ROUNDABOUT SAFETY EXPERIENCE

Chapter 5 of the Synthesis of North American Roundabout Practice

Philip Weber, P.Eng.
Ourston Roundabouts Canada

Paper prepared for presentation
at the Road Safety / Geometric Design Session
of the 2007 Annual Conference of the
Transportation Association of Canada
Saskatoon, Saskatchewan

Abstract

In 2006 Ourston Roundabouts Canada completed a "Synthesis of North American Roundabout Practice" for TAC. The synthesis consisted of a literature review of roundabout guides and current practice, research and case studies, supplemented with selected experience in other countries where appropriate. It also reported on the results of a web-based survey of public road agencies in Canada and the United States on roundabout planning, design and operating practices.

The synthesis found that roundabouts are usually constructed for one or more of three reasons: safety benefits, capacity benefits, or environmental benefits. Currently the main reason for constructing roundabouts in North America is greater intersection safety, as various studies have shown they can reduce injury collisions by about 75% compared to stop control or traffic signals.

This paper presents the results of the synthesis as they apply to roundabout safety. It explains why roundabouts have such a high potential for safety. It discusses the studies undertaken in North America (and in other countries where North American data is insufficient) to evaluate the effects of roundabouts on the safety of motorists, pedestrians and bicyclists. Finally, through a discussion of the web-based survey it describes what measures can be taken in the design of roundabouts to maximize their safety potential. These measures may vary depending on whether the roundabouts are single-lane or multi-lane, or whether there are any high-speed approaches.

Roundabout Safety Prediction

Although crash records at roundabouts in North America are limited, considerable research and data collection has been undertaken on safety at roundabouts in other countries. Most have simply reported before and after results with roundabout conversions. Some countries, such as the U.K., Sweden and Australia, have also developed models for predicting collisions involving motor vehicles. These models tend not to predict collisions involving pedestrians or other road users. All results should be used judiciously, much more so than for capacity analysis methods (discussed in Chapter 3 of the "Synthesis of North American Roundabout Practice") because of variation in the way collisions are reported between these countries and in North America.

The collision prediction model used in the U.K. was developed by the Transport Research Laboratory (TRL) as documented in LR1120 published in 1984 by Maycock and Hall. It uses a statistically derived formula based on a study of injury and fatal collisions at 84 roundabouts with varying geometric parameters in varying speed zones. As with the U.K. capacity model, the collision prediction model relates injury crashes to several geometric design parameters. It is available in the ARCADY software package.

The roundabout collision prediction model used in Australia was developed by Arndt in 1998. It uses several non-linear regression equations based on driver behaviour as reflected by speed and vehicle paths, as well as other significant predictors of crashes, and predicts crashes by type (single-vehicle, approach, entry-circulating, exit-circulating, sideswipe, and other). It is available in the ARNDT software package.

NCHRP 3-65 in the United States

National Cooperative Highway Research Program (NCHRP) 3-65 was a study undertaken to develop a set of operational, safety and design tools for roundabouts calibrated to U.S. field observations. The study has been finalized as NCHRP Report 572, *Roundabouts in the United States*.

The May 2006 draft report for NCHRP 3-65 proposes two methods for predicting collisions at roundabouts in the U.S. One is an intersection-level model that uses regression equations from data collected at 90 roundabouts to estimate total and injury collisions from average annual daily traffic (AADT). Roundabouts are classified by number of approaches and number of circulating lanes. The results can be calibrated by using local collision data if available.

The total number of collisions at a roundabout with 4 approaches and 2 circulating lanes can be predicted with:

$$0.0038\ (AADT)^{0.7490}$$

The number of injury collisions at a roundabout with 4 approaches and 1 or 2 circulating lanes can be predicted with:

$$0.0013\ (AADT)^{0.5923}$$

The other model is based on intersection approach geometry and traffic flows. It uses traffic flows and several geometric parameters collected at 139 approaches selected from the same 90 roundabouts, and provides an estimate of total annual collisions by type per roundabout approach. At this time the approach-level model does not classify collisions as to property damage only, injury or fatality.

For total annual entry-circulating crashes:

$$e^{-7.2158} (AADT_e)^{0.702} (AADT_c)^{0.132} e^{(0.051E-0.028\theta)}$$

For total annual exit-circulating crashes:

$$e^{-11.6805} (AADT_e)^{0.280} (AADT_c)0.253\ e^{(0.022ICD+0.111Cw)}$$

For total annual approach area crashes:

$$e^{-5.1527} (AADT_e)^{0.461} e^{(0.03V)}$$

where $AADT_e$ and $AADT_c$ are the entering and circulating AADT;
E = entry width of each approach (feet);
θ = angle to next leg;
ICD = inscribed circle diameter (feet);
Cw = circulatory width (feet); and
V = approach half-width (feet).

It is possible that both collision prediction methods may be incorporated into the two-lane and multi-lane highways sections of the U.S. Highway Safety Manual (HSM) currently under development.

Collisions can also be predicted on the basis of collision modification factors (CMF's) using the results of before/after studies of intersections converted to roundabouts. This is discussed in the next section.

Motor Vehicle Collisions

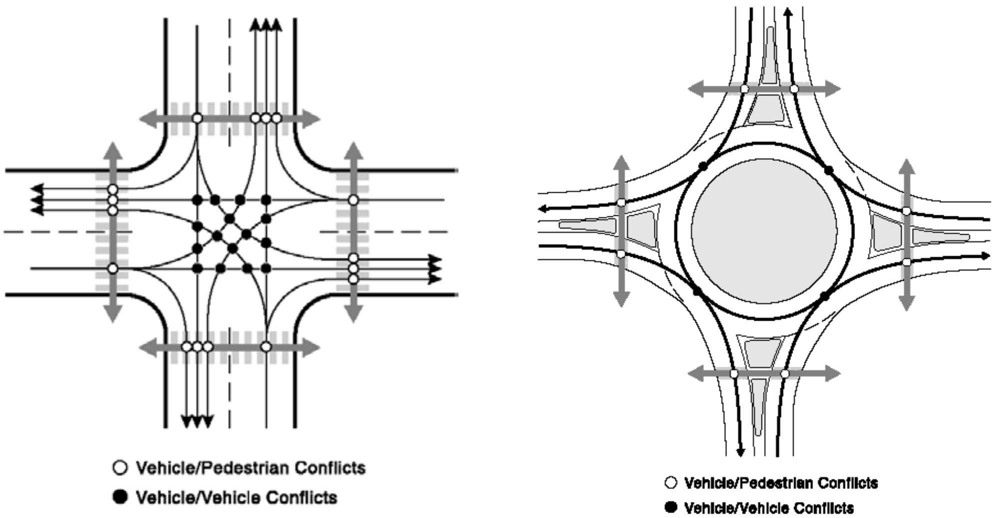
Compared to other intersections, roundabouts have fewer potential vehicle-vehicle conflict points. For a four-leg intersection, the reduction is significant – from 32 to 8 conflict points (see Figure 1). For a three-leg intersection the reduction is from 9 to 6 conflict points. Normally not all conflicts occur at the same time at other intersections, as certain movements are separated in time by a stop control or traffic signal. However, serious collisions can result when this separation in time does not occur (the case with red light running, for example).

The most severe right angle and opposing left turn collisions are eliminated at roundabouts. The remaining vehicle collisions that are common can be classified as:

- Failure to yield at entry (entry-circulating).
- Single-vehicle runoff the circulatory road.
- Single-vehicle loss of control at entry.
- Rear-end at entry.
- Exit-circulating.
- Single-vehicle loss of control at exit.
- Pedestrian involvement.
- Bicyclist involvement.

Entry-circulating crashes because of failure to yield at the entry are usually the most common type at roundabouts, as evidenced by crash experience in France, Australia and the United Kingdom.

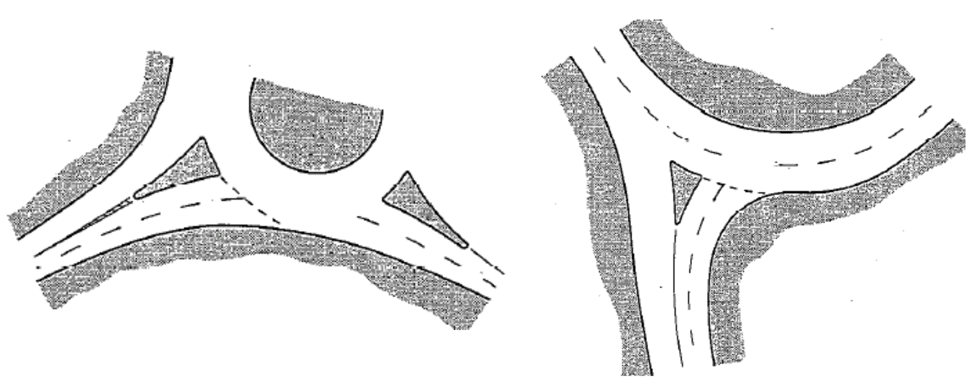
Figure 1
Comparison of Vehicle and Pedestrian Conflicts at a 4-Leg Intersection



Source: FHWA Roundabouts: An Informational Guide

Experience has shown that entry geometry plays an important role in determining what crash types are most probable. For example, an entry that is tangential to the circulating vehicle path will make entry-circulating collisions more likely because these drivers will be less inclined to yield. Conversely, an entry that is almost perpendicular to the circulating vehicle path will generate rear end and loss of control collisions more likely because abrupt braking may be necessary. The differences in entry geometry are illustrated in Figure 2. An entry geometry somewhere in between the two extremes is most appropriate, and it depends on entering versus circulating traffic volumes and site context.

Figure 2
Tangential and Straight Entry Geometry



Source: Ourston Roundabout Design Guidelines

The most well-known study of collision experience at roundabouts in North America is from a March 2000 report by the Insurance Institute for Highway Safety (IIHS) entitled “A Study of Crash Reductions Following Installation of Roundabouts in the United States”. The study looked at changes in motor vehicle crashes after the conversion of 24 intersections from stop or traffic signal control to roundabouts. The before and after data was collected from a mix of urban and rural locations in eight states, and involved 15 single-lane and 9 multi-lane roundabouts.

The study used an empirical Bayes approach, which accounts for regression-to-the-mean effects. It found the following highly significant relationships:

- Reduction in collisions of all types of 39%.
- Reduction in injury collisions of 76%.
- Reduction in fatal and incapacitating collisions of about 90%.

These CMF’s are “consistent with numerous international studies and suggest roundabout installation should be strongly promoted as an effective safety treatment for intersections”. This is given the large numbers of injury (700,000) and property damage (1,300,000) crashes that occur each year at stop signs and traffic signals in the U.S.

The IIHS study also noted that while concerns had been expressed with older drivers having difficulties adjusting to roundabouts, the average age of crash-involved drivers did not increase, suggesting that roundabouts do not pose a problem for older drivers.

The study was expanded in 2003 by the New York State Department of Transportation (NYSDOT) to 33 roundabouts, representing a more extensive database in terms of number of locations, years of data and diversity of conditions. The results are presented in Table 1, and show that roundabouts continue to have excellent safety records. Total collisions of all types were reduced by 47%, and injury collisions were reduced by 72%.

Table 1

Safety Impacts at U.S. Roundabouts

Condition Before Conversion to Roundabout	**Sites**	**Change in Collision Frequency**		
		PDO	**Injury**	**Total**
Single-Lane, Urban Stop Controlled	12	67%	80%	69%
Single-Lane, Rural Stop Controlled	9	63%	68%	65%
Multi-Lane, Urban Stop Controlled	7	0%	73%	8%
Urban Signalized	5	31%	75%	37%
All Sites	33	41%	72%	47%

Source: ITE 2004, Designing and Operating Safer Roundabouts

Comparing single-lane roundabouts to multi-lane roundabouts, the NYSDOT study shows that multi-lane roundabouts are more prone to property damage only (PDO) collisions. This is likely due to additional entry-circulating, exit-circulating and sideswipe conflicts and increased visibility obstructions. In this study, multi-lane roundabouts were not shown to be more prone to injury collisions when higher traffic volumes were accounted for. This was somewhat countered by a 2004 study of 11 roundabouts in the U.S. that showed greater reductions in collisions at single-lane roundabouts than at multi-lane roundabouts (73% versus 31%).

Additional before/after analysis for multi-lane roundabouts has come out of NCHRP 3-65:

- Conversion from a signalized intersection to a multi-lane roundabout (4 sites, suburban settings) yielded a 67% reduction in all crashes. In terms of injury crashes the sample size was too small to calculate a percentage, but of the 98 crashes in the after period, only 2 involved injury.
- Conversion from a two-way stop to a multi-lane roundabout (11 sites, urban/suburban settings) yielded an 18% reduction in all crashes and a 72% reduction in injury crashes. Of the 272 crashes in the after period, 13 involved injuries.

NCHRP 3-65 has also verified the collision reduction findings of the IIHS and NSYDOT studies, with a composite CMF for injury crashes of 75.8%. NCHRP 3-65 further disaggregates the CMF's by previous intersection control (two-way stop, all-way stop or signalized), study area (urban, suburban, rural) and number of entry lanes, although for the most part these sample sizes are small.

A number of other studies have been conducted in North America, most using limited sample sizes and no accounting for regression-to-the-mean effects. Some involved roundabouts installed at problem locations. All concluded that roundabouts reduced crashes. A report entitled "Roundabout - Providing an Excellent Service to the Road User" stated: "Even if there are variations in the accident rates observed in different countries, it is indisputable that the rates are much lower… and the accident severity is equally reduced."

Pedestrian-Vehicle Collisions

Roundabouts result in fewer potential vehicle-pedestrian conflict points compared to other intersections. A pedestrian crossing at a typical signalized intersection faces four potential vehicular conflicts, each coming from a different direction (see Figure 1):

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

For a four-leg intersection with single-lane entries and exits, this represents 16 vehicle-pedestrian conflicts. While the illegal movements are less likely to occur, they are potentially the most severe for a pedestrian and often occur without warning. Pedestrians at single-lane roundabouts face 2 conflicting vehicular movements on each approach: with entering vehicles, and with exiting vehicles. It should be noted that at both types of intersections, an additional conflict is added for each additional lane that a pedestrian must cross.

There are other advantages for pedestrians at roundabouts:

- Crossing distances are usually shorter.
- Crossings are less complex, requiring looking in only one direction at a time.
- Conflicting traffic speeds are generally lower, meaning less chance of injury in a collision.
- Drivers are more likely to see pedestrians in the crosswalk.
- Their actual level of safety is more related to their feeling of security. At signalized crossings, pedestrians can experience an exaggerated feeling of safety because of the walk indication that does not match their actual level of safety.

A potential disadvantage at roundabouts is the accommodation of visually impaired pedestrians. This is discussed in Chapter 8 of the “Synthesis of North American Roundabout Practice”.

Research on pedestrian safety at roundabouts in North America has been limited to only a few before/after studies. The IIHS study mentions that although the sample was too small to estimate effects on pedestrian crashes, none of the multi-lane roundabouts have had a single pedestrian crash so far, even though there were two crashes during the before period at these sites.

Elsewhere:

- A 1993 study in the Netherlands examined collision experience at 181 intersections converted to roundabouts. Pedestrian collisions (all injury severities) dropped 73% and pedestrian casualties dropped 89%.
- Evaluations in Sweden concluded that single-lane roundabouts are very safe for pedestrians, at about a 78% reduction in injuries, and that multi-lane roundabouts are about as safe as other intersections.
- A 2002 study of collision experience at the roundabouts in Park City, Vail, West Vail and Avon, Colorado, showed 2 pedestrian crashes prior to the roundabouts operating with over 164 million vehicle movements, compared to 1 pedestrian crash with roundabouts experiencing over 282 million vehicle movements.

Bicyclist-Vehicle Collisions

At most roundabouts bicyclists have the option of travelling through as would a motor vehicle, or dismounting and traversing as a pedestrian. Bicyclists therefore face about the same number of conflicts as drivers or pedestrians. However, because bicyclists typically ride on the right side of the road between intersections, they can face additional conflicts due to overlapping paths with motor vehicles when travelling through or exiting a roundabout as a vehicle. This is particularly the case at multi-lane roundabouts.

Bicyclists are often considered to be the most vulnerable users of roundabouts. Almost half of the collisions involving cyclists occur between an entering vehicle and a bicyclist who is already on the circulatory road. In many cases, these crashes occur when a driver does not yield on entry.

There has been even less research on bicyclist safety at roundabouts in North America than pedestrian safety. The most comprehensive study overseas was undertaken in western France at 1,238 signalized intersections and 179 roundabouts. The study found that in proportion to the total number of crashes, two-wheeled vehicles were involved in crashes more often at roundabouts (+16%), but were involved in injury crashes more often at signalized intersections (+77%).

A study in Sweden at 72 locations concluded that at single-lane roundabouts bicyclists were involved in 20% fewer injury collisions than at other intersections. However, at multi-lane roundabouts they were twice as likely to be involved in injury crashes (although these were classified as “light” injury crashes).

Studies in the Netherlands showed that roundabouts decreased bicyclist injuries by 44 to 73%. Separate bicycle paths were found to be the safest, while a bicycle lane within the circulatory road was found to be the least safe.

In general, it seems that collisions involving bicyclists are reduced somewhat with roundabouts, particularly in severity, but not to the same extent as for collisions involving motor vehicles or pedestrians.

Results of Survey

Through the Synthesis study, a web-based survey was sent out to 109 public agencies in the spring of 2006. Responses were received from 59 agencies for a response rate of 54%. The Canadian agencies reported a total of 59 roundabouts in 7 provinces or territories, and the U.S. agencies reporting in represented 459 roundabouts in 20 states.

Part of the survey addressed roundabout safety experience. Agencies were asked if they had conducted any formal studies to measure roundabout safety performance compared to the previous intersection control. They were also asked about types of crashes at their roundabouts and what mitigative measures have been used to prevent them.

1. Formal studies to measure roundabout safety performance were not reported by any of the agencies in the survey. Some had undertaken informal before/after comparisons with no regression-to-the-mean analysis. A few of the roundabouts in this survey were part of the IIHS "A Study of Crash Reductions Following Installation of Roundabouts in the United States".

2. Compared to the previous intersection control, overall 29% of the agencies responding indicated that property damage only collisions were lower, and 29% indicated that injury and fatal collisions were lower. Only 3% overall reported these collisions as being higher. The results with pedestrians and cyclists were generally inconclusive, likely due to low involvement rates, although no agencies reported that bicyclist crashes were higher.

3. About a quarter of the agencies did not know about the collision experience at their roundabouts, and approximately the same number had not collected data because the roundabouts were new intersections.

4. The results were fairly evenly split among crash types. Most reported were Approach crashes – Rear-End and Loss of Control (total of 47% of all responses and 33% of the "high" group). Entry-Circulating and Exit-Circulating crashes were also reported at about 20% each. There were very few pedestrian and bicyclist collisions reported. About a quarter of the agencies did not know what types of collisions had been occurring at their roundabouts.

5. Several measures have been implemented after construction by the various agencies to improve safety performance. The most commonly used were related to Signs and Pavement Markings at over 50% of the agencies each. This is not surprising, as these types of measures can be implemented quickly and inexpensively. The next most common measure is more Central Island Landscaping, again likely because of the low cost compared to other measures. Less common are measures to Increase Entry Deflection and Make Larger to Accommodate Trucks.

Interpretation and Conclusions

Similar to experience elsewhere, most agencies surveyed reported that the installation of roundabouts had lowered property damage only and injury collisions (including fatalities). No formal studies seem to have been undertaken to measure roundabout safety performance in North America apart from participation in the IIHS, NYSDOT or NCHRP 3-65 before/after studies.

Approach crashes were the most common type of collision according to the agencies surveyed, even though entry-circulating crashes are the most common type according to experience in other countries. This suggests that either too much entry deflection is being applied at these roundabouts (contrary to survey results from earlier in the Synthesis stating that insufficient deflection is the most common design deficiency), or that insufficient design treatments are present at roundabouts on high-speed roads.

The survey listed several methods to improve safety potential at roundabouts:

- Make larger to accommodate certain trucks.
- Increase entry deflection. This can decrease the potential for entry-circulating crashes but increase the potential for approach crashes.
- Decrease entry deflection. This can decrease the potential for approach crashes but increase the potential for entry-circulating crashes.
- Correct path overlap (multi-lane roundabouts) though realignment of the entries or exits.
- Improve sightlines.
- Make the central island more conspicuous with additional landscaping to cut off through sightlines.
- Relocate objects to outside of clear zones.
- Improve signage, particularly advance signage.
- Improve pavement markings. This can include applying or correcting circulatory road markings and making the yield line more prominent.

Pedestrian safety is an issue of perceived versus real risks. Even though pedestrian safety at roundabouts is generally high based on international experience and limited experience in North America, many do not perceive roundabouts to be safe for pedestrians due to the absence of a positive exchange of the right-of-way priority by a traffic signal. The general public takes these signals to mean it is safe to cross, when in fact they are still in conflict with drivers turning left or right across the crosswalk during a walk signal. More education of the public is needed in this regard.

Because collisions are not reduced to the same extent for bicyclists as for those involving vehicles or pedestrians, the relative benefits of roundabouts can be less for bicyclists. General international experience is that bicyclists are safer at roundabouts, particularly single-lane roundabouts, than at other intersections because of lower vehicle speeds and fewer conflicts.

More research is needed on pedestrian and bicyclist safety at roundabouts in North America, and for developing collision prediction models for these users. This research should use the largest sample size possible and account for regression-to-the-mean effects. In spite of this, overwhelming evidence exists that roundabouts are safer than other intersections for all road users.

References

1. Maycock, G. and R. Hall, *Accidents at 4-Arm Roundabouts*, Transport Research Laboratory Report LR1120, United Kingdom, 1984.

2. Arndt, O. and R. Troutbeck, *Relationship Between Roundabout Geometry and Accident Rates*, Queensland Department of Transport, Australia, 1998.

3. Fortuijn, L, *Pedestrian and Bicycle-Friendly Roundabouts; Dilemma of Comfort and Safety*, Delft University of Technology, The Netherlands.

4. National Cooperative Highway Research Program (NCHRP) Project 3-65, *Applying Roundabouts in the United States*, Status Report, July 2004.

5. National Cooperative Highway Research Program (NCHRP) Project 3-65, *Applying Roundabouts in the United States*, Draft Report, May 2006.

6. Quebec Ministère des Transports (MTQ), *Roundabouts: A Different Type of Management Approach*, 2005.

7. Persaud, B. et al, *Crash Reductions Following Installation of Roundabouts in the United States*, Insurance Institute of Highway Safety (IIHS), 2000.

8. Jacquemart, G, *Designing and Operating Safer Roundabouts*, ITE Toolbox on Intersection Safety, 2004.

9. Karesten G. et al, *Roundabout Providing an Excellent Service to the Road User*, TAC Annual Meeting, 1995.

10. Schoon, C. and J. van Minnen, *Literature Review on Vehicle Travel Speeds and Pedestrian Injuries*, U.S. Department of Transportation, NHTSA, 1999.

11. LSC Transportation Consultants, *Existing Roundabouts at Mountain Resorts*, Town of Truckee, 2002.

12. Service d'Études Techniques des Routes et Autoroutes (SETRA), Accidents en Carrefours à sens giratoire – étude d'enjou, France, 1999.

13. Swedish National Road and Transport Research Institute (VTI), *What Roundabout Design Provides the Highest Possible Safety*, Nordic Road and Transport Research, 2000.