

4.1.2 Crosswalks on Roundabout Exits

The evaluation results for a crosswalk on the exit side are listed in Table 4.2, with the two possibilities within each design element ranked from 1 to 2. As before certain objectives, such as minimizing vehicle queues impacting pedestrians, did not apply for the exit crosswalk, while with others there was determined to be no significant different between possibilities.

Table 4.2 – Evaluation for Crosswalks on Roundabout Exits

Objective	Location		Angle		Exit Design	
	1 Car Length	2 Car Lengths	Straight	Angled	Curved	Tangent
Max. visibility of pedestrians to drivers						
Min. impacts of vehicle queues on drivers	1	2				
Max. visibility of approaching vehicles to pedestrians						
Min. impacts of vehicle queues on pedestrians						
Min. walking distances	2	1				
Min. pedestrian exposure in the crosswalk						
Min. vehicle speeds through the crosswalk	2	1			2	1
Max. pedestrian refuge width	2	1			1	2
Total	**7**	**5**	**0**	**0**	**3**	**3**

Note: Blank cells in the table indicate no significant difference between possibilities.

From this simple evaluation there is no effect associated with a straight versus an angled crosswalk, and no distinct preference between a curved or tangential exit design. The only preference was with a crosswalk located one or versus two passenger car lengths from the roundabout.

4.2 DISCUSSION

Looking at a roundabout leg in its entirety, it can be seen that the only clear preference from this evaluation is that a crosswalk be located one car length from the roundabout on the exit side as opposed to two (or, presumably, more). This is a result of higher vehicle speeds being possible with a more distant crosswalk, as well as longer walking distances (for a through pedestrian movement) and a smaller pedestrian refuge area. The drawback to this location is that less storage is available for vehicles queued at the exit crosswalk.

There was determined to be no overall preference between straight and angled crosswalks. An additional consideration that was not part of the evaluation is that angled crosswalks may be better for pedestrians with vision loss. This is because it allows them to step off the curb at a right angle and more easily maintain alignment in the crosswalk.

There was determined to be no overall difference between a curved and a more tangential exit design. However it is possible results might be different with an exit much more curved than for the example roundabout.

It is recognized that the objective of maximizing pedestrian refuge width is double-counted when evaluating crosswalk location on each side of a roundabout leg separately. Removing it from consideration on the entry side results in a preference for a location two passenger car lengths from the yield line. Removing it from consideration on the exit side maintains the preference for one car length from the roundabout. If the entry and exit crosswalks are at difference distances then the crossing in the splitter island must be staggered, in which case a sufficiently wide splitter island will be needed.

It is also recognized that there is some double-counting associated with evaluating visibility of pedestrians to drivers, and visibility of vehicles to pedestrians, although the means by which they are measured can be different.

It was originally thought appropriate to weight the study objectives, as some are safety-related and others have more to do with pedestrian convenience, then rank the crosswalk designs on scale of 1 to 5. However this would have been a highly subjective process. Instead it was undertaken as a sensitivity analysis. On the entry side it showed a small preference for a straight crosswalk two car lengths from the yield line, depending on weighting, and on the exit side an angled crosswalk one car length from the yield line on a curved exit.

4.3 SUGGESTIONS FOR FURTHER STUDY

It can be seen that the objectives associated with pedestrian crosswalks at roundabouts compete with each other. Weighting the objectives at a given location may be appropriate to account for site context. For example, in an urban area with high traffic volumes and high pedestrian activity the impact of vehicle queues backing from an exit crosswalk into the roundabout may be override consideration of other objectives and result in locating the crosswalk more distant from a roundabout.

More study would help determine which study results are transferable to all roundabouts, and which are specific to site context. This could include examining the effects of varying weights for the objectives, and investigating the effects of varying roundabout geometric design. This could include single-lane roundabouts, three-lane roundabouts, flared entries and tapered exits, and crosswalk locations of three car lengths from the roundabout.

Also worthy of further study is the use of pedestrian beacons or signals at roundabouts, and how they affect crosswalk location, crosswalk angle and exit design. Pedestrian signals are being requested in some cases to improve the accessibility of roundabouts for pedestrians with vision loss.

Finally, a more human factors approach to the study may allow a better understanding of relevant driver and pedestrian workloads. This was attempted as part of this study, but insufficient information was found to account specifically for the driver and pedestrian tasks associated with using a roundabout.

5.0 CONCLUSIONS

The foregoing rational evaluation shows that the one clear preference in terms of pedestrian design at a roundabout is that a crosswalk be located one passenger car length from the roundabout on the exit side as opposed to two. There was determined to be no overall preference between straight and angled crosswalks, and no overall difference between a curved and a more tangential exit design.

The evaluation was undertaken for an example two-lane roundabout. It is possible that different results may be obtained with different geometric designs. This could include exits much more curved than for the example roundabout, as well as single-lane roundabouts, three-lane roundabouts, flared entries and tapered exits, and crosswalk locations of three car lengths from the roundabout. It is also possible that different results may be obtained with a different evaluation procedure that assigns weights to the study objectives based on their level of pedestrian safety or convenience.

Regardless of the specifics of the evaluation results, it can be seen that the objectives associated with pedestrian crosswalks at roundabouts compete with each other. Weighting the objectives may be appropriate to account for site context. A more human factors approach may allow a better understanding of the driver and pedestrian tasks associated with using a roundabout, and therefore a better means of evaluating various pedestrian design elements based on driver and pedestrian workloads.

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