Traffic safety for cyclists in roundabouts: geometry, traffic, and priority rules

A literature review

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Preface

This study was financed by the Swedish Innovation Agency (VINNOVA) through the Vinnmer Marie Curie Fellowship project “Traffic Safety for Him and Her: Enhanced injury protection for vulnerable road users”. The aim of the study was to conduct a literature review and identify best practice in design principles of roundabouts for cyclists and to identify possible knowledge gaps regarding roundabout design and priority rules with focus on cycling safety. Geometric characteristics, traffic conditions, and traffic regulations have been revised in the latest literature available.

Linköping, November 2017

Ary P. Silvano and Astrid Linder
Quality review

Internal peer review was performed in February 2017 by Jörgen Larsson. External peer review was performed by Professor Thomas Jonsson on August 2017. The research director, Astrid Linder examined and approved the report for publication in October 2017. The conclusions and recommendations expressed are the authors’ and do not necessarily reflect the opinion of VTI as an authority.

Kvalitetsgranskning

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Summary

Traffic safety for cyclists in roundabout: geometry, traffic, and priority rules
by Ary P. Silvano (VTI) and Astrid Linder (VTI)

The number of roundabouts has increased during the last decades worldwide due to the speed reduction effect and reduction of conflict points for turning vehicles which reduces the accident risk and injury severity. Delays are also more uniformly distributed, especially for minor roads compared to intersections with other types of signal control. Research shows that the accident risk and injury severity are reduced for motorised vehicles at converted roundabouts. Few studies have though addressed the impact on cycling safety. This study aims to carry out a literature review of roundabout geometric characteristics and traffic management regulations addressing the safety for cyclists.

A systematic search was conducted. The literature review examined articles from 1990 until 2017. An article was considered relevant as follows:

- Investigation of the relationship between roundabout geometric design and cyclist accidents (2 articles)
- Investigation of the relationship between roundabout geometric design and cyclist operation/interaction with other traffic, i.e., motorised vehicles (4 articles)
- Investigation of any safety impacts of the conversion of intersections into roundabouts for cyclists (9 articles)
- Psychological/behavioural studies of cycling at roundabouts (5 articles)

The results show that the impact on cyclist safety is not as clear as for motorised vehicles with some studies showing a deterioration for cyclists (Jensen, 2013; 2016; Daniels et al. 2008; 2009). The cycle facility type (e.g., mixed traffic, cycle lane, and cycle path) and the priority rules have the potential to increase safety for cyclists. For example, the priority rules vary among different countries and within some countries. From the literature, which priority rules provide the safest cycling environment remain unclear in terms of number of accidents and injury severity. The identified priority strategies are: (i) cyclists always yield to vehicles, (ii) shared yielding responsibility, (iii) vehicles always yield to cyclists, and (iv) an alternate solution ‘with’ and ‘without’ priority based on special characteristics (e.g., presence of vulnerable road users, geographic location). Furthermore, cycle lanes are the most unsafe cycle facility compared to mixed traffic or cycle paths. Likewise, coloured cycle lanes at roundabouts are less safe than non-coloured cycle lanes (Jensen, 2016). On the other hand, it is recommended that cyclists should ride in front of or behind vehicles in mixed traffic at single-lane roundabouts and in the middle of the lane, and should not ride parallel with vehicles (Cumming, 2012).

Some research directions are highlighted. The impact of the different priority rules needs further investigation in terms of number of accidents and injury severity. Some questions to study include: (i) what the best priority strategy is; (ii) what special road markings should be used; (iii) what the best distance is to place the cycle path from the circulatory roadway. Another research direction is to establish the impact on cyclist safety of cycle lanes at roundabouts. Finally, the impact on traffic safety, by cycling in the middle of the lane, needs further investigation as well.

The small number of studies found in the literature addressing cyclist safety in roundabouts points out that further research is needed to establish and ensure causal relationships of roundabout geometric characteristics on accident risk and injury severity as well as priority rules impacting cyclist safety.
Sammanfattning

Trafiksäkerhet för cyklister på cirkulationsplatser; utformningen, trafiken och företrädesreglerna

av Ary P. Silvano (VTI) och Astrid Linder (VTI)

Antalet cirkulationsplatser har ökat under de senaste decennierna i hela världen på grund av effekten av hastighetsminskningen och reduktion av konfliktpunkter för svängande fordon som minskar olycksrisken och skadornas svårhetsgrad. Fördjupningar är också mer enhetligt fördelade, särskilt för mindre vägar jämfört med korsningar med andra typer av signalstyrning. Forskning visar att olycksrisken och skadornas svårhetsgrad minskar för motorfordon i omvandlade cirkulationsplatser. Få studier har dock publicerats som studerar effekten för cyklister. Denna studie är en litteraturgenomgång av cirkulationsplatser geometriska egenskaper och trafikförordningars inverkan på cyklisters säkerhet.

En systematisk litteratursökning genomfördes. Litteraturgenomgången granskade artiklar från 1990 fram till 2017. En artikel ansågs relevant enligt följande:

- undersökning av förhållandet mellan cirkulationsplatser geometriska egenskaper och cykelolyckor (2 artiklar)
- undersökning av förhållandet mellan cirkulationsplatser geometriska konstruktion och cykelinteraktion med annan trafik, det vill säga motorfordon (4 artiklar)
- undersökning av säkerhetseffekterna av omvandlingen av korsningar till cirkulationsplatser för cyklister (9 artiklar).
- psykologiska/beteende-studier om att cykla i cirkulationsplatser (5 artiklar).


En av forskningsinriktningarna är bland annat att studera effekterna av olika företrädesregler när det gäller antalet olyckor och skadornas svårhetsgrad. Frågor till vidare studier är: (i) vilken den bästa företrädesstrategin är; (ii) vilka särskilda vägmarkeringar ska användas; (iii) på vilket avstånd från cirkulationsvägbanan är det bäst att placera cykelbanan. En annan forskningsinriktning är att undersöka cykelfälts inverkan på trafiksäkerheten för cyklister. Sist men inte minst behöver inverkan på trafiksäkerheten av att cykla i mitten av banan i cirkulationsplatser utredas vidare.

De få studier som finns om cykelsäkerhet på cirkulationsplatser påpekar på att ytterligare forskning behövs för att fastställa och säkerställa orsakssamband av cirkulationsplatser geometriska egenskaper som påverkar olycksrisken, svårhetsgrad samt företrädesreglers inverkan på cykelsäkerheten.

VTI notat 31A-2017
1. **Background**

The introduction of roundabouts in the transport network has increased during the last decades. For example, in Denmark the number of roundabouts has increased three times over a period of 20 years from 425 in 1995 to 1,450 roundabouts in 2010 (Jensen, 2016). In Sweden, the number of roundabouts has increased by 75% in a period of five years from 1,500 in 2005 to nearly 2,600 roundabouts in 2010 (Statistiska Centralbyrå, 2013) and in the Netherlands the number of roundabouts were 3,900 in 2010 (SWOV, 2012). Roundabouts are thus transport facilities where vehicle and cyclist interactions take place routinely. Some factors that contribute to the increasing popularity of roundabouts are the speed reduction effect due to the geometric design and the reduction of conflict points for turning vehicles reducing the accident risk and injury severity for motorised vehicles (Gross et al. 2013; Persaud et al. 2001). However, the impact on cyclist safety is unclear and need further investigation. For example, Jensen (2013, 2016) found that traffic safety has worsened for cyclists at converted roundabouts in Denmark. Other studies have also found roundabout designs that have worsened traffic safety for cyclists (Daniels et al. 2008, 2009). On the other hand, some studies showed that certain design characteristics improve the safety for cyclists under prevailing traffic conditions. For example, at traffic volume above 8,000 vehicles per hour, cyclists should be separated from motorised traffic and the introduction of cycle paths improve the safety for cyclists (Schoon & van Minnen, 1994; Brüde & Larsson, 1996). It is therefore important to identify roundabout geometric characteristics and priority rules that might worsen or improve cycling safety for guideline and policy implementation aiming for a better cycling environment.
2. Methods

After identification of a working title based on the problem being addressed, keywords were selected for further search of related articles. The following keywords were selected:

- Roundabout cyclist + safety / accidents
- Roundabout geometry design + cyclist
- Vehicle cyclist safety / interaction / accidents + roundabout

The slash symbol (/) refers to words used interchangeably and the plus symbol (+) refers to extra words added to narrow down the search. After identification of the keywords, the following databases were searched:

- SUMMON (VTI database) digital platform across international and Swedish databases.
- Web of Science (cross-disciplinary scientific citation indexing)
- Science Direct (cross-disciplinary scientific citation indexing)
- SCOPUS (bibliographic database of academic articles)
- TRID (integrated database of transportation research documentation)
- Google Scholar (open web search engine of scholarly literature)

The keywords were typed into the databases and related articles were first selected screening the titles and abstracts. Firstly, a number of 45 articles were pre-selected and after more careful reading only 20 articles were considered relevant for inclusion in the study. An article was considered relevant as follows:

- Investigation of the relationship between roundabout geometric design and cyclist accidents
- Investigation of the relationship between roundabout geometric design and cyclist operation/interaction with other traffic (i.e., motorised vehicles)
- Investigation of any safety impacts of the conversion of intersections into roundabouts for cyclists
- Psychological/behavioural studies of cycling at roundabouts

The literature review examined articles from 1990 until 2017.
3. Results

3.1. Searched articles

The articles included in the literature review were divided into four groups as follows: (i) group 1: roundabout design and cyclist accidents, (ii) group 2: intersection-to-roundabout conversion and cyclist traffic safety, (iii) group 3: roundabout and vehicle-cyclist interaction, and (iv) group 4: roundabout and cyclist behavioural studies. Most of the studies focused on addressing the impact on cycling safety of the conversion of intersections into roundabouts. The revised literature showed as well that few studies investigated behavioural aspects of cycling at roundabouts for example interaction with vehicles and cyclists’ perception of risk. Table 1 shows the results.

Table 1. Number of searched articles per group.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Design/accidents</th>
<th>Conversion/safety</th>
<th>Vehicle-cyclist interaction</th>
<th>Behavioural studies</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>2</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>

3.2. Converting intersections into roundabouts

With the advent of motorised vehicles, intersections have become the place where intersecting (conflicting) traffic meets. Intersections represent a small part of the traffic network; however, a substantial proportion of all accidents takes place at intersections (> 50%) (Bélanger, 1994). In the US, the National Cooperative Highway Research Program (NCHRP) Report 500, Vol 12 (Antonucci et al. 2004) proposes a strategy to reduce the number of accidents and injury severity at intersections by the conversion of intersections into roundabouts. The conversion to a roundabout reduces the number of conflict points (i.e., an intersection has 32 conflict points compared to only 8 conflict points at a roundabout) which reduces the accident risk. Injury severity is also reduced by converting intersections into roundabouts. For example, 90° collisions are eliminated by roundabouts.

Furthermore, the left turn movement is eliminated by roundabouts reducing the accident risk and injury severity (Gross et al. 2013). Other advantages of the conversion of intersections into roundabouts are (i) the speed reduction effect on approaching vehicles, and (ii) installation of traffic lights is not required (Schoon & van Minnen, 1994). Therefore, the conversion of intersections into roundabouts has been in widespread practice over the last decades to improve traffic safety for motorised vehicles (Elvik, 2003; Montella, 2011; Gross et al. 2013). However, the impact on cyclist safety has not yet been fully understood.

Typically, the impact on traffic safety of converting intersections into roundabouts has been investigated by comparative (i.e., before-after) safety studies based on police and hospital reported accidents. Elvik (2003) states that comparative studies should ideally control for factors such as vehicle flow, number of approaches (e.g., legs), signal control type (e.g., stop, yield, signalised), speed limit, incoming traffic on minor roads as well as the presence of transport facilities for vulnerable road users (e.g., mixed traffic, cycle lane, cycle path). The author conducted a meta-analysis of 28 non-US studies and put higher weight to studies that controlled for long-term trends and regression-to-the-
mean as more reliable practice. The author found that key factors influencing the accident rate at roundabouts include traffic volume, total volume entering from minor roads, speed limit, and the number of legs. Regarding accident types, the author was in favour of the conversion of intersections into roundabouts as evidence was found that the number and severity of injuries were reduced. The effect on property damage only (PDO) accidents was unclear while the effect on safety was greater in intersections controlled previously by yielding signs.

More recent studies show that specific design characteristics of such conversions are key factors influencing cyclist safety. For example, Jensen (2013, 2016) investigated the impact of the design of the central island and cycling facility types (e.g., mixed traffic, cycle lane, cycle path) on cyclist safety. The author studied the conversion of 255 intersections into single-lane roundabouts in Denmark (35 signalised intersections and 217 unsignalised intersections). Accident records over a five-year period were used, accounting for regression-to-the-mean and long-term trends in a before-after study. The author found that traffic safety was improved for vehicles and reduced for cyclists, moped riders, and motorcyclists. A similar trend was found for cyclists’ injuries as well. The studies did not include vehicle and cyclist volumes. Furthermore, the author conducted a literature study based on meta-analysis of 19 studies of intersections which had been converted into roundabouts which revealed that cyclists’ accidents had increased by 21%. In another study, Daniels et al. (2009) investigated the conversion of 90 intersections into roundabouts (before conversion: 21 signalised and 69 unsignalised) in Flanders, Belgium. The authors conducted a before-after study of accidents by regression analysis. According to the results, converting intersections into roundabouts resulted in more severe cyclists’ accidents regardless of the cycle facility type (e.g., mixed traffic, cycle lane, cycle path).

3.3. Roundabout geometric characteristics and cycling safety

3.3.1. Number of circulatory lanes

According to Brüde & Larsson (1999), single-lane roundabouts result in the best safety performance for cyclists for vehicle volume under 10,000 per day and cyclist volume under 1,000 per day. Furthermore, Schoon & van Minnen (1994) found that the number of casualties were significantly lower at single-lane roundabouts for vehicle volume under 8,000 per day. Jensen (2016) also found that single-lane roundabouts are safer for cyclists. Single-lane roundabouts are characterised by one entry/exit lane and one circulatory lane (Montella et al. 2012). Double-lane roundabouts show twice the amount of predicted accidents than single-lane roundabouts (Brüde & Larsson, 1999). Most often, the number of circulatory lanes as well as entry/exit lanes is based on traffic flow per day. Herland & Helmers (2002) conducted a literature review based on national guidelines for roundabout design in countries such as France, Germany, The Netherlands, Denmark, Norway, Great Britain, and Sweden. According to the revised guidelines, 2-lane roundabouts apply for traffic volume above 15,000 vehicles per day.

3.3.2. Entry/exit number of lanes

The number of entry/exit lanes is generally the same as the number of circulatory lanes which is more advantageous from a traffic safety perspective. However, roundabouts can also be designed with two circulatory lanes and one entry/exit lane. Research shows that one entry/exit lane is the most favourable for cyclist safety (Jensen, 2016; Brüde & Larsson, 1999). In locations with high vehicle volume (>10,000 per day) roundabout design can include two circulatory lanes with only one entry/exit lane. Designing roundabouts with two circulatory lanes and two exit/entry lanes only results in a capacity increase of 60% compared to a single-lane roundabout (Herland & Helmers, 2002).
3.3.3. Number of legs (approaches) and deflection angle

Schoon & van Minnen (1994) found that 3-leg roundabouts (i.e., the conversion of a T-intersection into a roundabout) have a higher number of accidents and casualties relative to the conversion of 4-leg intersections into roundabouts. In other words, the conversion of T-intersections into roundabouts is not as good as the conversion of 4-leg intersections into roundabouts in terms of accidents and casualties. According to the authors the reason for this is the bigger angle (3x120°) at 3-leg roundabouts which results in vehicles travelling at higher speeds compared to 4-leg roundabouts (4x90°). However, more recent roundabouts are designed with deflection angle and approaching legs bending to the left on entry lanes to reduce the speed of approaching vehicles.

Research also shows that an ample deflection angle at the entry/exit legs of roundabouts reduces vehicle speed which enhances cycling safety (Räsänen & Summala, 2000; Herland & Helmers, 2002). This geometric characteristic is related to the design of a bigger central island in modern roundabouts (Dabbour & Easa, 2008). For example, in rural areas where speed limits are higher, it is recommended that roundabout approaches veer to the left to reduce the speed of vehicles approaching to the circulatory roadway, which in turn increases the safety for cyclists (Herland & Helmers, 2002). Figure 1 shows different layouts of roundabout entry/exit legs to reduce vehicle speeds.

![Figure 1. Roundabout designs based on radial and tangential radii and leg deflection angle (Herland & Helmers, 2002).](image-url)
3.3.4. Refuge (splitter) and central island characteristics

The presence of a refuge island on roundabout legs reduces the speed of approaching vehicles. It also facilitates the crossing of cyclists and pedestrians. The recommended width of a refuge island is 2 metres (Herland & Helmers, 2002). Refuge islands also act as a barrier for separating the entering and exiting vehicle flow and preventing wrong-way driving (Montella et al. 2012).

The diameter of the central island is an important geometric characteristic of roundabouts. For example, it can be used to classify roundabouts as follows: (i) mini (<2 m), (ii) small (>2 m < 10 m), (iii) normal (> 10 m < 20 m), (iv) big (> 20 m) (Brüde & Larsson, 1999; Herland & Helmers, 2002; Jensen, 2016). A traversable apron may be installed on small roundabouts to provide a thoroughfare for trucks in the roundabout (Fortijun, 2003). The middle of the central island may also be raised. Jensen (2016) found that central islands which centre is elevated two metres or more is safer for cyclists than more ground level central islands. Brüde & Larsson (1999) found that a central island diameter between 10 and 20 metres encourage drivers to reduce speed while traversing the circulatory roadway. According to the literature, the central island diameter that provides the best safety for cyclists is a central island between 20 m and 40 m. Smaller or bigger central islands result in higher vehicle speeds (Jensen, 2016).

3.3.5. Geographic location

Different geographic settings such as urban and rural areas impact the safety performance of roundabouts due to different speed limits, vehicle and cyclist volumes, and land available to build the roundabout. Daniels et al. (2009) found that urban roundabouts tend to perform worse than rural roundabouts in terms of traffic safety. According to the authors, an explanation for this effect is that the vehicle and cyclist volumes in urban roundabouts are higher and the land available to build the roundabout on is scarce, which may limit the construction of cycle paths.

3.3.6. Cycling facilities

In the literature (Schoon & van Minnen, 1994; Herland & Helmers, 2002; Daniels et al. 2009; Jensen, 2016) cycling facilities at roundabouts can be categorised as follow:

- No facility (i.e., mixed traffic)
- Cycle lane next to circulatory roadway (e.g., non-coloured, or coloured such as red, blue, or green)
- Cycle path to bypass the roundabout on approaching legs
- Grade-separated cycle path to bypass the roundabout on approaching legs

Research shows that mixed traffic roundabouts are safer for cyclists compared to roundabouts with cycle lanes (Schoon & van Minnen, 1994, Daniels et al. 2009, Jensen, 2016). Schoon & van Minnen (1994) correlated the annual number of casualties for cyclists and moped riders against vehicle volume for the following cycle facilities: mixed traffic, cycle lane, and cycle path. They found indices of 0.6, 0.7, and 0.03 annual casualties for mixed traffic, cycle lane, and cycle path respectively for a vehicle volume of 13,000 per day. The authors further included the cyclist volume in the analysis and found that a roundabout with a cycle path is preferred for a daily vehicle volume above 8,000. For traffic volumes below 8,000 vehicles per day, mixed traffic and cycle paths perform equally safe. Sakshaug et al. (2010) investigated different design solutions for cyclists in roundabouts, namely, mixed traffic (defined by the authors as: integrated traffic) and separated cycle path. They found that mixed traffic operation increased the number of conflicts as well as more serious conflicts between cyclists and vehicles. One of the most serious conflict scenarios was a vehicle turning right to exit the roundabout while a cyclist was riding parallel to the exiting vehicle.
3.3.6.1. Mixed traffic

Mixed traffic should only be permitted at single-lane roundabouts (Schoon & van Minnen, 1994). According to the authors, mixed traffic and cycle paths perform equally safe for a daily vehicle volume below 8,000. Cyclists in mixed traffic are considered as vehicles and must follow standard traffic rules. A cyclist approaching a roundabout must yield for circulating vehicles. Similarly, approaching vehicles must yield for cyclists in the circulatory roadway. The provision of special cycling road markings improves the safety for cyclists in mixed traffic (Cumming, 2012) (see Appendix 1). Cyclists are also recommended to ride in the middle of the lane (in front of or behind vehicles) to increase their exposure (visibility) to drivers and to reduce conflict points, and cyclists should not ride in parallel (aside) to vehicles since it increases the risk of serious conflicts (Cumming, 2012).

3.3.6.2. Cycle lanes

Research shows that cycle lanes represent the most unsafe cycling environment (Brüde & Larsson, 1996, 1999; Schoon & van Minnen, 1994; Daniels et al., 2009; Polders et al., 2015; Jensen, 2016). Jensen (2016) found that coloured cycle lanes perform worse in terms of traffic safety for cyclists compared to non-coloured cycle lanes. Cycle lanes are generally located in the outer part of circulatory roadways. Similar to the previous case, cyclists in circulatory roadways are considered as vehicles and approaching vehicles must thus yield to circulating cyclists. Vehicles turning right to exit a roundabout must yield to circulating cyclists as well.

3.3.6.3. Cycle paths

According to the literature, cycle paths are safer for cyclists in high traffic volume (> 8,000 vehicles per day) compared to cycle lanes and mixed traffic (Schoon & van Minnen, 1994; Brude & Larsson, 1999). In Sweden, two types of cycling paths coexist: (i) cycle passages, and (ii) cycle crossings. Cycle passages have been marked with squared-dashed lines to guide cyclists to cross the road (Figure 2a), while cycle crossings are also marked with squared-dashed lines and supplemented with painted triangle give-way signs on the road, and vertical signs as shown in Figure 2b.

Figure 2. Cycling path facilities in Sweden (Transportstyrelsen No. 201510).
3.3.6.4. Grade separated

It has been shown that grade separated cycling paths are safer for multi-lane roundabouts (>1-lane), higher speed limits (>50 km/h), and high road capacity, i.e., high vehicle and cyclist volumes (Linderholm, 1996; Herland & Helmers, 2002).

3.3.7. Location of cycle paths

The distance between the circulatory roadway and the cycle path is also a key factor influencing safety for cyclists. Räsänen & Summala (2000) state that the cycle path should be placed as near as possible to the circulating roadway (e.g., 0 - 2 metres) to increase drivers’ yielding rate (proportion of drivers giving way to cyclists) as drivers are more alert/aware to other road users when entering/exiting roundabouts. Also, cyclists will be more visible to drivers. To place the cycle path further away than 6 metres is not recommended by Räsänen & Summala (2000) as it results in higher vehicle speeds and lower yielding rates. Likewise, Herland & Helmers (2002) state that the cycle path should be placed within 5 metres of the roundabout to make vulnerable road users more distinguishable by drivers. In the Norwegian Handbook of Road and Street Design, the cycle path should be located between 5 metres to 10 metres away from the circulatory roadway (Statens vegvesen, 2014). On the other hand, in the Netherlands, cycle paths are placed at different distances depending on whether the cyclist has priority or not. In urban roundabouts, cyclists have priority over vehicles thus the cycle path is placed 5 metres away from the circulatory roadway. In rural roundabouts, vehicles have priority over cyclists therefore the cycle path is placed 10 metres from the roundabout (Fortuijn, 2003; Dijkstra, 2004). See appendices 2 and 3.

3.3.8. Design classification of roundabouts

From the literature, roundabouts can be classified according to:

- Presence or absence of vulnerable road users (e.g., pedestrians, cyclists, and mopeds)
- Vehicle volume (e.g., < 8,000 vehicles per day)
- Geographic location (e.g., urban or rural areas)
- Central island diameter (e.g., mini-roundabout, small, medium (average) roundabout, large roundabout)
- Number of lanes (e.g., single-lane, double-lane, multi-lane)
- Speed limit (e.g., 30, 50, or 80 km/h)
- Street function (e.g., on local streets, on main streets)
- Modern roundabouts (e.g., turbo-roundabouts, C-roundabouts)

In the Netherlands, two clearly distinguishable types of roundabouts aim to guide drivers to adopt the appropriate driving behaviour by the following geometric characteristics:

1. Urban roundabouts with priority for vulnerable road users (i.e., car drivers entering/exiting a roundabout yield to any traffic in the crossings).
2. Rural roundabouts with priority for vehicles (i.e., pedestrians, cyclists, and moped riders yield to vehicle traffic).

An important aspect of the Dutch classification is the application of a self-explanatory design of roundabouts that signal which priority rules apply to the road users. For example, in urban roundabouts with priority for vulnerable road users, the cycle path is normally placed next to the pedestrian crossing. In rural roundabouts with priority for vehicles, the cycle path ends just before the road begins with yielding road markings and vertical yielding signs facing towards the cycle path.
3.4. Traffic operation and cyclist safety

3.4.1. Traffic flow
Recent studies correlating accident data and roundabout design do not include vehicle and cyclist volumes (Jensen, 2013, 2016; Daniels et al. 2008, 2009). However, vehicle and cyclist volumes play an important role in traffic safety studies. In a study of cyclist accidents at intersections in New Zealand and Australia, Turner et al. (2011) found a safety-in-numbers effect meaning that as the cyclist number increases the individual accident risk reduces. Jacobsen (2003) found that as the number of cyclists increases, the accident risk only increases at the power of 0.4. Furthermore, depending on the vehicle volume different treatments are suggested for cyclists passing through the roundabout. For example, mixed traffic (i.e., cyclists riding in the roundabout circulatory roadway interacting with vehicles) can be allowed if the daily vehicle volume is below 8,000 per day. This is because no difference in traffic safety was found compared to a cycle path (Schoon & van Minnen, 1994). In another study by Harkey & Carter (2006), cyclists can ride in the circulatory roadway at volume lower than 8,000 veh/day. On the other hand, Brüde & Larsson (1999) state that at vehicle volume higher than 10,000 per day and cyclist volume up to 1,000 per day cyclists should bypass the roundabout on special crossings and should not be mixed with vehicle traffic.

3.4.2. Speed
The approaching vehicle speed should be reduced as much as possible for a better cycling environment (Räsänen & Summala, 2000; Silvano et al. 2016, Harkey & Carter, 2006; Herland & Helmers, 2002). Traffic safety studies show that the higher the vehicle speed is the shorter the time will be for drivers to detect other road users (Räsänen & Summala, 2000). Higher vehicle speeds also result in lower yielding rates (Silvano et al. 2015; 2016). Hels & Orozova-Bekkevold (2007) found a positive correlation between vehicle speed and the number of cyclist accidents. In the literature, geometric characteristics of roundabouts used to reduce speed include central island diameter (i.e., between 20 – 40 metres), height of the middle of the central island (i.e., >2 metres), deflection angle on entry/exit legs, presence of refuge islands, and number of lanes. The average approaching speed limit in roundabouts located in urban areas is 40/50 km/h while in rural areas an approaching speed limit of 80 km/h may apply (Jensen, 2016). According to the reviewed literature, roundabout geometric characteristics that have the potential to reduce the speed of vehicles include:

- Narrow and radial entry/exit approaches with short connecting radius (Herland & Helmers, 2002; Montella et al. 2012)
- Deflection angle to the left for entry/exit approaches (Herland & Helmers, 2002; Montella et al. 2012)
- Narrow lane width of the circulatory roadway (Herland & Helmers, 2002)
- Raised circulatory roadways and raised cycle path crossings (Herland & Helmers, 2002)
- Central island diameter between 20 and 40 metres (Jensen, 2016)
- Presence of refuge islands (Herland & Helmers, 2002)
- Single-lane roundabout design (Schoon & van Minnen, 1994; Brüde & Larsson, 1999; Daniels et al. 2009)
- Installation of speed limit signs showing a lower speed limit (Herland & Helmers, 2002)
3.4.3. Priority rules

3.4.3.1. Mixed traffic and cycle lanes

In mixed traffic, a cyclist riding on the road is considered as a vehicle subject to standard traffic rules. For example, approaching vehicles at roundabouts should yield to circulating vehicles and cyclists. This also applies for approaching vehicles which should yield to cyclists riding on cycle lanes in the circulatory roadway. Furthermore, when a vehicle and cyclist are travelling in parallel trajectories in the circulatory roadway, the vehicle changing/crossing a lane should yield to the cyclist. For example, when a vehicle exits the roundabout, it should yield to circulating cyclists. These traffic rules apply also for cycle lanes.

3.4.3.2. Cycle paths

In Sweden, the priority rules are different for cycle passages and for cycle crossings (See Fig. 2). For approaching vehicles at roundabouts with cycle passages only (i.e., roundabouts without any pedestrian crossings), cyclists should yield to vehicles and drivers should adjust and reduce the speed accordingly to avoid being a danger to the cyclists (TSF 1998:1276; TSF 2014:1035; TS 201510). However, vehicles turning right to exit the roundabout should yield to cyclists at cycle passages. Hence, the priority rules are different on cycle passages for vehicles approaching and for vehicles exiting a roundabout. In the case of cycle crossings, vehicles approaching and exiting the roundabout should yield to cyclists (TSF 1998:1276; TSF 2014:1035; TS 201510).

In the Netherlands, the yielding rules are based on geographic location and presence of vulnerable road users. For example, roundabouts in urban areas have priority for vulnerable road users thus vehicles yield to cyclists. While, in rural areas, vehicle traffic has priority at roundabouts, thus cyclists should yield to vehicles (Fortuijn, 2003). However, a study by Dijkstra (2004) found that cyclists ‘with priority’ have higher number of accidents than cyclists ‘without priority’. In Germany, cyclists riding on cycle paths yield to vehicles (Herland & Helmers, 2002). In Denmark, there are roundabouts where cyclists yield to vehicles (Jensen 2016) which is also the case in Belgium (Daniels et al. 2009).

Factors influencing the yielding rate (proportion of vehicles giving way to cyclists) are vehicle and cyclist speeds, and the proximity of the cyclist to the crossing (Silvano et al. 2015; 2016). The yielding rate in Sweden is 58% (Pauna et al. 2009; Svensson & Pauna, 2010). An explanation for this low yielding rate may be the so-called ‘looked-but-fail-to-see’ errors, especially for experienced drivers (Herslund & Jörgensen, 2003). Another explanation is that drivers when entering a roundabout pay more attention to traffic coming from the left in the circulatory roadway than traffic on the right thus failing to yield to cyclists approaching from the right (Räsänen & Summala, 2000). Cyclists also overestimate the distance they are visible to drivers by a factor of 2 (Wood et al. 2009).
4. **Discussion**

From the small number of traffic safety studies found in the literature review, the majority focused on addressing the impact on cyclist safety of the conversion of intersections into roundabouts. This means that most studies investigated safety impacts of previous intersections compared to new built roundabouts. However, the safety impact of introducing changes in a roundabout was seldom investigated (e.g., upgrading, rebuilding an existing roundabout). The literature review revealed also that very few studies investigated behavioural aspects of cycling at roundabouts. For example, the impact of different roundabout geometric characteristics on yielding rates and on cyclists’ perception of risk.

The small number of roundabout studies found per group (See Table 1), suggest that the conversion of intersections into roundabouts improves the overall traffic safety for motorised vehicles. However, the safety for cyclists can be the opposite if corrective actions are not taken. More recently, research has pointed out roundabout design characteristics that have the potential to improve cycling environments as well as stressed some important aspects that need further research and clarity. For example, for cycle paths, what priority rules provide the safest cycling environment need further research. Priority rules need to be as clear as possible to avoid misinterpretation or confusion to ensure that road users behave as expected. However, in the case of roundabouts with cycle paths the priority rules vary among different countries and within countries. For example, in Sweden depending on the cycle path type (e.g., cycle passage or cycle crossing) the priority rules differ. For cycle passages, cyclists should yield to approaching vehicles at roundabouts and drivers have the responsibility to adjust the speed to avoid being a danger to the cyclists (TSF 1998:1276; TSF 2014:1035; TS 2015:10). In this way, the responsibility to yield is shared by both users (i.e., the driver and the cyclist) (Helmers & Herland, 2002; TS 2015:10). However, vehicles turning right to exit the roundabout should yield to cyclists. For cycle crossings, the yielding rules are clearer. Approaching vehicles and vehicles turning right to exit a roundabout should yield to cyclists (TSF 1998:1276; TSF 2014:1035; TS 2015:10). The application of the priority rules in Sweden might be subject to confusion/misinterpretation. For example, the driver must be aware of the cycle path type to decide whether to yield or not when approaching a roundabout. At the same time, the cyclist should be aware of the cycle path type as well. The cycle passage is the most difficult type as it has different priority rules for approaching vehicles and for vehicles turning right to exit the roundabout. Two situations may occur: (i) approaching vehicles yield most of the time then cyclists may believe they always have right-of-way (False!), and (ii) cyclists yield to both approaching and exiting vehicles although cyclists have right-of-way over vehicles turning right to exit the roundabout.

In the Netherlands, the priority rules vary also within the country. The road users are alerted to the priority rules by geometric characteristics and road markings. Urban roundabouts give priority to cyclists while rural roundabouts give priority to vehicles. The Dutch approach is based on the notion of self-explaining roads (i.e., the road environment transmits to the drivers the proper driving behaviour) (Theeuwes & Godthelp, 1995). Specific to the roundabout case, is that the design should clearly transmit to the driver when to yield to cyclists. Whether the Dutch approach may confuse drivers or not need further investigation as Dijkstra (2004) found a higher number of accidents for cyclists with priority compared to without priority. In Germany, cyclists riding on cycle paths yield to vehicles (Herland & Helmers, 2002) and in Denmark cyclists on cycle paths yield to vehicles as well (Jensen, 2016). Belgian priority rules vary as well, with priority and no priority for cyclist in roundabouts. From the literature, which priority rule provides the safest cycling environment is unknown in terms of number of accidents and injury severity. The identified priority strategies are: (i) cyclists always yield to vehicles, (ii) shared yielding responsibility, (iii) vehicles always yield to cyclists, and (iv) an alternate solution ‘with’ and ‘without’ priority based on special characteristics (i.e., presence of vulnerable road users, geographic location). Further research is needed to identify the best priority rules from a traffic safety perspective.
For mixed traffic at single-lane roundabouts, Cumming (2012) suggests that cyclists should ride in front of or behind vehicles, in the middle of the lane to increase the visibility towards drivers and increase the safety for cyclists. Special road markings are then needed to guide the cyclists as to what to do while traversing the roundabout. It is advocated that cyclists should not ride parallel to vehicles (Cumming, 2012). In this way, the most serious conflict scenario is removed for mixed traffic (Sakshaug et al. 2010), i.e., a vehicle turning right to exit a roundabout cutting off the trajectory of a circulating cyclist. However, the impact on traffic safety, by cycling in the middle of the lane at single-lane roundabouts, needs further investigation.

The few studies found points out that cycle lanes were the most unsafe cycle facility compared to mixed traffic or cycle paths (Schoon & van Minnen, 1994; Brüde & Larsson, 1996, 1999; Daniels et al. 2009; Jensen, 2013, 2016). Coloured cycle lanes in roundabouts provided even less safety than non-coloured cycle lanes (Jensen, 2016). The studies have correlated accident records in before-after comparative studies to draw conclusions. However, why cycle lanes in roundabouts provide less safety remain unclear. One possible explanation might be that cycle lanes force cyclists to ride parallel to vehicles which create more conflict points with vehicles while simultaneously making it more difficult for drivers to detect cyclists when turning right to exit a roundabout (Sakshaug et al. 2010). Another explanation might be that it creates a feeling of protection (especially for coloured cycle lanes) which potentially induces cyclists to ride faster or pay less attention to other interacting traffic. The yielding rate at cycle lanes might also be interesting to investigate. Are cycle lanes less safe because drivers fail to yield when entering a roundabout or because drivers have more difficulties detecting circulating cyclists. Further evidence is needed to better understand the impact of cycle lanes at roundabouts.
5. Conclusions

Factors increasing the accident risk for cyclists in general:

According to the revised literature, the factors that increase the accident risk and injury severity for cyclists at roundabouts include:

- High vehicle speeds (e.g., longer reaction time, longer braking distance, lower yielding rate)
- High vehicle volume (i.e., increases the interaction with other road users)
- Low cyclist volume (i.e., the safety in numbers effect: drivers are not expecting cyclists)
- Number of lanes (i.e., increases the number of conflict points)
- 3-leg roundabouts (i.e., higher approaching speeds than 4-leg roundabouts)
- Diameter of central island (i.e., high circulating speed for too small or too large roundabouts)
- Mixed traffic (i.e., for traffic volume > 8,000 per day)
- Presence of cycle lanes (i.e., increases conflict points with circulating vehicles)
- Different priority rules (e.g., lower yielding rate, confusion, misinterpretation)

Best practices

From the literature review, potential measures to increase cyclist safety in roundabouts are highlighted below:

- Reduce approaching vehicle speed as much as possible (<30 km/h).
- Single-lane roundabout design provides the safest environment.
- Diameter of the central island between 20 to 40 metres.
- Left veering and deflection angle on approaching legs.
- Tangential angle on exiting lanes.
- For daily vehicle volume less than 8,000, mixed traffic can be allowed. For daily vehicle volume above 8,000, cycle paths perform better.
- Mixed traffic can perform better with specific road markings to guide cyclists to the middle of the lane (See Appendix 1).
- In mixed traffic, it is advocated that cyclists should ride in front of or behind vehicles but not in parallel trajectory with vehicles.
- Grade-separated cycle crossings perform better on multi-lane and high vehicle speed roundabouts.

From the reviewed literature, there is no straightforward evidence on what the best priority strategy is. It depends on the cultural context. For example, Sweden, The Netherlands, Germany, and Denmark all have different approaches and the safest traffic system will depend on how the distinct parts fit together. Some potential examples are listed below provided that future research elucidate the best priority strategy.
Potential application examples:

Urban context:

Mixed traffic
- Speed limits of 30 or 40 km/h
- Daily vehicle volume below 8,000
- Single-lane roundabout with inner central island diameter of 10 metres
- Special road markings to guide cyclists to the middle of the lane in the roundabout

Cycle path
- Speed limit of 50 km/h
- Daily vehicle volume above 8,000
- Single-lane roundabout with inner central island diameter of 20 metres
- Cycle path crossing placed at 5 metres of the circulatory roadway
- Priority for vulnerable road users (i.e., vehicles yield to all other traffic in the crossing)

Rural context:

Cycle path
- Speed limit of 50 km/h
- Daily vehicle volume above 8,000
- Single-lane roundabout with inner central island diameter of 20 metres
- Cycle path crossing placed at 10 metres from the circulatory roadway
- Specific road markings on the cycle path alerting cyclists to give way to vehicles
- Priority for vehicles

Grade-separated
- Speed limits of 70 or 80 km/h
- High vehicle volume (>10,000 vehicle per day)
- Central island inner diameter up to 40 metres
- Multi-lane roundabout (> 1-lane)
6. Further research

The impact of different priority rules on traffic safety for cyclists is unclear in the studies found in the revised literature. For example, in Sweden, the priority rules depend on the cycle path type (e.g., cycle passage or cycle crossing) with different priority rules on cycle passages for approaching vehicles and vehicles turning right to exit the roundabout. In the Netherlands, the geographic location and presence of vulnerable road users determine the priority rule. In Germany, cyclists riding on cycle paths yield to vehicles bypassing roundabout legs. The impact of the different approaches needs further investigation in terms of number of accidents and injury severity. Some questions to study further include: (i) what the best priority strategy is; (ii) what special road markings should be used; and (iii) what the best distance is to locate the cycle path away from the circulatory roadway. Möller & Hels (2008) found a need to increase knowledge about traffic rules in roundabouts.

In urban areas, the land available to build roundabouts may limit the construction of cycle paths. Mixed traffic can be allowed up to 8,000 vehicles per day. It is advocated that the cyclists should ride in the middle of the lane at single-lane roundabouts. However, the impact on traffic safety of such application needs further investigation. Another important research direction is the understanding of the impact cycle lanes have on cyclist safety. According to the few studies found, cycle lanes are the most unsafe cycling facility. However, why cycle lanes at roundabouts provide less safety remain unclear and further research is needed to better understand the impact of cycle lanes at roundabouts.

Few studies included vehicle and cyclist volumes in the analysis (Schoon & van Minnen, 1994; Brüde & Larsson, 1999; Hels & Orozova-Bekkevold, 2009). More recent studies have not included vehicle and cyclist volumes as explanatory variables into accident prediction models either. However, representative roundabouts may be monitored over time so that traffic and cyclist volumes can be incorporated into prediction models for richer analysis more frequently.

The popularity of electric cycles (e-bikes) is increasing. Generally, e-bikes facilitate higher cruising speeds (>1–3 km/h) than standard cycles (Schepers et al. 2014) which might be a safety concern when interacting with vehicles. Furthermore, Langford et al. (2015) found that on average the on-road speed of e-bikers is 3 km/h faster than standard cycles. What is the impact on traffic safety of e-bikes interacting with motorised vehicles (i.e., at roundabouts) would be an important research to conduct.
Referenser


Cumming, B. "High rate of crashes at roundabouts involving cyclists may be reduced with careful attention to conflict paths." In: Australasian Road Safety Research, Policing and Education Conference, 4-6 October 2012, Wellington, New Zealand, 2012.


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Road marking signage for mixed traffic (Obs: Left hand driving) (Cumming, 2012)
Roundabout design with priority for cyclists (Fortuijn, 2003)
Roundabout design with priority for vehicles (Fortuijn, 2003)

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