Roundabout Design and Cycling Safety

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ABSTRACT

Roundabouts reduce the frequency and severity of motor vehicle crashes and therefore the number installed has increased dramatically in the last 20 years in many countries. However, the safety impacts of roundabouts for bicycle riders are a source of concern, with many studies reporting lower injury reductions for cyclists than car occupants. This paper summarises the results of a project undertaken to provide guidance on how cyclist safety could be improved at existing roundabouts in Queensland, Australia, where cyclist crashes have been increasing and legislation gives motor vehicles priority over cyclists and pedestrians at roundabouts. The review of international roundabout design guidelines identified two schools of design: tangential roundabouts (common in English-speaking countries, including Australia), which focus on minimising delay to motor vehicles, and radial roundabouts (common in continental Europe), which focus on speed reduction and safety. While it might be expected that radial roundabouts would be safer for cyclists, there have been no studies to confirm this view. Most guidelines expect cyclists to act as vehicle traffic in single-lane, typically low-speed, roundabouts. Some jurisdictions do not permit cyclists to travel on multi-lane roundabouts, and recommend segregated bicycle facilities because of their lowest crash risk for cyclists. Given that most bicycle-vehicle crashes at roundabouts involve an entering vehicle and a circulating cyclist, the greatest challenges appear to be reducing the speed of motor vehicles on the approach/entry to roundabouts and other ways of maximizing the likelihood that cyclists will be seen. Lower entry speeds are likely to underpin the greater safety of compact roundabouts for cyclists and, conversely, the higher than expected crash rates at two-lane roundabouts. European research discourages the use of bike lanes in roundabouts which position cyclists at the edge of the road and contributes to cyclists being less likely to be noticed by drivers.

Keywords: bicycle safety, roundabouts, design guidelines, bike lanes, cycling.

1 INTRODUCTION

Roundabouts have been shown to be effective in reducing the frequency and severity of motor vehicle crashes, but safety impacts for bicycle riders have been a source of concern. This research was commissioned in response to a doubling of the number of Police-reported bicycle crashes at roundabouts in the state of Queensland, Australia, from 1992 to 2011. The increase in crashes occurred within a context of more roundabouts being installed and growth in cycling. This review begins by examining international roundabout design guidelines, and design guidelines specifically providing for cyclists at roundabouts. Research findings regarding to the overall safety effects of roundabouts are then summarised. What is known about the safety benefits of roundabouts for cyclists and the effect of roundabout design features on cyclist crashes is then presented. The associated factors of cyclists' perceptions of roundabouts and cyclist positioning are also described.

2 ROUNDABOUT DESIGN GUIDELINES

Approaches to roundabout design differ across the world and appear to vary according to motorist expectations, cycling culture, and legislative frameworks. A primary point of difference in roundabout design among countries relates to the design of roundabout entries. Countries including the United Kingdom (UK), Sweden, New Zealand and Australia recommend tangential entries, while Germany, France, Denmark and the Netherlands recommend radial entries (see Figure 1). In radial roundabout designs, the approach arms are aligned towards the middle of the centre island, and should not be deflected to the left. Tangential entries allow motor vehicles to keep higher travel speeds, which increase capacity. Radial entries result in greater deflections which reduce vehicle speeds and improve visibility [1].

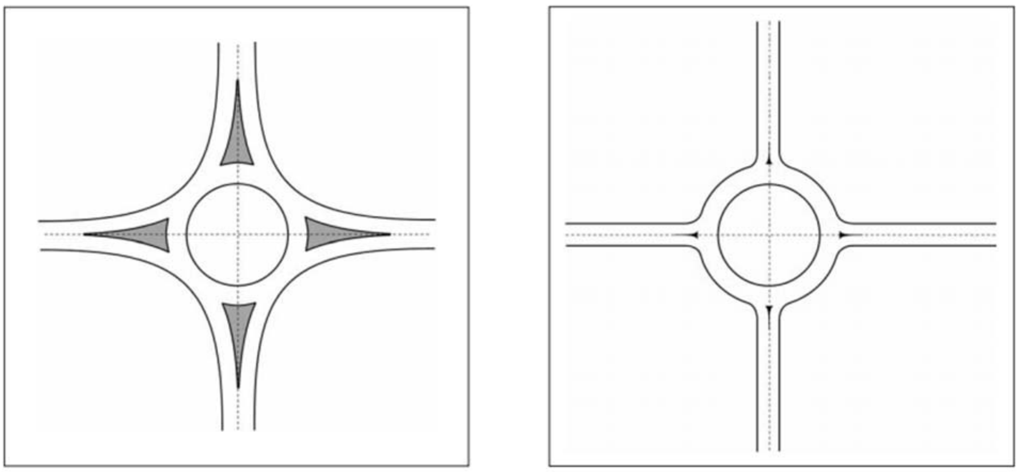

Figure 1. Basic schematics of tangential and radial roundabout designs [1]

Several published research papers have compared the roundabout design guidelines of various countries. The basic geometric elements of a roundabout are shown in Figure 2. A 2003 article [2] compared the United States Federal Highway Administration guidelines, the Dutch CROW guidelines, and Dutch local area guidelines for an area with higher heavy vehicle traffic volumes. The Dutch guidelines generally recommend smaller inscribed circle diameters and smaller circulatory roadway radii. The Dutch guidelines also provide specific guidelines on traversable apron dimensions (raised section of pavement that provides additional width for long vehicles) while the United States guidelines do not. While the design traffic speeds are similar for single-lane roundabouts in the USA and Netherlands, the design traffic speeds are lower for Dutch double-lane roundabouts.

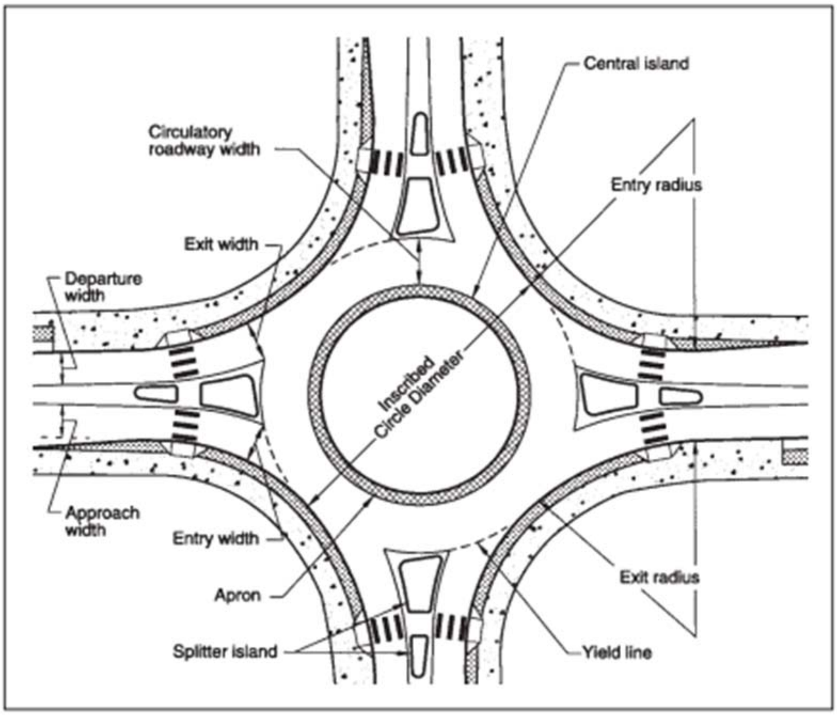

Figure 2. Basic geometric elements of a roundabout [3]

A later article [4] compares the roundabout design guidelines from Australia/New Zealand, the United States (US), the UK, France, Switzerland, Italy, and the Lombardy region of Italy. All of the jurisdictions that use mini-roundabouts recommend their use at local junctions, although vehicle operating speeds are only defined for the US and the UK where local speed limits can be higher than 50 km/h. No mini-roundabout design guidelines existed at the time of publication in Australia, and mini-roundabouts in NZ were typically being replaced with single-lane roundabouts (see Table 1 for design differences) except where the mini-roundabouts were installed as part of a traffic calming initiative [4]. Each jurisdiction provides slightly different recommendations for inscribed circle diameter, the central island treatment, and use of splitter islands on approach. European guidelines for single-lane roundabouts recommend smaller maximum dimensions for inscribed circle diameters, and the use of non-traversable central islands. Only France and Italy recommend the use of truck aprons where necessary. For multi-lane roundabouts the French and Italian national guidelines recommend inscribed circle diameters that are smaller than those recommended for the United States, the United Kingdom, Australian/New Zealand, and the Lombardy region. Switzerland does not provide any guidelines on inscribed circle diameter for multi-lane roundabouts.

The various methods for controlling vehicle speeds through roundabouts across the jurisdictions are also identified. Australia, New Zealand, the USA and UK all use entry path radius to control vehicle speeds. However France and the Lombardy region use the radius of deflection, while Switzerland and the Italian standards use the deviation angle to control vehicle speeds through roundabouts.

Table 1 Comparison of mini, continental, and conventional roundabout designs (Transport for London, 2005)

	UK mini	UK Continental	UK Conventional
Approach arms	Perpendicular recommended, can be skewed	Perpendicular	Perpendicular recommended, can be skewed
Entry width	Variable	1 lane, 4m wide	Add one lane to entries
Entry radius	Not specified	>10m	6m – 20m
Entry angle	Deflection desirable	30°-45°	20°-60°
Entry path curvature	-	Not greater than 100m	Not greater than 100m
Exit arms	Not specified	Tight perpendicular exits	Easy exits
Exit radius	Max 5m	Approx 10m	20m minimum, 40m desirable
Exit width	Not specified	Single lane, 4-5m wide	Add extra lane
External Inscribe Circle Diameter	2-4m	16-25m	Min 4m
Island diameter	Dependant on vehicle movements	16-25m	Minimum 4m
Circulatory Carriageway	5-7m	Single lane 5-7m	1-1.2 times entry width

2.1 Provisions for cyclists at roundabouts

The provisions outlined in the design guidelines for cyclists at roundabouts also vary among countries. In the UK, the provisions are primarily on-road, with no off-road provisions. However, alternate route signage is suggested for roundabouts that would be difficult to negotiate [5]. Circulating traffic lanes that do not provide sufficient space for vehicles to overtake are recommended at mini-roundabouts. Entry width, and entry angle, should be set appropriately as excessive width can encourage excessive entry and circulatory speeds. While the UK engineering standard guidelines provide for cycle lanes to be marked on the circulating roadway of roundabouts, organisations responsible for providing guidance on designing for bicycles do not recommend that cycling lanes be positioned at the periphery of the circulatory roadway and they are not provided at exit arms [6].

The Irish National Cycle Manual states that bicycle lanes should not be provided within the circulating traffic area [7]. It is recommended that cyclists act as traffic in a traffic lane, or on segregated facilities. Segregated facilities are recommended at roundabouts where the traffic volume is greater than 6,000 vehicles per day. Narrow circulating lanes are recommended, as this can limit vehicle speeds. Radial roundabout design should be employed, the central island should be large enough to cause a deflection in the path travelled, flares at entry should not be used for approach lanes, and multi-lane approaches are not recommended. The guidelines also recommend that approaches that are currently flared should be converted to single lane right-angled approaches.

In addition to the previously described roundabout design guides for bicycle provisions at roundabouts, Poland has roundabouts where the bicycle lane in positioned in the centre of the travel lanes of the roundabout. Additional traffic signs are provided on the approach roads to alert drivers, and drivers are notified that they are permitted to travel ahead of or behind the cyclists but not beside them [8]. The sign can be translated as: "Caution: bicycle roundabout. All vehicles ahead of or behind, NOT beside a cyclist!".

In the German roundabout design guidelines [9], no cyclist provisions are outlined for mini-roundabouts, as they are only applicable in areas with maximum posted speed of 50 km/h where the maximum traffic volume is 20,000 vehicles per day. Circulating bicycle lanes can be used at compact single-lane roundabouts, although they are not permitted when traffic volumes are high. There are no design guidelines for the provision of cyclists on multi-lane roundabouts in Germany. Traffic rules in in Germany prohibit cyclists from travelling in the circulating travel lanes at multi-lane roundabouts [9, 10]. Segregated cycle paths, or alternate routes, are provided at multi-lane roundabouts.

In summary, the guidelines for roundabouts differ across jurisdictions in terms of the extent to which they attempt to constrain vehicle speeds and among locations, according to traffic volumes and speed limits. In general, they propose designs where cyclists act as vehicles in the lower speed tighter roundabouts, and aim for segregation in the higher speed larger roundabouts. The safety outcomes of these designs are examined in the sections that follow.

3 ROUNDABOUT SAFETY

The section below summarises some of the many evaluations that have demonstrated improved safety outcomes resulting from the conversion of both signalised and un-signalised intersections to roundabouts. The extent of the safety improvement has differed somewhat according to the country (and style of roundabout) [11] but importantly has been greater for vehicle occupants than unprotected road users including cyclists.

3.1 Overall safety at roundabouts

Most studies have demonstrated substantial overall safety benefits for roundabouts. The Handbook of Road Safety Measures [12] concluded that roundabouts result in a 36% reduction in total crashes, a 66% reduction in fatal crashes and a 46% reduction in injury crashes. Modelling work indicates that crashes in the United Kingdom would be reduced by between 23% and 28% if intersections were replaced with roundabouts [13]. In the United States, installing roundabouts resulted in between 76% and 80% reduction in injury crashes [14, 15]. Similar results were observed in New Zealand and Australia [16, 17]. While roundabouts did result in crash reductions, they were less effective treatments as black spot treatments [18].

The complexity of the roundabout environment influences the safety of roundabouts. Increasing the number of entry arms increases the crash rate [19], and this is observed across all roundabout designs in the United Kingdom.

In the United Kingdom, while private passenger vehicles are involved in the most crashes at roundabouts (77% of all crashes), occupants of private passenger vehicles only represent 6% of serious injury and fatality crashes [19]. Cyclists are only involved in 8% of crashes, and represent 10% of all serious injury and fatality crashes.

The variations in safety improvements probably reflect differing design approaches, and differing road user expectations. While there has been an overall improvement in road safety, the conversions of intersections to roundabouts has not been positive for all road user groups. A summary of the findings is presented in Table 2.

Table 2. Summary of selected research regarding overall roundabout safety

Study	Country	Rounda-bout type	Method	Impact on safety
Elvik, Høye, Vaa & Sørensen (2009)	UK, Denmark, Sweden, Norway, Australia, Netherlands, Switzerland, Germany, US, Belgium	All	Estimates of effect	Reduction: All crashes by 36%; Fatal crashes by 66%; Injury crashes by 46%; Increase: Property Damage Only crashes by 10%
Persaud, Retting, Gerder & Lord (2001)	US	All	Before-after	40% reduction in crashes; 80% reduction in injury crashes
Retting, Persaud, Barder & Lord (2001)	US	All	Before-after	38% reduction in crashes; 70% reduction in injury crashes
Campbell, Jurisich & Dunn (2011)	New Zealand	All	Case-control	47% reduction in injury crashes
Troutbeck (1993)	Australia		Before-after	74% reduction in crash rates
Bureau of Infrastructure, Transport and Regional Economics (2012)	Australia	All	Before-after	70% reduction in injury crashes
Highways Agency (2007)	UK	All		

3.2 Safety of cyclists at roundabouts

In contrast to the general roundabout safety research reported in the previous section, several European studies have concluded that roundabouts may be less safe for cyclists than signalised intersections but safer than other intersections without traffic signals [20]. These studies are presented below and then summarised in Table 3. A before-and-after study using data from a sample of 91 roundabouts in Flanders [21] found that overall, the conversion of an intersection to a roundabout in built-up areas increased injury accident involving cyclists by 27%. Where an intersection was not previously signalised, there was a 55% increase in accidents involving cyclists. The effect was reduced when the intersection was previously controlled by traffic signals, with an increase of 23%. There was no statistically significant change in crashes involving bicycles at roundabout conversions outside built-up areas [21].

Other studies have investigated the nature of the conflicts and behaviours underlying cyclist crashes at intersections. Firstly, field studies based on the Swedish Traffic Conflict Technique (TCT) were conducted to determine the accident risk and the type of conflicts experienced [22]. Subsequently, video recordings were collected and reviewed to determine types of interactions, behaviour and route choices of cyclists. A crash analysis was also conducted for two roundabouts in Sweden. The TCT study was conducted at two roundabouts, one mixed traffic roundabout and a roundabout with segregated bicycle facilities. More motor vehicle-bicycle conflicts were observed at the mixed traffic roundabout. There were 10 serious conflicts observed at the mixed traffic roundabout, corresponding to 4.6 serious conflicts per 1000 cyclists. The largest proportion of conflicts observed (40%) at mixed use roundabouts were entering motorists failing to yield to a circulating cyclist. The next most common conflict observed was entering cyclists failing to yield to a circulating motorist (30%), followed by a circulating cyclist travelling parallel to a vehicle who should have yielded when exiting (20%), and lastly a cyclist nearly being squeezed when exiting a roundabout parallel with a heavy vehicle [22]. At the roundabout with segregated bicycle facilities only 2 serious conflicts between bicycles and motor vehicles were observed, corresponding to 2.3 serious conflicts per 1000 cyclists. In both cases the motor vehicle failed to yield to the crossing cyclist. At roundabouts with segregated cycling facilities, motorists were more likely to yield to cyclists crossing the approach road on marked crossings when entering the roundabout, particularly when vehicles were queued at entry. Drivers of motor vehicles were more likely to yield when cyclists were approaching from the left (in the direction of the roundabout circulation). Observations gathered at the mixed traffic roundabout were used to understanding yielding behaviour. Vehicles entering a roundabout with an already circulating cyclists were observed on 138 occasions, and the motorist did not yield in 4% (n = 6). In four of the six occasions where the driver failed to yield to the circulating cyclist, the motorist did not adjust their speed in any way. Even when the motorists did yield, there were several occasions (8%, n=11) where cyclists were observed adjusting their speed or direction. Cyclists entering the roundabout with an already circulating vehicle were observed on 171 occasions, and the cyclist did not yield 14% (n = 24) of the time.

An analysis of crash data found that at segregated roundabouts, crashes were equally likely with exiting or entering vehicles. Crashes were more likely (63%) when cyclists were travelling against the direction of circulating traffic (when the cyclists are travelling clockwise, against the anti-clockwise travelling vehicles). Analysis of crash data from integrated roundabouts supports the findings from the observation study, with the most common crash (73%) was an entering vehicle colliding with an already circulating bicycle. It is important to note the Swedish yielding rules for roundabouts. At segregated roundabouts (where separate bicycle facilities are provided) both motor vehicles and cyclists should yield at crossing points. Cyclists are required to consider motor vehicles, and should only cross if it can be done safely. The driver of a motor vehicle has a greater obligation to yield when exiting a roundabout, compared with entering a roundabout. A driver of a motor vehicle who crosses a bicycle crossing should drive slowly and let crossing cyclists pass [22]. At integrated roundabouts (where no separate bicycle facilities are provided) cyclists follow the same rules as motor vehicles where entering vehicles should yield to circulating vehicles, as in Australia.

The scenarios resulting in bicycle-motor vehicle collisions in the UK are less clear. The majority of bicycle-motor vehicle crashes occurred when a motor vehicle is travelling straight [23]. When examining the cyclists' movement in bicycle-motor vehicle crashes on roundabouts, the greatest number of crashes occurred when the rider was travelling straight on the roundabout and crossed the path of a vehicle entering the roundabout, followed by a vehicle overtaking a cyclist travelling straight ahead [24]. Motor vehicles continuing straight ahead at the roundabout are subject to minimum path deflections, and are able to maintain speed due to the nature of UK roundabout designs [23]. Signalised roundabouts have been found to significantly reduce cyclist casualties. The use of traffic signals at roundabouts may reduce motor vehicle speeds [23].

Several studies have examined the safety of cyclists in Australia. Researchers conducted analysis of Victorian roundabout crash data. Of the 2084 crashes reported during 2005-2009, 497 involved a bicycle. The majority (82%) of crashes involving a bicycle at roundabouts (82%) were the result of an entering vehicle colliding with an already circulating cyclist [10]. No other crash type accounted for more than 4% (exiting vehicles colliding with a circulating bicycle = 4%; loss of control = 4%; bike entering roundabout from driveway or footpath = 4%; rear end = 3%; lane side swipe = 3%). It is of interest that the crash nature for crashes involving a bicycle differed from crashes where no bicycle was involved. While entering vehicle-circulating vehicle conflict was the most frequent crash type (37%) for crashes when no cyclist was involved, loss of control (32%) and rear end (19%) were more prevalent [10]. Entering vehicles colliding with cyclists is responsible for 69% of cyclist injuries for roundabout crashes in New Zealand [16]. Analysis of Queensland crash data, specifically bicycle crashes involving other vehicles, found that 10.5% of multi-unit bicycle crashes occurred at roundabouts [25]. Analysis of the vehicle at fault at these crashes found that bicycle riders were less likely to be at fault in roundabout crashes.

In addition to travelling on the carriage way, cyclists may also travel on off-road bicycle paths, off-road shared paths or on footpaths (depending on the jurisdiction). Therefore cyclists may also be impacted by roundabouts when not travelling on roads. Research has examined the risk to pedestrians and cyclists using pedestrian crossings at roundabouts [26]. Drivers' yielding behaviours was location-dependent (83.3% yielded at one location, while on 41.4% yielded at another). Drivers appeared to be somewhat less likely to yield to cyclists than pedestrians, although there was no statistically significant difference [26]. Pedestrian crossings are rarely installed at Queensland roundabouts, and when bicyclists use pedestrian crossing points at roundabouts they do not have priority and must rely on gaps in traffic or drivers yielding.

Making direct comparisons of levels of roundabout safety for cyclists is difficult due to the different design principles outlined earlier. The specific geometric features at roundabouts may influence safety. Several studies have examined the influence of geometric features on cyclist safety. Installing small roundabouts as traffic calming measures in Sweden was found to reduce car-bicycle and car-pedestrian conflicts [27]. The result was a 60% reduction in bicycle-car injury crash risk following the installation of a small roundabout. After the installation of roundabouts, pedestrians at crossings were more likely to be given priority by car drivers. Drivers were also more likely to appropriately yield to cyclists when entering [27]). A survey of attitudes towards the installation of roundabouts found that both vulnerable road users and vehicle drivers had a generally positive attitude towards these roundabouts, and cyclists believed that roundabouts improved safety. Further analysis of crash data for 72 roundabouts in Sweden found that the number of traffic lanes was the most important factor in determining a roundabout safety, when exposure measures were not included in the analysis (the number of motor vehicles and cyclists negotiating the roundabout) [28]. The number of crashes observed at two-lane roundabouts was more than double the predicted number of crashes. Analysis of single lane roundabout crash data has found that locations where the central island has a radius of ≥10m (in this study the radius included any additional trafficable area around the central island) have fewer bicycle accidents per year, and a fewer bicycle accidents per million crossing cyclists. Research has also found that roundabouts where cyclists use bicycle bypass provisions are safer than roundabouts where cyclists use the traffic lanes [28]. Single-lane roundabouts are also safer for pedestrians, when compared with multi-lane roundabouts.

Research was conducted in Denmark to examine the effect of roundabout design features on cyclist safety [29]. Regression methods (Poisson and logistic) were used to examine the relationship between cyclist crash rates, roundabout geometry, age of roundabout (year of construction) and traffic volume. A total of 171 cyclist crashes, at 88 roundabouts, reported to a hospital emergency department in the years 1999-2003 were examined. Older roundabouts, and roundabouts with higher traffic volumes were found to have higher crash risks [29]. The study also highlights the under-reporting of bicycle crashes in police data, with only 24.6% of the hospital data replicated in the police data. Roundabouts with narrow aprons, a large drive curve (measured as the radius of the shortest vehicle path), and high cyclist and vehicle volumes were more dangerous.

Analysis of the safety effects of various cycling provisions (cyclists mixed with traffic, cycle lanes in circulatory area, separate cycle paths and grade-separated cycle paths) installed at roundabouts in Belgium was conducted [30]. An Empirical Bayes before-and-after study was conducted using 90 roundabouts. Roundabouts with cycle lanes were shown to have a significant increase in the number of injury crashes involving cyclists, whereas the other three design types (cyclists mixed with traffic, separate cycle paths and grade-separated cycle paths) were found to decrease the number of crashes [30].

The safety effect of various types of bicycle facilities provided at roundabouts in the Netherlands was examined [31]. Roundabouts with segregated cycle tracks had significantly less casualties for all road users, and specifically cyclists, than those with on-road circulating bicycle lanes. When the roundabouts with no facilities were compared with roundabouts with on-road circulating bicycle lanes almost no difference in casualties was observed between roundabout types. The research also examined the safety effect of different priority rules at the crossing points on roundabout approach roads for roundabouts with segregated off-road cycling tracks. A comparison of priority and no priority for bicycles at crossing points was modelled. More injury crashes were predicted to occur if cyclists had priority over vehicles at crossing points [31].

Table 3. Summary of research regarding cyclist safety at roundabouts

Study	Country	Roundabout type	Method	Cyclist safety
De Brabander & Vereeck (2007)	Belgium	All	Before-after	Injury accidents for vulnerable road users increase by 28% (at 50 km/h junctions)
Daniels, Nuyts & Wets (2008)	Belgium			
Daniels, Brijs, Nuyts & Wets (2009)	Belgium			
Sakshaug, Laureshyn, Svensson, & Hydén (2010)	Sweden	Mixed and segregated	TCT	More conflict at mixed-traffic roundabouts; Vehicle failing to yield to cyclist most common;
		Segregated	Historical rash data	63% of crashes with cyclist travelling against traffic
Reid & Adams (2010)	UK	All		Most common bicycle-motor vehicle crash when vehicle travelling straight ahead
Cumming (2012)	Australia	All	Historical crash data	82% of crashes a result of vehicle failing to yield
Campbell, Jurisich & Dunn (2011)	New Zealand			69% of crashes a result of a vehicle failing to yield
Stone & Broughton (2003)	UK	All		Majority of crashes a result of a vehicle failing to yield
Haworth & Debnath (2013)	Australia	All		10.5% of bicycle-vehicle collisions occur at roundabouts; Vehicle more likely to be at fault
Hourdos, Richfield & Shauer (2012)	US	All	Historical crash data	Drivers' yielding to users on priority crossings is location-dependent (41.1% at one location, 83.3% at another)
Hydén & Várhelyi (2000)	Sweden	Small, traffic calming	Before-after	60% reduction in bicycle-vehicle injury crashes; Improved driver yield behaviours to pedestrians
Brüde & Larsson (2000)	Sweden	All	Historical crash data	Central island radius >10m safer for cyclists; Cyclist bypass facilities safer than mixed-traffic roundabouts
Hels & Orozova-Bekkvold (2007)	Denmark	All	Poisson and logistic modelling	Roundabouts with higher traffic volumes, or built to older design standards have higher crash risks
Daniels, Nuyts & Wets (2008)			Before-after	Injury crashes higher at roundabouts with cycle lanes
Dijkstra (2005)	Netherlands	All	Historical crash data	Roundabouts with circulating cycling lanes have more casualties

Certain roundabout designs may improve cyclist safety. However, road authorities are concerned that improvements for cyclists could impede traffic flow. While narrow entry roundabouts would be expected to reduce traffic flow if there was a high volume of heavy vehicles, a traffic study found that heavy vehicle volumes were lower in peak times compared with other times of the day (4% and 8% respectively). As a result, this design is not expected to have a significant impact on capacity [16]. Observations of bicycle-motor vehicle interactions in the United States at roundabouts have identified some aspects of roundabout design that require additional attention. Ensuring that there are proper sight lines, and that vehicle speeds are adequately reduced, can be improved with appropriate exit leg designs [32].

In summary, while research from Europe provides some information on design features that improve or reduce cyclist safety, consideration should be given to the differing roundabout design features and road user behaviours. Limited research has been conducted on design features in countries which implement tangential roundabout designs.

3.3 Cyclist perceptions of risk at roundabouts

Cyclists' perceptions of safety of roundabouts differ among jurisdictions, which may be a result of an interaction between road user behaviour and design approaches. A summary is provided **Error! Reference source not found.**. US and UK studies found that cyclists considered roundabouts to be more risky than signalised junctions [33, 34]. In contrast, only about one third of Danish cyclists perceived roundabouts as generally dangerous. Perception of risk was location-specific, and differed between survey locations [35]. When riding at roundabouts particular manoeuvres were considered more risky, such as circulating while a car enters or exits a roundabout. The provision of bicycle facilities at roundabouts had differing effects on cyclists' perception of safety across jurisdictions. In Denmark, the provision of bicycle facilities reduced the perceived risk [35]. This scenario is also perceived to present the greatest risk for bicycle riders in the US [32]. Roundabouts with bicycle facilities in the UK are perceived to be more risky than roundabouts without provisions [34]. In both Denmark and the UK, locations with higher traffic volumes are considered more risky. Cyclists with differing levels of experience perceived risks differently. For example, people who do not cycle perceive more risk than regular cyclists for travel on residential roads. However, occasional cyclists perceive less risk for residential streets than regular cyclists [34]. Research conducted in the US has found that that cyclists and pedestrians do not avoid travelling through roundabouts, despite reporting feeling uncomfortable [33].

3.4 Cyclist positioning at roundabouts

Cyclist positioning at roundabouts may influence safety. A summary of the relevant research is presented in Table 5. Observations of cyclist lane positioning at single-lane roundabouts were conducted in Melbourne, Australia [10]. The majority (62%) of cyclists were observed "straight-lining" (riding from the kerbside at entry, to near the island and returning to the kerbside to maintain speed of travel), while the majority of the remaining cyclists were observed "edge-riding" (riding in the outer edge of the traffic lane from entry to exit). When cyclists travel at the outside edge of the circulating lane there is the potential for drivers to fail to observe the cyclist. Only a very small proportion (0.4%) of cyclists was observed travelling in the centre of the traffic lane, positioned where vehicles travel [10]. A later study examined cyclist positions at a number of locations in Australia (Melbourne, Perth and the Gold Coast) [36]. The majority of riders (only straight through cycling movements were tracked) were observed riding towards the outer edge of the traffic lane. While roundabout configurations differed between sites, the majority of sites were single-lane roundabouts, and the median distance travelled from the kerb was similar. At locations where circulating bicycle lanes were present, less than half of the riders were observed riding in the bicycle lanes [36]. When treatments were implemented at two locations (the termination of the bicycle lane on approaches was moved from 10m prior to 20m prior at one location, and bicycle symbols not lanes were painted on the roadway at the other), cyclist tracking moved towards the centre of the traffic lane as a result of both treatments.

Table 4. Summary of research regarding cyclists' perceptions of risk at roundabouts

Study	Country	Roundabout type	Perception of safety	Most risky manoeuvre
Møller & Hels (2008)	Denmark	All	25% - 45% of riders perceived roundabouts to be generally dangerous (location dependent); Roundabouts without a bicycle facility more risky	When cycling on the roundabout, being struck by an exiting vehicle
Parkin, Wardman & Page (2007)	UK	All	Roundabouts are more risky than signalised junctions; Roundabouts with a bicycle facility more risky	-
Harkey	US	All	-	Junction of the circulatory lane with the exit lane
Arnold	US	All	32% of riders report feeling uncomfortable riding a roundabout	-

Table 5. Summary of research regarding cycling positioning, and impact

Study	Country	Roundabout type	Cyclist positioning	Drivers visual attention focus
Cumming (2012)	Australia	All	62% of cyclists observed taking shortest route through roundabout (towards the kerbside on entry, the island, returning to the kerb on exit); 0.4% travelled in the centre of the traffic lane	-
Wilke, Lieswyn & Munro (2013)	Australia	All	Less than half rode within a provided bicycle lane; Majority of cyclists rode towards the outer edge of circulating lane	-
Lund (2009	Denmark	All	-	Cyclists observed earlier when no bicycle facility is present; Drivers attention on cyclists as larger at roundabouts with no facilities

Simulator research has provided results that confirm cyclist positioning may influence the likelihood of drivers observing cyclists on roundabouts [37]. Various design features were examined, including road humps on approach, bicycle lanes in circulatory road area, orange fences separating circulatory roadway and footpath, and the provision of no bicycle facilities at roundabouts. The visibility at roundabout approaches was also manipulated by changing plant heights and the height of the central island. The research found that drivers observed circulating cyclists earlier when no bicycle facility was present at the roundabout. Neither blue cycle lane painted on the circulating area, nor orange fences decreased driver detection times of cyclists. Drivers' visual attention to cyclists was also greater at roundabouts without bicycle facilities [37].

4 DISCUSSION AND CONCLUSION

The review of international roundabout design guidelines identified two schools of design: tangential roundabouts (common in English-speaking countries, including Australia), which focus on minimising delay to motor vehicles, and radial roundabouts (common in continental Europe), which focus on speed reduction and safety. While it might be expected that radial roundabouts would be safer for cyclists, there have been no studies to confirm this view. There are also varying guidelines on the provision for cyclists at roundabouts. At low-speed roundabouts, the recommendation is for cyclists to behave as part of the traffic stream. There is less consistency for roundabouts at higher traffic speeds, and higher traffic volumes. Some jurisdictions do provide guidelines for the provision of cycling lanes on circulatory roadway, while others recommend the provision of segregated bicycle facilities. In Germany, cyclists are not permitted to travel on multi-lane roundabouts in the circulatory area.

Regardless of jurisdiction, and subsequently the roundabout design approach, replacing signed and signalised junctions with roundabouts has an overall safety benefit. Unfortunately, cyclists do not receive the same safety benefits and are overrepresented in roundabout crashes. Most bicycle-vehicle crashes at roundabouts involve an entering vehicle and a circulating cyclist, suggesting that the greatest challenges appear to be reducing the speed of motor vehicles on the approach/entry to roundabouts and maximizing the likelihood that cyclists will be seen. Lower entry speeds are likely to underpin the greater safety of compact roundabouts for cyclists and, conversely, the higher than expected crash rates at two-lane roundabouts.

European research discourages the use of bike lanes in roundabouts which position cyclists at the edge of the road and contributes to cyclists being less likely to be noticed by drivers. Roundabouts with no bicycle lanes had the lowest crash rates for all road users, while roundabouts with bicycle lanes had the highest crash rate. Bicycle lanes on roundabouts may position cyclists, road users that can be more difficult for drivers to see, where drivers are not looking. Simulator research has shown that drivers observed circulating cyclists earlier, and the visual attention is greater, at roundabouts without bicycle facilities.

It is important to recognise that people who ride bicycles are not a homogeneous group. Confident, fast riders may be well-suited to riding as traffic through mixed roundabouts, but segregated facilities may be needed to protect and reassure less experienced cyclists and to encourage children (and their parents) to ride. As such, the variety of cyclists and their different attitudes and motivations may need to be acknowledged in roundabout design.

The safety outcomes of roundabouts for cyclists appear to be influenced by their design, but driver and cyclist expectations and legal requirements are perhaps even more important than physical design. While research from Sweden and the Netherlands has found segregated cycling paths at roundabouts can reduce cyclist crashes, this may not be the case in other jurisdictions where the priority requirements differ. For example, in Sweden, vehicles do not have priority when exiting the roundabout, but in Australia, pedestrians are required to yield to traffic. Traffic regulations in the Netherlands have different requirements, with larger traffic having to take more care when interacting with more vulnerable road users.

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