5 Safety

Chapter 5 Safety

Roundabouts may improve the safety of intersections by eliminating or altering conflict types, by reducing speed differentials at intersections, and by forcing drivers to decrease speeds as they proceed into and through the intersection. Though roundabout crash records in the United States are limited, the experiences of other countries can be used to help design roundabouts in this country. Understanding the sensitivity of geometric element parameters, along with the crash experience, will assist the designer in optimizing the safety of all vehicle occupants, pedestrians, and bicyclists.

Roundabouts may improve intersection safety by:

- **Eliminating or altering conflicts**
- **Decreasing speeds into and through the intersection**
- **Decreasing speed differentials**

5.1 Introduction

Many studies have found that one of the benefits of roundabout installation is the improvement in overall safety performance. Several studies in the U.S., Europe, and Australia have found that roundabouts perform better in terms of safety than other intersection forms (1, 2, 3, 4). In particular, single-lane roundabouts have been found to perform better than two-way stop-controlled (TWSC) intersections in the U.S. (5). Although the frequency of reported crashes is not always lower at roundabouts, the reduced injury rates are usually reported (6). Safety is better at small and medium capacity roundabouts than at large or multilane roundabouts (1, 7). While overall crash frequencies have been reduced, the crash reductions are most pronounced for motor vehicles, less pronounced for pedestrians, and equivocal for bicyclists, depending on the study and bicycle design treatments (4, 6, 7). Crash statistics for various user groups are reported in Section 5.3.

The reasons for the increased safety level at roundabouts are:

- Roundabouts have fewer conflict points in comparison to conventional intersections. The potential for hazardous conflicts, such as right angle and left turn head-on crashes is eliminated with roundabout use. Single-lane approach roundabouts produce greater safety benefits than multilane approaches because of fewer potential conflicts between road users, and because pedestrian crossing distances are short.
- Low absolute speeds associated with roundabouts allow drivers more time to react to potential conflicts, also helping to improve the safety performance of roundabouts.
- Since most road users travel at similar speeds through roundabouts, i.e., have low relative speeds, crash severity can be reduced compared to some traditionally controlled intersections.
- Pedestrians need only cross one direction of traffic at a time at each approach as they traverse roundabouts, as compared with unsignalized intersections. The conflict locations between vehicles and pedestrians are generally not affected by the presence of a roundabout, although conflicting vehicles come from a more defined path at roundabouts (and thus pedestrians have fewer places to check for conflicting vehicles). In addition, the speeds of motorists entering and exiting a roundabout are reduced with good design. As with other crossings

requiring acceptance of gaps, roundabouts still present visually impaired pedestrians with unique challenges, as described in Chapter 2.

For the design of a new roundabout, safety can be optimized not only by relying on recorded past performance of roundabouts in general, but primarily by applying all design knowledge proven to impact safety. For optimum roundabout safety and operational performance the following should be noted:

- Minimizing the number of potential conflicts at any geometric feature should reduce the multiple vehicle crash rate and severity.
- Minimizing the potential relative speed between two vehicles at the point of conflict will minimize the multiple vehicle crash rate and severity (it may also optimize capacity). To reduce the potential relative speed between vehicles, either the absolute speeds of both vehicles need to be reduced or the angle between the vehicle paths needs to be reduced. Commuter bicyclist speeds can range from 20 to 25 km/h (12 to 15 mph) and designs that constrain the speeds of motor vehicles to similar values will minimize the relative speeds and improve safety. Lower absolute speeds will also assist pedestrian safety.
- Limiting the maximum change in speed between successive horizontal geometric elements will minimize the single vehicle crash rate and severity.

5.2 Conflicts

Conflict points occur where one vehicle path crosses, merges or diverges with, or queues behind the path of another vehicle, pedestrian, or bicycle.

The frequency of crashes at an intersection is related to the number of *conflict points* at an intersection, as well as the magnitude of conflicting flows at each conflict point. A conflict point is a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other.

Besides conflicts with other road users, the central island of a roundabout presents a particular hazard that may result in over-representation of single-vehicle crashes that tend to occur during periods of low traffic volumes. At cross intersections, many such violations may go unrecorded unless a collision with another vehicle occurs.

Conflicts can arise from both legal and illegal maneuvers; many of the most serious crashes are caused by failure to observe traffic control devices.

The following sections present a variety of conflicts among vehicles, bicycles, and pedestrians. Both legal conflicts (queuing at an intersection, merging into a traffic stream) and conflicts prohibited by law or by traffic control devices (failure to yield to pedestrians, running a stop sign) have been included for completeness. Even though traffic control devices can significantly reduce many conflicts, they can not eliminate them entirely due to violations of those devices. Many of the most serious crashes are caused by such violations.

As with crash analyses, conflict analyses are more than the simple enumeration of the number of conflicts. A conflict analysis should account for the following factors:

- Existence of conflict point;

- Exposure, measured by the product of the two conflicting stream volumes at a given conflict point;
- Severity, based on the relative velocities of the conflicting streams (speed and angle); and
- Vulnerability, based on the ability for a member of each conflicting stream to survive a crash.

5.2.1 Vehicle conflicts

5.2.1.1 Single-lane roundabouts

Exhibit 5-1 presents a diagram of vehicle-vehicle conflict points for a traditional three-leg ("T") intersection and a three-leg roundabout. As the figure shows, the number of vehicle-vehicle conflict points for roundabouts decreases from nine to six for three-leg intersections. Note that these diagrams do not take into account the ability to separate conflicts in space (through the use of separate left or right turning lanes) or time (through the use of traffic control devices such as stop signs or traffic signals).

Roundabouts bring the simplicity of a "T" intersection to intersections with more than three legs.

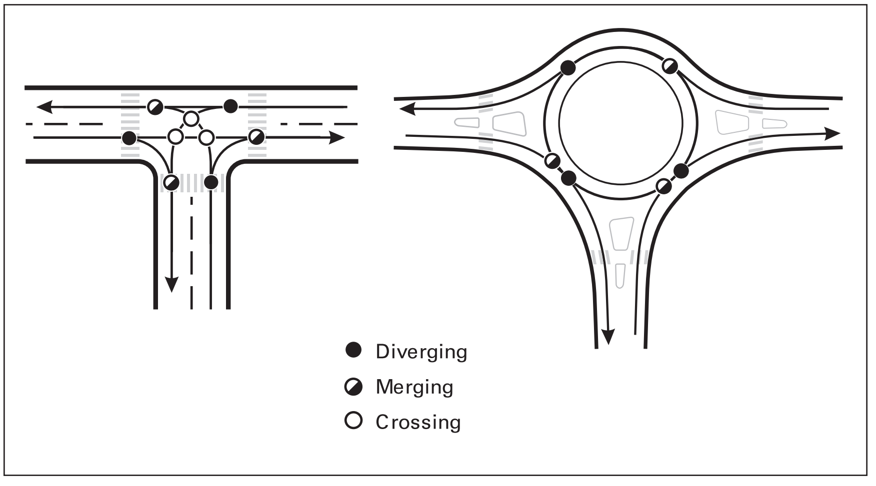
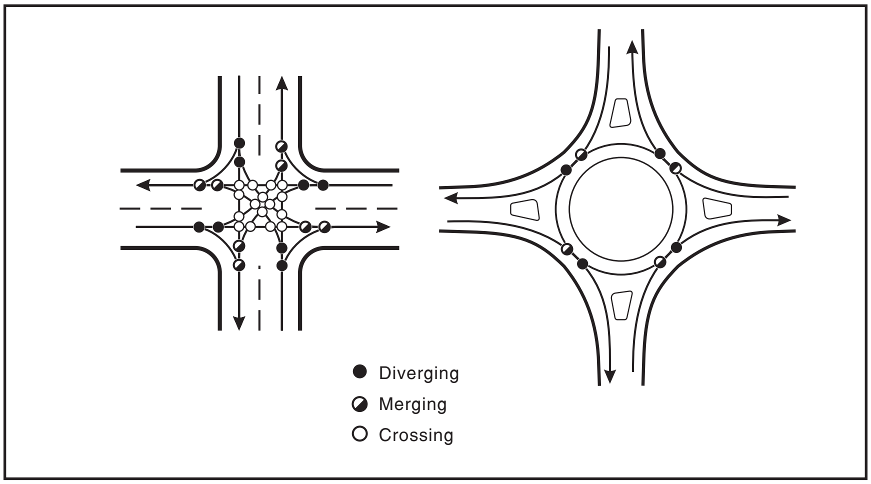


Exhibit 5-1. Vehicle conflict points for "T" Intersections with single-lane approaches.

Exhibit 5-2 presents similar diagrams for a traditional four-leg ("X" or "cross") intersection and a four-leg roundabout. As the figure shows, the number of vehicle-vehicle conflict points for roundabouts decreases from 32 to 8 for four-leg intersections.

Exhibit 5-2. Vehicle conflict point comparison for intersections with single-lane approaches.



A four-leg single-lane roundabout has 75% fewer vehicle conflict points—compared to a conventional intersection.

Conflicts can be divided into three basic categories, in which the degree of severity varies, as follows:

- *Queuing conflicts.* These conflicts are caused by a vehicle running into the back of a vehicle queue on an approach. These types of conflicts can occur at the back of a through-movement queue or where left-turning vehicles are queued waiting for gaps. These conflicts are typically the least severe of all conflicts because the collisions involve the most protected parts of the vehicle and the relative speed difference between vehicles is less than in other conflicts.
- *Merge and diverge conflicts.* These conflicts are caused by the joining or separating of two traffic streams. The most common types of crashes due to merge conflicts are sideswipes and rear-end crashes. Merge conflicts can be more severe than diverge conflicts due to the more likely possibility of collisions to the side of the vehicle, which is typically less protected than the front and rear of the vehicle.

Crossing conflicts are the most severe and carry the highest public cost.

- *Crossing conflicts.* These conflicts are caused by the intersection of two traffic streams. These are the most severe of all conflicts and the most likely to involve injuries or fatalities. Typical crash types are right-angle crashes and head-on crashes.

As Exhibit 5-1 and Exhibit 5-2 show, a roundabout reduces vehicular crossing conflicts for both three- and four-leg intersections by converting all movements to right turns. Again, separate turn lanes and traffic control (stop signs or signalization) can often reduce but not eliminate the number of crossing conflicts at a traditional intersection by separating conflicts in space and/or time. However, the most severe crashes at signalized intersections occur when there is a violation of the traffic control device designed to separate conflicts by time (e.g., a right-angle collision due to running a red light, and vehicle-pedestrian collisions). Therefore, the ability of single-lane roundabouts to reduce conflicts through physical, geometric features has been demonstrated to be more effective than the reliance on driver obedience of traffic control devices.

5.2.1.2 Double-lane roundabouts

In general, double-lane roundabouts have some of the same safety performance characteristics as their simpler single-lane counterparts. However, due to the presence of additional entry lanes and the accompanying need to provide wider circulatory and exit roadways, double lane roundabouts introduce additional conflicts not present in single-lane roundabouts. This makes it important to use the minimum required number of entry, circulating and exit lanes, subject to capacity considerations. For example, according to United Kingdom roundabout crash models, for a 10,000 entering Average Daily Traffic (ADT), flaring the entry width from one to two lanes is likely to increase injury crashes by 25 percent (8).

Double-lane roundabouts have some of the same safety performance characteristics as single-lane roundabouts, but introduce additional conflicts.

The number of vehicular and pedestrian conflicts points in both conventional intersections and roundabouts increases considerably when they have additional approach lanes. The designer is encouraged to graphically determine conflicts for a particular location, as this information can raise awareness of design issues and may be useful in public presentations.

The types of conflicts present in multilane roundabouts that do not exist in single-lane roundabouts occur when drivers use the incorrect lane or make an improper turn. These types of conflicts are depicted in Exhibit 5-3 and Exhibit 5-4, respectively. While these types of conflicts can also be present in other intersection forms, they can be prevalent with drivers who are unfamiliar with roundabout operation. The conflicts depicted in Exhibit 5-4, in particular, can be created by not providing a proper design geometry that allows vehicles to travel side-by-side throughout the entire roundabout (see Chapter 6). Crashes resulting from both types of conflicts can also be reduced through proper driver education.

Incorrect lane use and incorrect turns are multilane roundabout conflicts that do not exist in single-lane roundabouts.

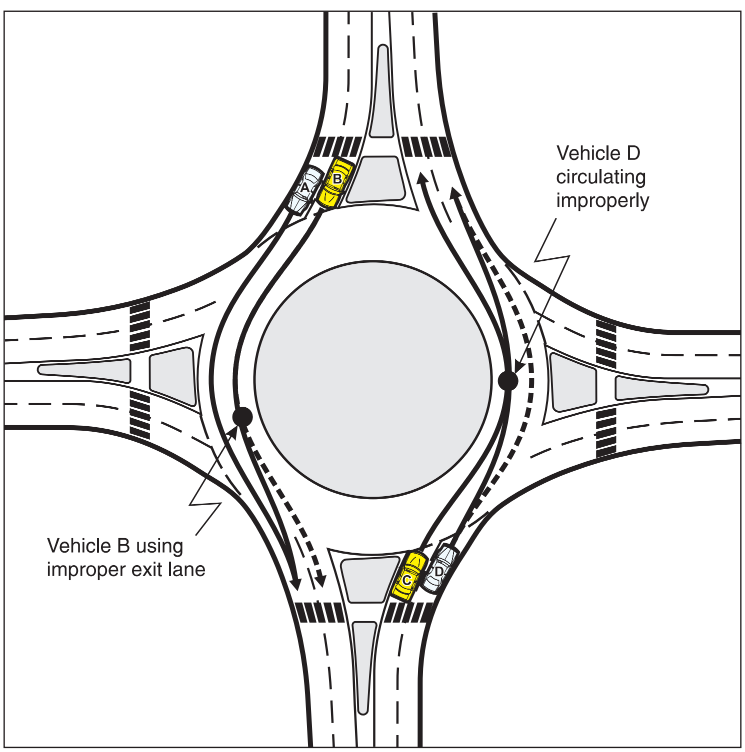
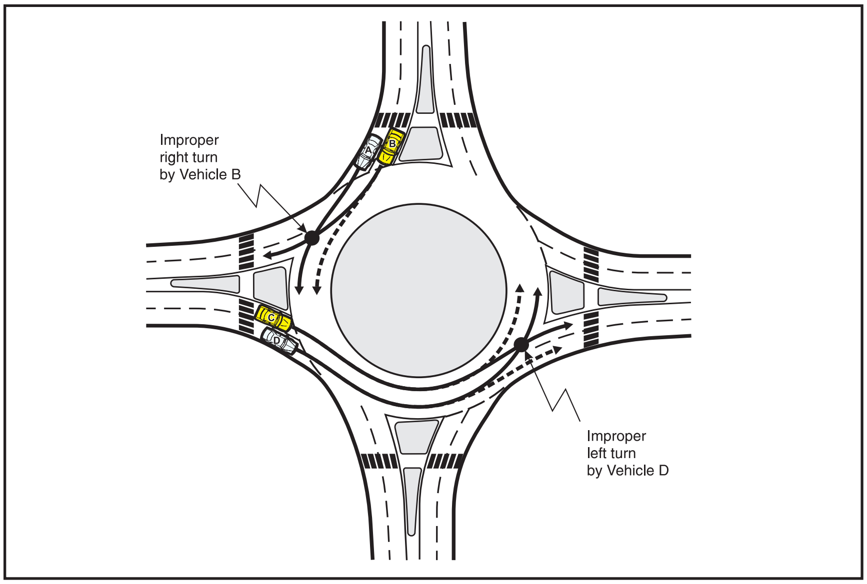


Exhibit 5-3. Improper lane-use conflicts in double-lane roundabouts.

Exhibit 5-4. Improper turn conflicts in double-lane roundabouts.



As with single-lane roundabouts, the most severe vehicular crossing conflicts are eliminated and replaced by less severe merging conflicts. The additional conflicts unique to multilane roundabouts are generally low-speed sideswipe conflicts that typically have low severity. Therefore, although the number of conflict points increases at multilane roundabouts when compared to a single lane roundabouts, the overall severity of conflicts is generally less than alternative intersection control.

5.2.2 Pedestrian conflicts

Vehicle-pedestrian conflicts can be present at every intersection, even those with minimal pedestrian volume. The following sections examine pedestrian conflicts at signalized intersections and at roundabouts.

Signalized intersections offer the opportunity to reduce the likelihood of pedestrian-vehicle conflicts through the use of signal phasing that allows only a few movements to move legally at any given time. Exhibit 5-5 summarizes the typical pedestrian conflicts present on one approach to a signalized intersection. As the exhibit shows, a pedestrian crossing at a typical signalized intersection (permitted or protected-permitted left turns, right turns on red allowed) faces four potential vehicular conflicts, each coming from a different direction:

- Crossing movements on red (typically high-speed, illegal)
- Right turns on green (legal)
- Left turns on green (legal for protected-permitted or permitted left turn phasing)
- Right turns on red (typically legal)

Types of pedestrian crossing conflicts present at signalized intersections.

In terms of exposure, the illegal movements should be accorded a lower weight than legal conflicts. However, they may be accorded an offsetting higher weight in terms of severity. For an intersection with four single-lane approaches, this results in a total of 16 pedestrian-vehicle conflicts.

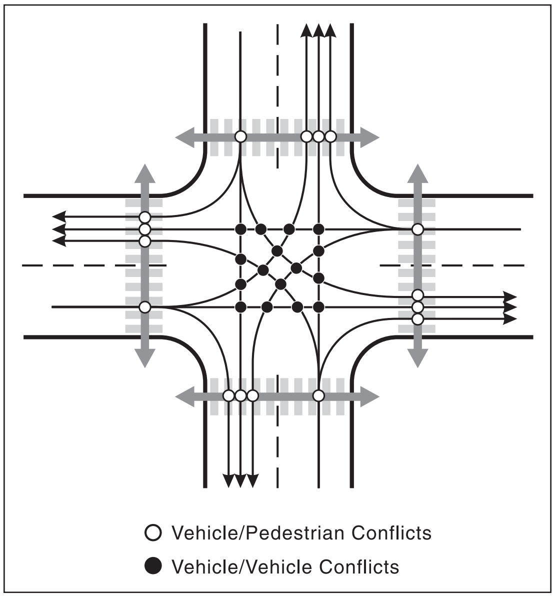


Exhibit 5-5. Vehicle-pedestrian conflicts at signalized intersections.

Pedestrians at roundabouts, on the other hand, face two conflicting vehicular movements on each approach, as depicted in Exhibit 5-6:

- Conflict with entering vehicles; and
- Conflict with exiting vehicles.

The direction conflicting vehicles will arrive from is more predictable for pedestrians at roundabouts.

At conventional and roundabout intersections with multiple approach lanes, an additional conflict is added with each additional lane that a pedestrian must cross.

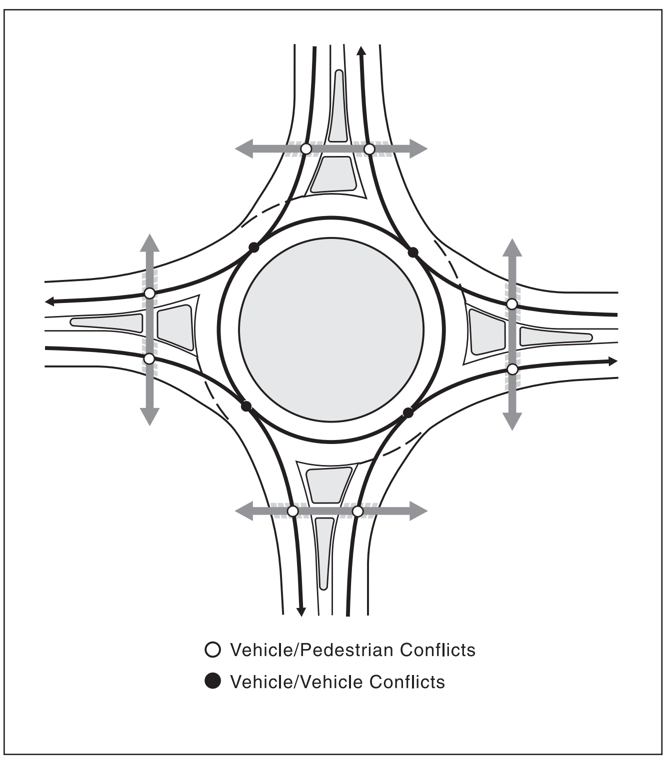
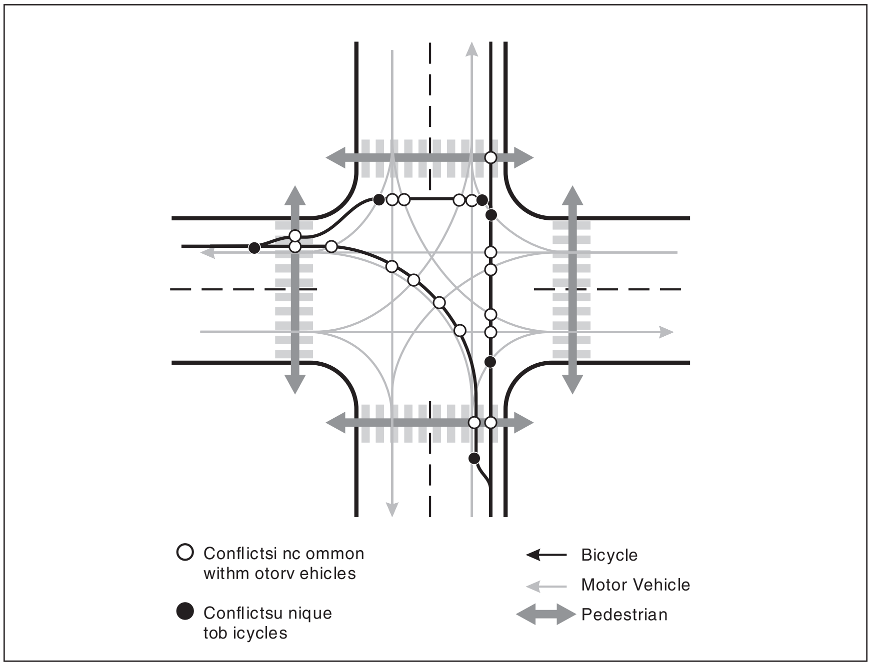


Exhibit 5-6. Vehicle-pedestrian conflicts at single-lane roundabouts.

5.2.3 Bicycle conflicts

Bicycles face similar conflicts as motor vehicles at both signalized intersections and roundabouts. However, because bicyclists typically ride on the right side of the road between intersections, they face additional conflicts due to overlapping paths with motor vehicles. Conflicts unique to bicyclists occur on each approach to conventional four-leg intersections, as depicted in Exhibit 5-7 (showing left turns like motor vehicles or left turns like pedestrians).

Exhibit 5-7. Bicycle conflicts at conventional intersections (showing two left-turn options).



Bicycles can be provided with the option of traveling as either a vehicle or a pedestrian through a roundabout.

At roundabouts, bicycles may be provided the option of traveling as a vehicle or as a pedestrian. As a result, the conflicts experienced by bicyclists are dependent on how they choose to negotiate the roundabout, as shown in Exhibit 5-8. When traveling as a vehicle at a single-lane roundabout, an additional conflict occurs at the point where the bicyclist merges into the traffic stream; the remainder are similar to those for motor vehicles. At double-lane and larger roundabouts where bicycles are typically traveling on the outside part of the circulatory roadway, bicyclists face a potential conflict with exiting vehicles where the bicyclist is continuing to circulate around the roundabout. Bicyclists may feel compelled to "negotiate" the circle (e.g., by indicating their intentions to drivers with their arms) while avoiding conflicts where possible. Bicyclists are less visible and therefore more vulnerable to the merging and exiting conflicts that happen at double-lane roundabouts.

When traveling as a pedestrian, an additional conflict for bicyclists occurs at the point where the bicyclist gets onto the sidewalk, at which point the bicyclist continues around the roundabout like a pedestrian. On shared bicycle-pedestrian paths or on sidewalks, if bicyclists continue to ride, additional bicycle-pedestrian conflicts occur wherever bicycle and pedestrian movements cross (not shown on the exhibit).

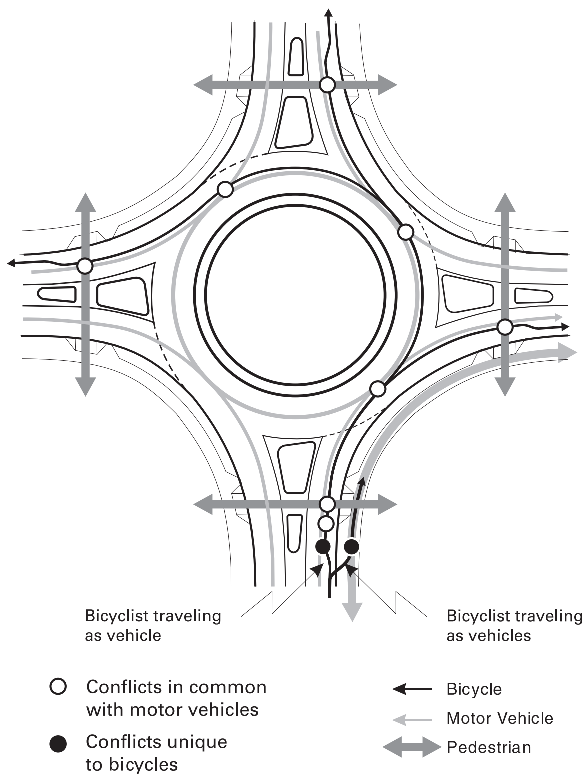


Exhibit 5-8. Bicycle conflicts at roundabouts (showing two left-turn options).

Bicycle-pedestrian conflicts can also occur on shared pathways adjacent to the roundabout.

5.3 Crash Statistics

This section summarizes the overall safety performance of roundabouts in various countries (including the U.S.) and then examines the detailed collision types experienced in France and Queensland, Australia. Pedestrian and bicycle crash statistics are discussed separately, including design issues for visually impaired pedestrians.

5.3.1 Comparisons to previous intersection treatment

Exhibit 5-9 shows the crash frequencies (average annual crashes per roundabout) experienced at eleven intersections in the U.S. that were converted to roundabouts. As the exhibit shows, both types of roundabouts showed a reduction in both injury and property-damage crashes after installation of a roundabout. It should be noted that due to the small size of the data sample, the only result that is statistically significant is the injury crash reduction for small and moderate roundabouts.

Exhibit 5-9. Average annual crash frequencies at 11 U.S. intersections converted to roundabouts.

Type of Roundabout	Sites	Before Roundabout Total	Inj.[3]	PDO[4]	Roundabout Total	Inj.	PDO	Percent Change[5] Total	Inj.	PDO
Small/Moderate[1]	8	4.8	2.0	2.4	2.4	0.5	1.6	-51%	73%	-32%
Large[2]	3	21.5	5.8	15.7	15.3	4.0	11.3	-29%	-31%	-10%
Total	11	9.3	3.0	6.0	5.9	1.5	4.2	-37%	-51%	-29%

Notes:
1. Mostly single-lane roundabouts with an inscribed circle diameter of 30 to 35 m (100 to 115 ft).
2. Multilane roundabouts with an inscribed circle diameter greater than 50 m (165 ft).
3. Inj. = Injury crashes
4. PDO = Property Damage Only crashes
5. Only injury crash reductions for small/moderate roundabouts were statistically significant.
Source: (9)

Compared to results from Australia, France, and the United Kingdom, these crash frequencies are quite high. Annual crash frequencies in France, Australia, and United Kingdom of 0.15, 0.6, and 3.31 injury crashes per roundabout, respectively, have been reported (1, 10). The reader should note that the UK has many high-volume, multilane roundabouts.

In spite of the higher frequencies, injury crash *rates*, which account for traffic volume exposure, are significantly lower at U.S. roundabout sites. In a recent study of eight single-lane roundabouts in Maryland and Florida, the injury crash rate was found to be 0.08 crashes per million entering vehicles (5). By comparison, the injury crash rate was reported to be 0.045 crashes per million entering vehicles in France and 0.275 crashes per million entering vehicles in the United Kingdom (1, 10).

Experiences in the United States show a reduction in crashes after building a roundabout of about 37 percent for all crashes and 51 percent for injury crashes. These values correspond with international studies with much larger sample sizes, as shown in Exhibit 5-10.

Exhibit 5-10. Mean crash reductions in various countries.

Country	Mean Reduction (%) All Crashes	Injury Crashes
Australia	41 - 61%	45 - 87%
France		57 - 78%
Germany	36%	
Netherlands	47%	
United Kingdom		25 - 39%
United States	37%	51%

Source: (2), France: (11)

The findings of these studies show that injury crashes are reduced more dramatically than crashes involving property damage only. This again is in part due to the configuration of roundabouts, which eliminates severe crashes such as left turn, head-on, and right angle collisions. Most of these studies also show that crash reduction in rural areas is much higher than in urban areas.

Caveats for comparing the results of crash studies.

Note that the geometry of many studied sites may not necessarily conform to good roundabout design. Improved design principles, such as an emphasis on achieving consistent speeds, may result in better safety performance. It should also be noted that these crash reductions are generally for sites where roundabouts were selected to replace problem intersections. Therefore, they do not necessarily represent a universal safety comparison with all other intersection types.

Collisions at roundabouts tend to be less severe than at conventional intersections. Most crashes reported at roundabouts are a result of drivers failing to yield on entry, referred to as entering-circulating crashes. In addition, rear-end collisions and single vehicle crashes have been reported in many studies. Exhibit 5-11 shows the percentage of the three main crash types reported in different countries.

Exhibit 5-11. Reported proportions of major crash types at roundabouts.

			Type of Crash[1]		
Country	Crash Description	Type of Roundabout	Entering-circulating	Rear-end	Single Vehicle
Australia	All crashes	Single and multilane	51%	22%	18%
France	Injury crashes	Single and multilane	37%	13%	28%
Germany	All crashes	Single lane	30%	28%	17%
Switzerland	All crashes	Single and multilane	46%	13%	35%
United Kingdom	Injury crashes	Single and multilane	20 - 71%	7 - 25%	8 - 30%

1. Percentages do not necessarily sum to 100% because only three major crash categories are shown.
Source: (10)

5.3.2 Collision types

It is instructive for designers to examine details of collision types and location at roundabouts. Statistics are available for roundabouts designed according to local practices in France, Queensland (Australia), and the United Kingdom. It should be noted that the reported frequencies are to some extent related to the specific design standards and reporting processes used in these countries.

Exhibit 5-12 presents a summary of the percentage of crashes by collision type. The numbered items in the list correspond to the numbers indicated on the diagrams given in Exhibit 5-13 as reported in France. The French data illustrate collision types for a sample of 202 injury crashes from 179 urban and suburban roundabouts in France for the period 1984–1988 (12). For comparison purposes, data from Queensland, Australia (13) and the United Kingdom (1) have been superimposed onto the same classification system.

The results in Exhibit 5-12 are instructive for a number of reasons:

- A variety of collision types can take place at roundabouts. A designer should be aware of these collision types when making decisions about alignment and location of fixed objects. It is recommended that these collision types be adopted as conflict types in the U.S. to conduct traffic conflict analysis and report crashes at roundabouts.
- Although reporting methodologies may vary somewhat, crash experience varies from country to country. This may be due to a combination of differences in driver behavior, and design features.

Exhibit 5-12. Comparison of collision types at roundabouts.

Collision Type	France	Queensland (Australia)	United Kingdom[1]
1. Failure to yield at entry (entering-circulating)	36.6%	50.8%	71.1%
2. Single-vehicle run off the circulatory roadway	16.3%	10.4%	8.2%[2]
3. Single vehicle loss of control at entry	11.4%	5.2%	[2]
4. Rear-end at entry	7.4%	16.9%	7.0%[3]
5. Circulating-exiting	5.9%	6.5%	
6. Pedestrian on crosswalk	5.9%		3.5%[4]
7. Single vehicle loss of control at exit	2.5%	2.6%	[2]
8. Exiting-entering	2.5%		
9. Rear-end in circulatory roadway	0.5%	1.2%	
10. Rear-end at exit	1.0%	0.2%	
11. Passing a bicycle at entry	1.0%		
12. Passing a bicycle at exit	1.0%		
13. Weaving in circulatory roadway	2.5%	2.0%	
14. Wrong direction in circulatory roadway	1.0%		
15. Pedestrian on circulatory roadway	3.5%		[4]
16. Pedestrian at approach outside crosswalk	1.0%		[4]
Other collision types		2.4%	10.2%
Other sideswipe crashes		1.6%	

Notes:
1. Data are for "small" roundabouts (curbed central islands > 4 m [13 ft] diameter, relatively large ratio of inscribed circle diameter to central island size)
2. Reported findings do not distinguish among single-vehicle crashes.
3. Reported findings do not distinguish among approaching crashes.
4. Reported findings do not distinguish among pedestrian crashes.
Sources: France (12), Australia (13), United Kingdom (1)

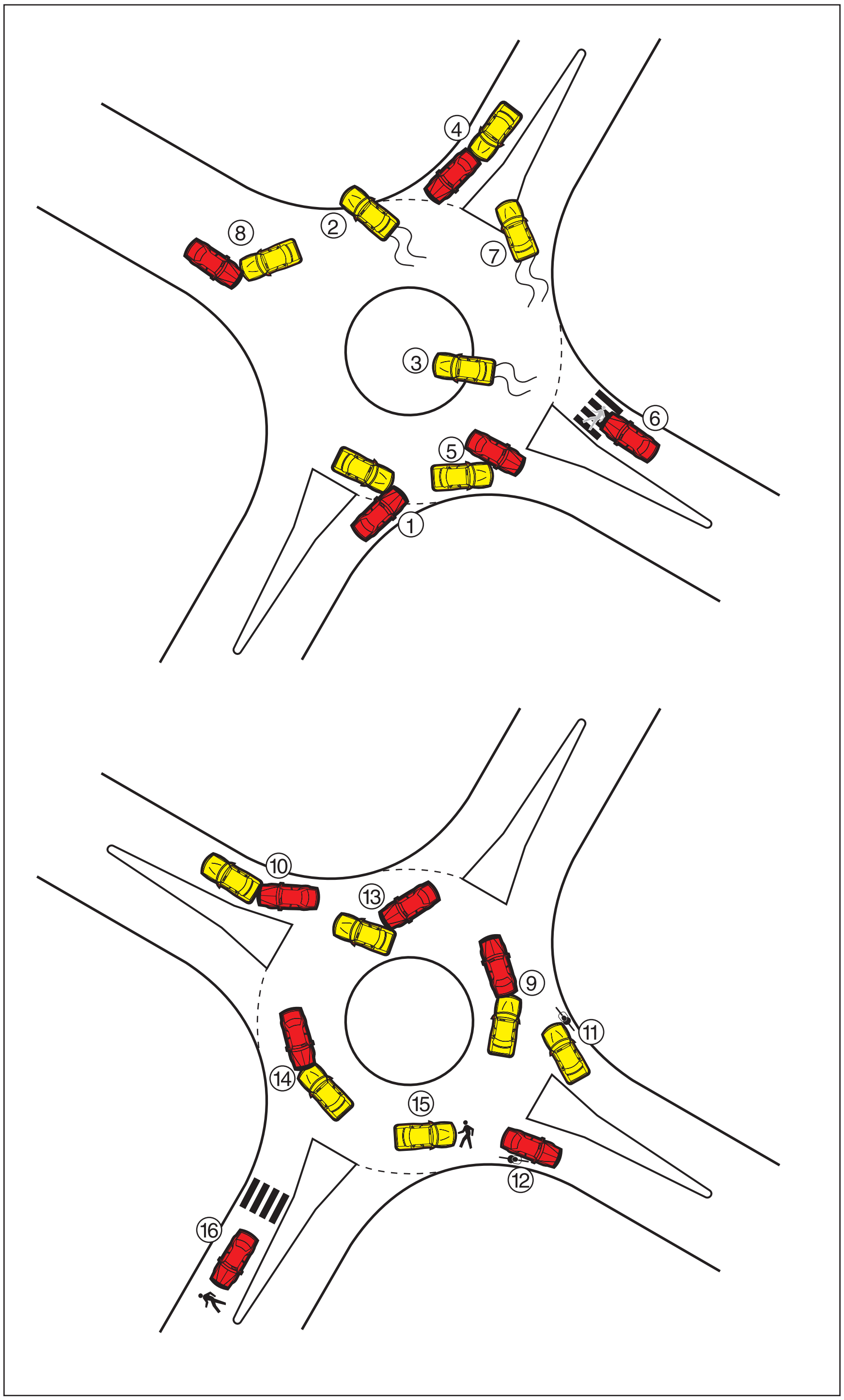


Exhibit 5-13. Graphical depiction of collision types at roundabouts.

Source (8)

Three of the predominant types of collision are: (1) failures to yield at entry to circulating vehicles, (2) single vehicle run-off the circulatory roadway, and (3) single vehicle run-into the central island. A more recent crash study (14) confirmed a high proportion of single vehicle crashes: 49 percent in rural areas, versus 21 percent in urban areas. According to crash models from the United Kingdom, single vehicle crashes range between 20 and 40 percent depending on traffic and design characteristics of sites. In the United Kingdom models, separation by urban and rural areas is not provided.

To reduce the severity of single vehicle crashes, special attention should be accorded to improving visibility and avoiding or removing any hard obstacles on the central island and splitter islands in both urban and rural environments. A French study (14) identified a number of major obstacles that caused fatalities and injuries: trees, guardrail, concrete barriers, fences, walls, piers, sign or light poles, landscaping pots or hard decorative objects, and steep cross-slopes on the central island.

In rural areas, the benefit of lighting has not yet been quantified. In France, only 36 percent of the rural sites are lighted. At these sites, 46 percent of all crashes, and 49 percent of single vehicle crashes occur at night (14).

The French study (7) in 15 towns of 202 urban roundabout crashes compared with all crossroads reported the percentage of crashes by user type, as shown in Exhibit 5-14. The percentage of crashes concerning pedestrians was similar to all crossroads. However, the percentage of crashes involving bicycles and mopeds was larger—15.4 percent for urban crossroads overall versus 24.2 percent for roundabouts, i.e., almost 60 percent more.

Exhibit 5-14. Crash percentage per type of user for urban roundabouts in 15 towns in western France.

User	All Crossroads	Roundabouts
Pedestrians	6.3%	5.6%
Bicycles	3.7%	7.3%
Mopeds	11.7%	16.9%
Motor cycles	7.4%	4.8%
Cars	65.7%	61.2%
Utility vehicles	2.0%	0.6%
Heavy goods vehicles	2.0%	3.0%
Bus/coach	0.8%	0.6%
Miscellaneous	0.4%	0.0%
Total	100.0%	100.0%

Source: (7)

5.3.3 Pedestrians

As was described previously, vehicular injury crashes normally decrease when roundabouts are installed at an existing intersection. The safety benefits of roundabouts have been found to generally carry over to pedestrians as well, as shown in British statistics of Exhibit 5-15. This may be due to the reduced speeds at roundabouts as compared with the previous intersection forms.

Exhibit 5-15. British crash rates for pedestrians at roundabouts and signalized intersections.

Intersection Type	Pedestrian Crashes per Million Trips
Mini-roundabout	0.31
Conventional roundabout	0.45
Flared roundabout	0.33
Signals	0.67

Source: (1, 15)

For pedestrians, the risk of being involved in a severe collision is lower at roundabouts than at other forms of intersections, due to the slower vehicle speeds. Likewise, the number of conflict points for pedestrians is lower at roundabouts than at other intersections, which can lower the frequency of collisions. The splitter island between entry and exit allows pedestrians to resolve conflicts with entering and exiting vehicles separately.

A Dutch study of 181 intersections converted to roundabouts (4) found reductions (percentage) in all pedestrian crashes of 73 percent and in pedestrian injury crashes of 89 percent. In this study, all modes shared in the safety benefits to greater (passenger cars) or lesser extents (bicycles), as shown in Exhibit 5-16.

Exhibit 5-16. Percentage reduction in the number of crashes by mode at 181 converted Dutch roundabouts.

Mode	All Crashes	Injury Crashes
Passenger car	63%	95%
Moped	34%	63%
Bicycle	8%	30%
Pedestrian	73%	89%
Total	51%	72%

Source: (4)

Zebra-stripe markings are recommended at most roundabouts to indicate pedestrian crossings.

A risk analysis of 59 roundabouts and 124 signalized intersections was carried out on crash data in Norway between 1985 and 1989. Altogether, 33 crashes involving personal injury were recorded at the 59 roundabouts. Only 1 of these crashes involved a pedestrian, compared with the signalized intersections, where pedestrians were involved in 20 percent of the personal injury crashes (57 of 287 injury crashes) (16).

Further, there is no quantitative evidence of increased safety for pedestrians at roundabouts with striped (zebra) crossings, where pedestrians have priority. Therefore, striped crossings have generally not been used in other countries. However, in the U.S., it is recommended that all crosswalks be striped except at rural locations with low pedestrian volumes. Although this is not their intended function, striped crosswalks may further alert approaching drivers to a change in their appropriate speed near the yield point.

Safety of visually impaired pedestrians at roundabouts requires further research.

Crash data have not been collected to indicate whether a pedestrian has a disability, and no studies have focused specifically on the safety of visually impaired pedestrians at roundabouts. This is an area requiring further research.

5.3.3.1 Information access for blind or visually impaired pedestrians

Challenges that roundabouts pose to visually impaired pedestrians.

Roundabout crossing skills may be difficult for disabled pedestrians to perform without assistance. For example, audible pedestrian-activated signals may be considered on an approach, although this treatment is not typical. Any leg of any roundabout could be equipped with a pedestrian-activated signal at the pedestrian crossing, if a balanced design requires providing assistance to pedestrians at that location. For example, motorized volume that is too heavy at times to provide a sufficient number of gaps acceptable for pedestrians may warrant a pedestrian signal equipped with audible devices to assist people with visual disabilities.

When crossing a roundabout, there are several areas of difficulty for pedestrians who are blind or visually impaired. It is desirable that a visually impaired pedestrian with good travel skills should be able to arrive at an unfamiliar intersection and cross it with pre-existing skills and without special, intersection-specific training. Roundabouts pose problems at several points of the crossing experience, from the perspective of their access to information:

- The first task of the visually impaired pedestrian is to locate the crosswalk. This can be difficult if the roundabout is not properly landscaped and if the curb edge of the ramp is not marked with a detectable warning surface (see Chapter 6). The crosswalk direction must also be unambiguous.
- Depending upon whether the visually impaired pedestrian is crossing the roundabout in a clockwise or counterclockwise direction, they must listen for a safe gap to cross either the entrance or exit lane(s). The primary problem is the sound of traffic on the roundabout, which may mask the sound of cars approaching the

crosswalk. While crossing the exit lane poses the greater hazard to the pedestrian who is visually impaired because of the higher speed of the vehicles, crossing the entrance may also pose significant problems. Entering traffic, while slower, may also be intimidating as it may not be possible to determine by sound alone whether a vehicle has actually stopped or intends to stop. Sighted pedestrians often rely upon communication through eye contact in these situations; however, that is not a useful or reliable technique for the pedestrian who is visually impaired. Both these problems are further exacerbated at roundabouts with multilane entrances and exits. In these roundabouts, a stopped car in the near lane may mask the sounds of other traffic. It may also block the view of the driver in the far lane of the cane or guide dog of a person who is visually impaired who begins to cross (this is also a problem for children and people using wheelchairs on any crossing of a multilane road).

- The third task is locating the splitter island pedestrian refuge. If this refuge is not ramped, curbed, or equipped with detectable warnings, it is not detectable by a pedestrian who is visually impaired.
- Crossing the remaining half of the crossing (see the second bullet above).
- Locating the correct walkway to either continue their path or locate the adjacent crosswalk to cross the next leg of the roundabout.

Unless these issues are addressed by a design, the intersection is "inaccessible" and may not be permissible under the ADA. Chapters 6 and 7 provide specific suggestions to assist in providing the above information. However, more research is required to develop the information jurisdictions need to determine where roundabouts may be appropriate and what design features are required for people with disabilities. Until specific standards are adopted, engineers and jurisdictions must rely on existing related research and professional judgment to design pedestrian features so that they are usable by pedestrians with disabilities.

Chapters 6 and 7 provide suggestions on designing roundabouts to accommodate persons with disabilities.

Possible design remedies for the difficulties faced by pedestrians include tight entries, raised speed tables with detectable warnings, treatments for visually impaired pedestrians to locate crosswalks, raised pavement markers with yellow flashing lights to alert drivers of crossing pedestrians, pedestrian crossings with actuated signals set sufficiently upstream of the yield line to minimize the possibility of exiting vehicle queues spilling back into the circulatory roadway (6). However, the safety of these treatments at roundabouts has not been tested in the United States.

5.3.4 Bicyclists

As shown in Exhibit 5-17, at British roundabouts bicyclists fare worse in terms of crashes at roundabouts than at signalized intersections.

Exhibit 5-17. British crash rates (crashes per million trips) for bicyclists and motorcyclists at roundabouts and signalized intersections.

Intersection Type	Bicyclists	Motorcyclists
Mini-roundabout	3.11	2.37
Conventional roundabout	2.91	2.67
Flared roundabout	7.85	2.37
Signals	1.75	2.40

Source: (1, 15)

A French study (7) compared the crashes in 1988 in 15 towns in the west of France at both signalized intersections and roundabouts, as shown in Exhibit 5-18. The conclusions from the analysis were:

- There were twice as many injury crashes per year at signalized intersections than at roundabouts;
- Two-wheel vehicles were involved in injury crashes more often (+77 percent) at signalized intersections than on roundabouts;
- People were more frequently killed and seriously injured per crash (+25 percent) on roundabouts than at signalized intersections;
- Proportionally, two-wheel vehicle users were more often involved in crashes (16 percent) on roundabouts than at signalized intersections. Furthermore, the consequences of such crashes were more serious.

Exhibit 5-18. A comparison of crashes between signalized and roundabout intersections in 1998 in 15 French towns.

	Signalized Crossroads	Roundabouts
Number of crossroads	1,238	179
Number of personal injuries	794	59
Number of crashes involving 2-wheel vehicles	278	28
Personal injury crashes/year/crossroad	0.64	0.33
2-wheel vehicle crashes/year/crossroad	0.23	0.13
Crashes to 2-wheel vehicles per 100 crashes	35.0	40.7
Serious crashes/year/crossroad	0.14	0.089
Serious crashes to 2-wheel vehicles/year/crossroad	0.06	0.045
Serious crashes/100 crashes	21.9	27.1
Serious crashes to 2-wheel vehicles/100 crashes to a 2-wheel vehicle	27.0	33.3

Source: (7)

All European countries report that a more careful design is necessary to enhance bicyclists' safety. The type of bicycle crashes depends on the bicycle facilities provided at the roundabout. If there are no bicycle facilities, or if there is a bike lane on the outer area of the circulatory roadway, crashes typically occur between entering cars and circulating bicyclists as well as between cars heading into an exit and circulating bicyclists. Improperly placed signs on the splitter island may also be a contributing factor.

Typical European practice is to provide separated bicycle facilities outside the circulatory roadway when vehicular and bicycle volumes are high.

As a result, most European countries have the following policies:

- Avoid bike lanes on the outer edge of the circulatory roadway.
- Allow bicyclists to mix with vehicle traffic without any separate facility in the circulatory roadway when traffic volumes are low, on single lane roundabouts operating at lower speeds (e.g., up to 8,000 vehicles per day in the Netherlands (4)).
- Introduce separated bicycle facilities outside the circulatory roadway when vehicular and bicycle volumes are high. These separated bicycle facilities cross the exits and entries at least one car length from the edge of the circulatory roadway lane, adjacent to the pedestrian crossings. In some countries, bicyclists have priority over entering and exiting cars, especially in urban areas (e.g., Germany). Other countries prefer to give priority to car traffic showing a yield sign to bicyclists (e.g., Netherlands). The latter solution (i.e., separate bicycle facilities with vehicular traffic priority at the crossing points) is the standard solution for rural areas in most European countries.

Speed is a fundamental risk factor in the safety of bicyclists and pedestrians. Typical bicyclist speeds are in the range of 20 to 25 km/h (12 to 15 mph), and designs that constrain the speeds of vehicles to similar values will minimize the relative speeds and thereby improve safety. Design features that slow traffic such as tightening entry curvature and entry width, and radial alignment of the legs of a roundabout, such as with the urban compact design, are considered safe treatments for bicyclists (17).

In the Netherlands, a 90 percent decrease in injury crashes was experienced with separate bicycle paths around roundabouts where bicyclists do not have right-of-way at the crossings (17).

A bicycle crash prediction model from Sweden has been validated against data for Swedish, Danish, and Dutch roundabouts (18). The model provides reasonable results for roundabouts with up to 12,000 vehicles per day and 4,000 bicycles per day. The model tends to over-predict crashes (i.e., is conservative) for roundabouts carrying more than 12,000 vehicles per day that are also designed with separate bicycle paths with crossings on the approach legs. It is calibrated for crossroad intersections as well as roundabouts. To obtain the expected cycling crashes per year at roundabouts, the value derived from the general junction model is factored by 0.71, implying that bicycle crashes at roundabouts are 71 percent less frequent than at junctions in general. However, the reader is cautioned when extrapolating European bicycling experience to the U.S., as drivers in Europe are more accustomed to interacting with bicyclists.

5.4 Crash Prediction Models

Crash prediction models have not been developed for U.S. roundabouts.

Crash prediction models have been developed for signalized intersections in the U.S., as discussed previously in Chapter 3. However, no crash prediction models exist yet for U.S. roundabouts and driver behavior. Given the relatively recent introduction of roundabouts to the U.S. and driver unfamiliarity with them, crash prediction models from other countries should be used cautiously. As reported earlier in Section 5.3, crash statistics vary from country to country, both in terms of magnitude and in terms of collision types. Consequently, the application of a crash prediction model from another country may not accurately predict crash frequencies at U.S. locations. Nonetheless, these crash prediction models from other countries can be useful in understanding the *relative* effects of various geometric features on the number of crashes that might be expected. The user is thus cautioned to use these models only for comparative purposes and for obtaining insights into the refinement of individual geometric elements, not to use them for predicting *absolute* numbers of crashes under U.S. conditions.

Crash models relating crash frequency to roundabout characteristics are available from the United Kingdom. The sample consisted of 84 four-leg roundabouts of all sizes, small to large and with various number of approach lanes and entry lanes (flared or parallel entries) (1). Approach speeds were also evenly represented between 48 to 64 km/h (30 to 40 mph) and 80 to 113 km/h (50 to 70 mph). Crash data were collected for periods of 4 to 6 years, a total of 1,427 fatal, serious, and slight injuries only. The proportion of crashes with one casualty was 83.7 percent, and those with two casualties was 12.5 percent. The models are based on generalized linear regression of the exponential form, which assumes a Poisson distribution. Their goodness of fit is expressed in terms of scaled deviations that are moderately reliable. No additional variables, other than those listed below, could further improve the models significantly (see also (8)).

The British crash prediction equations (1), for each type of crash are listed in Equations 5-1 through 5-5. Note that these equations are only valid for roundabouts with four legs. However, the use of these models for relative comparisons may still be reasonable.

Entry-Circulating: (5-1)

$$A = 0.052 Q_e^{0.7} Q_c^{0.4} \exp\left(-40C_e + 0.14e - 0.007ev - \frac{1}{1 + \exp(4R - 7)} + 0.2P_m - 0.01\theta\right)$$

where: A = personal injury crashes (including fatalities) per year per roundabout approach;
- Q_e = entering flow (1,000s of vehicles/day)
- Q_c = circulating flow (1,000s of vehicles/day)
- C_e = entry curvature = $1/R_e$
- e = entry width (m)
- v = approach width (m)
- R = ratio of inscribed circle diameter/central island diameter
- P_m = proportion of motorcycles (%)
- θ = angle to next leg, measured centerline to centerline (degrees)

Approaching: $A = 0.0057 Q_e^{1.7} \exp(20 C_e - 0.1 e)$ (5-2)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg;
Q_e = entering flow (1,000s of vehicles/day)
C_e = entry curvature = $1/R_e$
R_e = entry path radius for the shortest vehicle path (m)
e = entry width (m)

Single Vehicle: $A = 0.0064 Q_e^{0.8} \exp(25 C_e + 0.2v - 45 C_a)$ (5-3)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg
Q_e = entering flow (1,000s of vehicles/day)
C_e = entry curvature = $1/R_e$
R_e = entry path radius for the shortest vehicle path (m)
V = approach width (m)
C_a = approach curvature = $1/R_a$
R_a = approach radius (m), defined as the radius of a curve between 50 m (164 ft) and 500 m (1,640 ft) of the yield line

Other (Vehicle): $A = 0.0064 Q_e^{0.8} \exp(25 C_e + 0.2v - 45 C_a)$ (5-4)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg
Q_{ec} = product $Q_e \cdot Q_c$
Q_e = entering flow (1,000s of vehicles/day)
Q_c = circulating flow (1,000s of vehicles/day)
P_m = proportion of motorcycles

Pedestrian: $A = 0.029 Q_{ep}^{0.5}$ (5-5)

where: A = personal injury crashes (including fatalities) per year at roundabout approach or leg
Q_{ep} = product $(Q_e + Q_{ex}).\ Q_p$
Q_e = entering flow (1,000s of vehicles/day)
Q_{ex} = exiting flow (1,000s of vehicles/day)
Q_p = pedestrian crossing flow (1,000s of pedestrians/day)

According to the U.K. crash models, the major physical factors that were statistically significant are entry width, circulatory width, entry path radius, approach curvature, and angle between entries. Some of the effects of these parameters are as follows:

- *Entry width*: For a total entry flow of 20,000 vehicles per day, widening an entry from one lane to two lanes is expected to cause 30 percent more injury crashes. At 40,000 vehicles per day, widening an entry from two lanes to three lanes will cause a 15 percent rise in injury crashes. Moreover, the models could not take into account the added hazard to bicyclists and pedestrians who will have to travel longer exposed distances. (8)

- *Circulatory width*: Widening the circulatory roadway has less impact on crashes than entry width. Crashes are expected to rise about 5 percent for a widening of two meters. (8)
- *Entry path radius*: Entry-circulating collision type increases with entry path radius (for the fastest path), while single vehicle and approach collision types decrease. For a double-lane approach, an optimum entry path radius is 50 to 70 m (165 to 230 ft). (8)
- *Approach curvature*: Approach curvature is safer when the approach curve is to the right and less so when the curve is to the left. This implies that a design is slightly safer when reverse curves are provided to gradually slow drivers before entry. For a double-lane approach roundabout with entering flow of 50,000 vehicles per day, changing a straight approach to a right-turning curve of 200 m (650 ft) radius reduces crash frequency by 5 percent. (8)

Maximize angles between entries.

- *Angle between entries*: As the angle between entries decreases, the frequency of crashes increases. For example, an approach with an angle of 60 degrees to the next leg of the roundabout increases crash frequency by approximately 35 percent over approaches at 90-degree angles. Therefore, the angle between entries should be maximized to improve safety.

An approach suggested in Australia (13) differs from the British approach in that the independent variables are based on measures related to driver behavior. For instance, the collision rate for single vehicle crashes was found to be:

$$A_{sp} = 1.64 \times 10^{-12} \times Q^{1.17} \times L \times (S + \Delta S)^{4.12} / R^{1.91} \quad (5\text{-}6)$$

and

$$A_{sa} = 1.79 \times 10^{-9} \times Q^{0.91} \times L \times (S + \Delta S)^{1.93} / R^{0.65} \quad (5\text{-}7)$$

where: A_{sp} = the number of single vehicle crashes per year per leg for vehicle path segments prior to the yield line.
A_{sa} = the number of single vehicle crashes per year per leg for vehicle path segments after the yield line.
Q = the average annual daily traffic in the direction considered—one way traffic only (veh/d)
L = the length of the driver's path on the horizontal geometric element (m).
S = the 85th-percentile speed on the horizontal geometric element (km/h).
ΔS = the decrease in the 85th-percentile speed at the start on the horizontal geometric element (km/h). This indicates the speed change from the previous geometric element.
R = the vehicle path radius on the geometric element (m).

These equations demonstrate a direct relationship between the number of crashes, overall speed magnitudes, and the change in speed between elements. Therefore, this equation can be used to estimate the *relative* differences in safety benefits between various geometric configurations by estimating vehicle speeds through the various parts of a roundabout.

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