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Bicycle safety at roundabouts: a systematic literature review

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ABSTRACT

As roundabouts become increasingly popular, and as many communities promote bicycle use, the safety of roundabouts for people bicycling is of major concern. Although converting an intersection to a roundabout may reduce crashes overall, some research from northern Europe suggests that roundabouts may actually increase the frequency of bicycle crashes. We perform a systematic literature review on this topic, reviewing 49 different resources with empirical findings (most from Europe, some from Australia/New Zealand, few from the US). Many studies analyse (limited) bicycle crash data or observe driver/cyclist behaviours and interactions, while a few survey cyclists' safety perceptions. Consistent with design guidance, bicycle safety performance is worse for higher-speed, multilane roundabouts and when on-roadway bike lanes are provided. Crash data and observations suggest that when cyclists "take the lane" and operate as vehicles – as is allowed or even recommended in some current design guidelines – this leads to conflicts and crashes between circulating cyclists and entering drivers who may have "looked but failed to see" (and thus failed to yield to) the cyclist. Providing separated cycle paths around the roundabout seems to be a lower-risk and more comfortable design solution, although care must be taken to encourage appropriate yielding at crossings. Future research should investigate more design features, socio-demographic characteristics, cyclist safety perceptions, and impacts outside of Europe. Studies should continue to explore ways to overcome limited bicycle crash and exposure data and to utilise naturalistic methods, driving simulators, and stated choice experiments.

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Bicycling; roundabouts; safety; design; behaviour

Introduction

Modern roundabouts – circular junctions with one-way traffic around a central island – offer transportation agencies the opportunity to improve traffic flow by eliminating stop signs or signals and to improve safety by reducing the number of conflict points and reducing the speed of motor vehicles at remaining conflict points. Roundabouts are an increasingly popular design solution to replace traditional intersections in many parts of Europe, Australia, and the United States. A meta-analysis of studies done outside of the US showed that the installation of a roundabout was associated with a 30–50% reduction in the number of traffic injuries and an even larger 50–70% reduction

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in traffic fatalities (Elvik, 2003). Similarly, within the US, the conversion of two-way stop-controlled intersections and signalised intersections to roundabouts has yielded an 82% and 78% reduction (respectively) in severe crashes (FHWA, 2017). Given this overwhelming reduction in severe traffic crashes, injuries, and fatalities, the increased popularity of roundabouts is not surprising. In the US alone, the number of roundabouts has increased from zero in the early 1990s to more than 4,200 estimated in 2016 (Rodegerdts, 2017).

Despite the impressive safety record of roundabouts, their safety effects for people bicycling ("cyclists") are less clear and potentially deleterious in certain contexts. Research from Europe – where roundabouts are more common and have been used for longer – suggests that roundabouts may yield an overall increase in vehicle–bicycle crashes. A before/after analysis of 91 roundabouts in the Flanders region of Belgium (using crash data from 1991 to 2001) found a significant 27% increase in bicyclist injury collisions

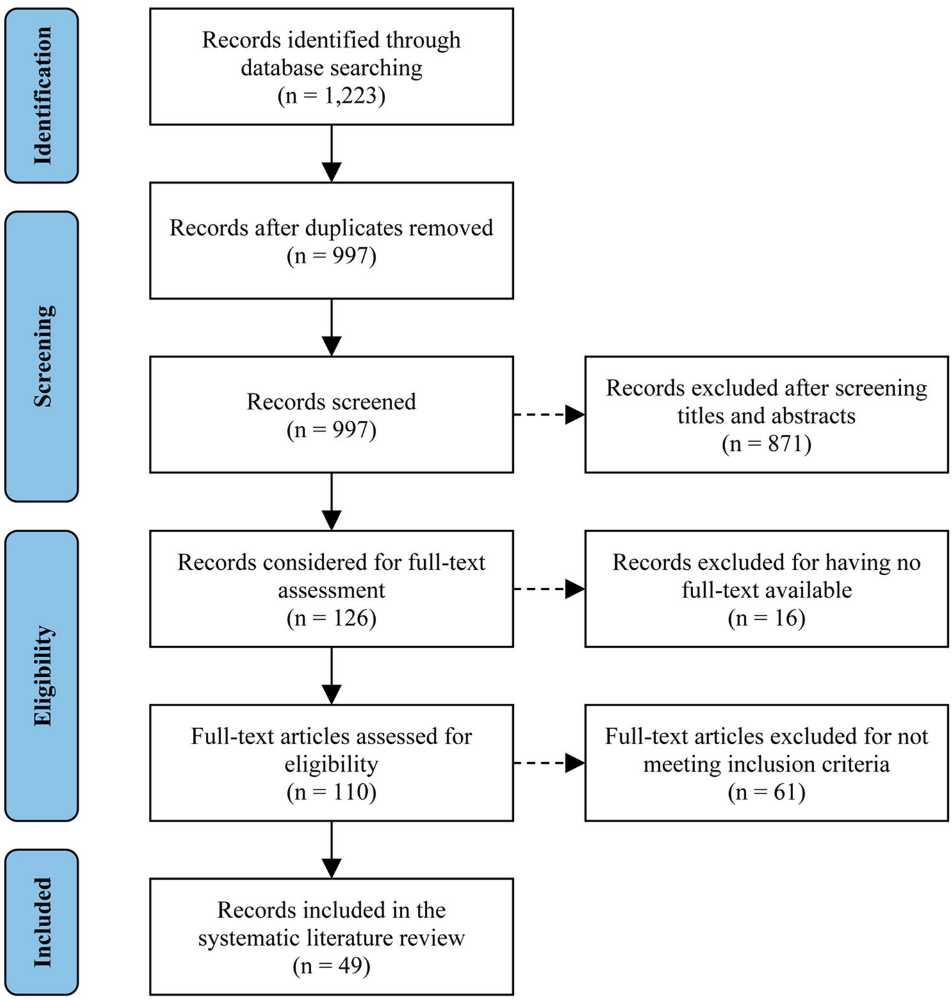

Figure 1. PRISMA flow diagram for the systematic literature review of bicycle safety at roundabouts.

Table 1. Studies on bicycle safety at roundabouts.

Citation	Location	Sample size	Methodology	Associations with factors and other findings
Akgün, Dissanayake, Thorpe, and Bell (2018)	United Kingdom	209 roundabouts, 439 injury crashes	Crash data (logistic regression)	Injury severity: speed (+), # of approach lanes (+), entry path radius (+), approach capacity (+).
Arnold et al. (2010)	US (various)	2 roundabouts, <10 crashes	Crash data	Crash rates vary between locations.
Arnold et al. (2010)	US (various)	3 roundabouts	Observations (video)	Many cyclists chose shared-used path, when available. Most cyclists in the roundabout used outside edge of the lane.
Arnold et al. (2010)	US (various)	87 cyclists, 36 adults	Questionnaire, focus groups	32% of cyclists feel uncomfortable and 25% of cyclists would change route to avoid multilane roundabouts. Most cyclists preferred signalised intersections, not roundabouts.
Aumann et al. (2017)	Australia; New Zealand	2,766 crashes	Crash data	Most common crash type was adjacent direction crashes at the roundabout entry, and most common error was failure to yield. Cyclist was reported "at fault" in only 15% of crashes.
Bahmankhah, Fernandes, Teixeira, and Coelho (2019)	Aveiro, Portugal	2 roundabouts, 4 crashes, 2 cyclists	Crash data, observations (GPS) using test cyclists	Low bicycle volume roundabout had higher driving volatility (jerk), bicyclist stops, and more motor vehicle – bicycle conflicts.
Berthaume and Knodler (2013)	Massachusetts, US	9 roundabouts, 64 cyclists	Observations (in-person)	Most common cyclist behaviours were: using the sidewalk, and creating a bicycle lane. A few cyclists rode the wrong way.
Brüde and Larsson (2000)	Sweden	72 roundabouts, 67 crashes	Crash data	Crash frequency: motor vehicle volume (+), bicycle volume (+), multiple lanes (+), central radius >10 m (−), special bicycle crossing (−).
Campbell, Jurisich, and Dunn (2006)	Auckland, New Zealand	58 multilane roundabouts, 59 crashes	Crash data	Most common crash type was between entering vehicle and circulating cyclist.
Campbell et al. (2006)	Auckland, New Zealand	195 cyclists	Questionnaire	Multilane roundabouts were perceived as more dangerous and an obstacle to avoid. Most common concerns were conflicts with vehicles when entering or exiting.
Cumming (2011a, 2011b)	Victoria, Australia	497 crashes	Crash data	Roundabout crashes disproportionately involved cyclists. Most bicycle-vehicle crashes were entering-circulating.

(*Continued*)

Table 1. Continued.

Citation	Location	Sample size	Methodology	Associations with factors and other findings
Cumming (2012)	Victoria, Australia	162 crashes	Crash data	Injury severity: speed (–).
Cumming (2012)	Victoria, Australia	5 roundabouts, 130 cyclists	Observations (in-person)	Most cyclists took one of two paths: “straight-lining” or “edge-riding.”
Daniels et al. (2008)	Flanders, Belgium	91 roundabouts, 411 crashes	Crash data (before/after with comparison group)	All injury crashes increased by 27%, and fatal/serious injury crashes increased by 41–46%. Injury crashes increased more in urban areas and for previously-signalised intersections in rural areas.
Daniels, Brijs, Nuyts, and Wets (2009)	Flanders, Belgium	90 roundabouts, 411 crashes	Crash data (before/after with comparison group, regression)	Injury crashes increased by 93% with bike lanes but not increase with cycle paths. Change in crashes: bike lane (+), signal (+).
Daniels, Brijs, Nuyts, and Wets (2010)	Flanders, Belgium	90 roundabouts, 280 crashes	Crash data (Poisson, gamma regression)	Crash frequency: motor vehicle volume (+), bicycle volume (+), moped volume (+), bike lane (+).
Daniels, Brijs, Nuyts, and Wets (2011)	Flanders, Belgium	148 roundabouts, 410 crashes	Crash data (Poisson, gamma regression)	Crash frequency: motor vehicle volume (+), bicycle volume (+), cycle path (–).
Dijkstra (2004)[a]	The Netherlands	Unknown	Crash data (before/after, cross-sectional)	Cyclist and moped crashes decreased by 60%.
Dijkstra (2004)[a]	The Netherlands	Unknown	Crash data (cross-sectional)	Fewer crashes with cycle tracks than cycle lanes. For cycle tracks, fewer crashes if cyclists did not have priority.
Ferguson et al. (2019)	US (various); Ontario, Canada	355 roundabouts, 74 crashes	Crash data	Crash frequency: urban (+), multiple lanes (+), three legs (–).
Harkey and Carter (2006); Rodegerdts et al. (2007)	US (various)	7 roundabouts, 640 cyclists	Observations (video)	Most common cyclist positions were: edge of lane, shoulder, or bike lane (entering/exiting) and taking the lane (circulating). 18% of cyclists used the sidewalk.
Hels and Orozova-Bekkevold (2007)	Funen, Denmark	88 roundabouts, 171 crashes	Crash data (Poisson, logistic regression)	Crash frequency: motor vehicle volume (+), bicycle volume (+), drive curve (+), apron width (–), construction year (+).
Herslund and Jørgensen (2003)	Denmark	1 roundabout, 289 drivers	Observations (in-person)	Drivers accepted smaller time gap when only a bicycle was present than when both bicycle and motor vehicle were present.
Hollenstein, Hess, Jordan, and Bleisch (2019)	Berne, Switzerland	294 roundabouts, >167 crashes	Crash data (logistic regression)	Crash (yes): central island radius (–), motor vehicle volume (+), urban location (+), four or five legs (+).
Hourdos, Richfield, and Shauer (2012)	Minnesota, US	2 roundabouts, 7,534 cyclists	Observations (video)	Driver yielding rates at crossings were 36% (low cyclist volume) and 82% (high cyclist volume), both lower than for pedestrians.

(*Continued*)

Table 1. Continued.

Citation	Location	Sample size	Methodology	Associations with factors and other findings
Hydén and Várhelyi (2000)	Växjö, Sweden	21 temporary small roundabouts, 142 and 26 cyclists	Observations (in-person, video), crash data (before/after), interviews	Fewer serious bicycle-car conflicts after installation of roundabouts. 70% of cars overtook circulating cyclists. 60% of cyclists yielded for circulating cars. 20–34% of cyclists made inappropriate path choices to navigate roundabout. Cyclists had positive opinions about roundabout safety, primarily because of lower speeds.
Jensen (2013a)[a]	Denmark; Sweden; The Netherlands	1,156 fatal and non-fatal injury crashes	Meta-analysis	Compared to roundabouts with no bicycle facilities: a separate bicycle path (cyclists do not have priority) reduces crashes by 84% (95th-percentile confidence interval: −91% to −69%); a cycle track (curb separated, cyclists have priority) reduces crashes by 26% (−56% to +24%); a marked cycle lane increases crashes by 33% (+12% to +58%).
Jensen (2013b)	Denmark	332 roundabouts, 326 crashes	Crash data (before/after with comparison group)	All crashes increased by 65%, and injury crashes increased by 40%. Crashes increased more for lower-speed roundabouts, with bike lanes, and in the short-term. Crashes decreased for cycle path without priority.
Jensen (2013c)	Denmark	20 roundabouts, 180 people	Questionnaire (video clips, ordinal logit regression)	Perceived satisfaction: cycle track or path (+), blue-painted cycle lane (+), regular cycle lane (−), shared roadway (−), motor vehicle volume (−), inscribed circle radius (−), central island radius (+), blue-painted cycle crossing (+), regular cycle crossing (−).
Jensen (2017)	Denmark	255 single-lane roundabouts, unknown crashes	Crash data (before/after with comparison group)	Crashes increased for urban areas, low central islands (<2 m) especially in urban areas, and bike lanes. Crashes decreased for high central islands (>2 m) and separated cycle paths.
Jensen and Buch (2015)	Denmark	105 crossings near roundabouts, 384 crashes (unknown % at roundabouts)	Crash data (negative binomial regression)	Two-way cycle path crossings were safer when path users had to yield to road users.

(Continued)

Table 1. Continued.

Citation	Location	Sample size	Methodology	Associations with factors and other findings
Jonsson, Hydén, and Svensson (2007)	Sweden	38 crossings (8 at roundabouts)	Observations (in-person)	Driver yielding to cyclists at roundabouts was generally high (~60%); no difference due to speed. Driver yielding to cyclists was higher when entering and lower when exiting the roundabout.
Kaplan and Prato (2013)	Denmark	7,967 crashes (7.7% at roundabouts)	Crash data (latent class analysis)	Injury severity was lower for urban roundabouts than at other urban intersections.
Kircher, Ihlström, Nygårdhs, and Ahlstrom (2018)	Linköping, Sweden	1 roundabout, 41 cyclists	Observations (video)	Cyclists took 10 different paths to traverse the roundabout. Cyclists who "take it easy" were more likely to stop, walk, and be delayed at the roundabout.
Macioszek and Lach (2019)	Silesian Voivodeship, Poland	300 respondents	Questionnaire	Roundabout type preference among cyclists: single-lane > turbo > two-lane > spiral. Cyclists ranked two-lane roundabout slightly better than did drivers.
Møller and Hels (2008)	Denmark	5 roundabouts, 1,019 cyclists	Questionnaire (linear regression)	Danger perception: vehicle volume (–), cyclist volume (+), cycle facility (–), female (+), involved in near miss (+). Most dangerous and highest risk situation was conflict between circulating cyclist and exiting driver. Most common safety improvement suggestions were: fewer cars, slower speeds, and building a cycle facility.
Parkin, Wardman, and Page (2007)	Bolton, UK	10 intersections (5 roundabouts), 144 commuters	Questionnaire (video clips, logistic regression)	Perceived risk: roundabout (+), bike lane (+), male (+).
Polders, Daniels, Casters, and Brijs (2015)	Flanders, Belgium	28 roundabouts, 399 crashes (46 cyclist and moped)	Crash data (logistic regression)	Crash severity was highest for cyclists. More crashes with bike lanes, and fewer with separated cycle paths.
Räsänen and Summala (2000)	Finland; Sweden; Denmark	6 single-lane roundabouts, 2,152 drivers	Observations (video) using a test cyclist	Looking opposite direction of travel: cyclist approaching from opposite direction of travel (+), other traffic (–), speed (–). Yielding: crossing setback distance (–), cyclist approaching from opposite direction of travel (–), other traffic (+), speed (–).

(*Continued*)

Table 1. Continued.

Citation	Location	Sample size	Methodology	Associations with factors and other findings
Rodegerdts et al. (2007)	US (various)	39 roundabouts, 8 crashes	Crash data	Bicycle crashes were too infrequent to analyse or yield conclusions.
Sadeq and Sayed (2016)	Vancouver, Canada	1 roundabout, 84 conflicts	Observations (video)	Most cyclist conflicts were with motor vehicles (82%), while others were with pedestrians (12%) or other cyclists (6%).
Sakshaug, Laureshyn, Svensson, and Hydén (2010)	Lund, Sweden	2 roundabouts, 1,440 interactions	Observations (in-person, video)	With separate cycle path, yielding was highest at entry with cyclist approaching same direction, and lowest at exit with cyclist approaching same direction of travel. With no cycle facility, most common conflict was between entering motor vehicle and circulating cyclist.
Sakshaug et al. (2010)	Sweden	81 crashes	Crash data	Most common crash types were between entering vehicle and cyclist approaching from opposite direction of travel, and exiting vehicle and cyclist approaching from opposite direction of travel (with separate cycle path), and between entering motor vehicle and circulating cyclist (with no cycle facility).
Saul, Junghans, and Hoffmann (2017)	Berlin, Germany	1 roundabout, 3,451 cyclists, 252 conflicts	Observations (video)	Cyclist conflicts with motor vehicles was associated with motor vehicle volumes. Conflicts between exiting vehicles and circulating cyclists were frequent.
Schoon and Van Minnen (1993)[a]	The Netherlands	201 roundabouts	Crash data (before/after)	Crashes were reduced by 30%.
Schoon and Van Minnen (1993)[a]	The Netherlands	201 roundabouts	Crash data (cross-sectional)	At high motor vehicle volumes (>8,000 ADT), a separate cycle path was safer than a bike lane or no cycle facility.
Schreiber, Ortlepp, and Bakaba (2014)	Germany	100 roundabouts, 1,015 crashes (all modes)	Crash data	Cyclist injury crashes made up a higher share of injury crashes at roundabouts (~38%) than at signalised intersections (15%). Bicycle volume and bicycle × motor vehicle volume were both positively associated with bicycle crashes.

(*Continued*)

Table 1. Continued.

Citation	Location	Sample size	Methodology	Associations with factors and other findings
Schreiber et al. (2014)	Germany	10 roundabouts	Observations	For roundabouts with mixed traffic, high traffic volumes increase chance of cyclists using sidewalks. For cycle paths with priority, more assertive at crossings and greater share of wrong-way riding, compared to cycle paths without priority.
Silvano, Ma, and Koutsopoulos (2015); Silvano, Koutsopoulos, and Ma (2016)	Stockholm, Sweden	1 roundabout, 187 interactions	Observations (video) (binary logit regression)	Yielding: distance of cyclist to crossing (−), speed (−).
Shen, Wang, Zheng, and Yu (2020)	United Kingdom	9,127 crashes	Crash data (partial proportional odds model)	Injury severity: male (−), age (+), speed limit (−), urban (−), wet road (+), raining (−).
Tan et al. (2019)	Melbourne, Australia	1 roundabout, 740 respondents	Questionnaire, observations (video)	After converting roundabout with in-road bike lanes to (bicycle) protected roundabout, increased safety perceptions among cyclists.
Tang (2018)	Norrköping, Sweden	4 roundabouts, 39 crashes	Crash data	Roundabout with the fewest cyclists and highest motor vehicle volumes had the most crashes, injuries, and fatalities.
Turner, Roozenburg, and Smith (2009)	New Zealand	104 roundabouts	Crash data (Poisson, negative binomial regression)	Crash frequency (entering motor vehicle vs. circulating cyclist): motor vehicle volume (+), bicycle volume (+), speed (+). Crash frequency (other crashes): motor vehicle volume (+), bicycle volume (+).
Vandenbulcke, Thomas, and Panis (2014)	Brussels, Belgium	644 crashes (unknown % at roundabouts)	Crash data (case-control)	Crashes were more likely (OR = 16–17) at roundabouts with bike lanes and slightly more likely (OR = 2–3) at roundabouts without bicycle facilities.
Wilke et al. (2014)	Australia; New Zealand	Unknown	Crash data	Roundabout crashes disproportionately involved cyclists.
Wilke et al. (2014)	Australia	10 roundabouts, 1,346 cyclists	Observations (video)	Most cyclists rode in the outermost 50% of the lane. When present, less than half of cyclists used bike lanes. Pavements markings helped to encourage lane sharing.

Notes: [a]Information from abstract only or other reference (full text not in English).

Figure 2. Types of bicycle facilities at roundabouts: None (top left); On-roadway bicycle lane within the roundabout (top right); Shared-use path with bicycle ramps (bottom left); Separated cycle path or "protected roundabout" (bottom right). Images: (top left; bottom left) by Dan Burden from https://www.pedbikeimages.org (used with permission); (top right) "The Magic Roundabout of Randlay" by Richard Law from https://www.geograph.org.uk/photo/1623802 (licensed CC BY-SA 2.0); (bottom right) by Dan Burden (used with permission).

and a larger increase (>40%) in fatal and serious injury crashes involving bicyclists (Daniels, Nuyts, & Wets, 2008). A similar study of 332 roundabouts (constructed between 1995 and 2009) in Denmark found a 65% increase in total bicycle crashes and a 40% increase in bicycle injury crashes after their installation (Jensen, 2013b). These two studies accounted for general crash trends, regression-to-the-mean, and design factors, but they did not have the data to control for bicycle volume or exposure. Older research from the Netherlands found some reductions in bicycle crashes after the installation of roundabouts, but decreases were generally smaller than for motor vehicles (Dijkstra, 2004; Schoon & Van Minnen, 1993). Research conducted in Denmark, the UK, and Australia determined that bicycle crashes are overrepresented at roundabouts, compared to other modes and different intersection types (Allot & Lomax, 1991, as cited in Jørgensen & Jørgensen, 2002; Räsänen & Summala, 2000, as cited in Cumming, 2011a, 2011b; Møller & Hels, 2008; Wilke, Lieswyn, & Munro, 2014).

A number of factors complicate research on the safety of roundabouts for people cycling. Bicycle activity levels are comparatively low in many parts of the world where roundabouts are becoming common, so the majority of literature comes from Europe (e.g. Hels & Orozova-Bekkevold, 2007) with some from Australia and New Zealand (e.g. Aumann, Pratt, & Papamiltiades, 2017). Research results from one geographic and cultural context may not be completely transferrable to other places, given differences in traffic laws and driver/cyclist behaviours and norms. Even in higher-cycling countries in northern

Europe, collisions between vehicles and bicycles are rare events, requiring multiple years of study across many sites to yield robust findings from purely crash data analyses (Daniels et al., 2008). In a recent US national research project, Ferguson et al. (2019) proposed to create robust roundabout crash prediction models for vehicle–bicycle crashes but concluded that there were an insufficient number of bicycle crashes (only 75 at the 355 roundabouts in the study). The frequent underreporting of bicycle crashes (Shinar et al., 2018) exacerbates this issue. As a result, some researchers have turned to measuring vehicle–bicycle conflicts and cyclists' safety perceptions (e.g. Arnold et al., 2010) rather than objective safety outcomes. Complicating matters are the various roundabout geometric design approaches utilised in different countries (Aumann et al., 2017).

Overall, there is a relative lack of research on bicycle safety at roundabouts and a need to summarise and consolidate various research findings and identify knowledge gaps, especially in places where roundabouts are becoming a popular design solution. Studying the relationships between roundabouts and safety for people bicycling is also important as cities seek to promote cycling for transportation. For instance, in the US since around 2000, bicycling has increased by roughly 2% or more per year, according to national-level survey data and traffic counts (Le, Buehler, & Hankey, 2019). At the same time, bicycle injuries and fatalities in the US have been increasing since 2009 (Buehler & Pucher, 2020), and cyclists now represent more than 2% of all road user fatalities (NHTSA, 2018).

With this review paper, we aim to provide a systematic review of the literature on bicycle safety at roundabouts. We expand upon the occasional reviews that do exist, most recently Silvano and Linder (2017). Although we focus our attention on reviewing study methodologies and operational and design-related factors associated with bicycle safety at roundabouts, we also consider driver and cyclist behaviours, since behaviour responds to design and design should accommodate expected behaviours. By examining and classifying existing knowledge on this topic, our work provides guidance for future researchers wishing to study bicycle safety at roundabouts, as well as to practitioners seeking to translate knowledge into on-the-ground solutions. Despite the challenges and limitations noted above, there is a growing body of research that suggests certain preferred (from the point-of-view of bicycle safety and comfort) roundabout designs and operational treatments that account for driver and cyclist behaviours and safety perceptions, which we will highlight.

The next section details the literature search strategy, and in the following section, we describe the various types of methodologies used to examine bicyclist safety, focusing on crash data, video recordings, and user perceptions. The large subsequent section summarises the many factors associated with roundabout safety, including geometric, design, operational, behavioural, and perceptual characteristics and considerations. We conclude by discussing the limitations of existing methods and gaps in existing knowledge and suggesting opportunities for future research.

Literature search

Given data challenges and limited existing knowledge on bicyclist safety at roundabouts, it is important to cast a wide net when examining this topic. Thus, we searched the Transport Research International Documentation (TRID) and Scopus databases (final search: September 2020) for relevant literature using the following search phrase: "*(bicycl* OR cycl* OR bike) AND* *(roundabout*) AND (safety OR crash OR collision OR perception)*". Furthermore, a Google Scholar search (final search: September 2020) was conducted for articles containing both "*bicycle*" and "*roundabout*" and at least one of the following: "*safety*," "*crash*," "*collision*," or "*perception*." While all of the results from TRID and Scopus were considered, only the first 700 results from Google Scholar were considered (very few results after the first several hundred were relevant).

Regarding inclusion criteria, resources were required to: (1) be written in English (or with an English-language abstract); (2) be published after 1990; and (3) have some empirical or analytical components (i.e. we excluded those solely discussing design considerations, literature reviews, and pure simulation studies). Fundamentally, documents also had to be about bicycling and roundabouts and have something to do with safety (e.g. use crash data, ask about safety perceptions, observe conflicts or road user behaviours). We considered peer-reviewed academic journal articles as well as grey literature, including published reports, conference presentations, and student theses/dissertations.

Figure 1 depicts the systematic literature search process. We retrieved 1,223 results from the initial search of databases (111 from Scopus, 412 from TRID, and 700 from Google Scholar). After removing duplicates, we were left with 997 unique records to review. After reviewing titles and abstracts, 126 records were considered for the full-text review; although 16 of these had no full-text available. Thus, 110 full-text records were fully reviewed against our inclusion criteria and for topical relevance. After a detailed assessment, 49 papers were included in the systematic literature review. Each of the 56 studies (some documents included multiple studies) is detailed in Table 1.

Study methodologies

As roundabouts are dominantly present in Europe, more than half of the literature in our study comes from a northern European context, mainly from Sweden, Denmark, Belgium, the Netherlands, and Germany (31 studies); some studies took place in the United Kingdom (3) and elsewhere in Europe (4) (Finland, Poland, Switzerland, and Portugal). The other portion of studies are from Australia and New Zealand (10) and from North America (9) (mostly the United States, with some from Canada). We identified no studies from Asia, Africa, or South America. (Totals exceed 49 due to multiple studies and countries in some documents).

Various methodologies have been used to study bicycle safety at roundabouts, which we categorise based on the predominant type of data analysed: reported crashes (before and after analysis, regression analysis), observations of road user behaviours/interactions (video or in-person observations, conflict analysis), and survey responses about safety perceptions (questionnaires or interviews, stated preferences). In our literature review, more than half of studies (33) used crash data analysis; 18 studies used observations; and only 8 studies used questionnaires or interviews. (Totals exceed 49 due to multiple studies and methods in some documents.) We detail these three types of study methodologies in the following sections.

Crash data and statistical modelling of observed crashes

Statistical modelling of crash data is a conventional and strong approach for objective and substantive traffic safety analysis. Early contributions showing the generally positive safety effects of roundabouts for total (all mode) crashes (Elvik, 2003; Persaud, Retting, Garder, & Lord, 2001) relied upon analyses of crash data. Crash data analyses typically model crash frequencies (using before/after analysis or cross-sectional regression methods) or crash severities.

Before/after analysis of the change in safety performance of intersections (before and after the installation of a roundabout) is a robust quasi-experimental statistical method (AASHTO, 2010), since it measures within-location changes over time as a result of a treatment (installing a roundabout). This is particularly true when also utilising a comparison/control group (to control for general safety trends and regression-to-the-mean); however, the challenge lies in finding comparable sites where roundabouts were not added and obtaining sufficient longitudinal data. Several recent studies have used before/after crash data analysis with comparison groups: Daniels et al. (2008, 2009) studied changes in bicycle injury crash frequencies at 91 locations where roundabouts were installed (1994–2001) in Belgium, while Jensen (2013b, 2017) analysed 332 and 225 sites (respectively) converted to roundabouts (1995–2009) in Denmark. Some earlier research in the Netherlands (Dijkstra, 2004; Schoon & van Minnen, 1993) and Sweden (Hydén & Várhelyi, 2000) counted bicycle crashes before and after roundabouts were installed, without using comparison groups.

Most other crash frequency studies used cross-sectional statistical methods, often performing (e.g. Poisson, negative binomial) regressions on bicycle crash frequencies to identify traffic volume, geometric, and other characteristics associated with safety at roundabouts (Brüde & Larsson, 2000; Daniels et al., 2010, 2011; Hels & Orozova-Bekkevold, 2007; Hollenstein et al., 2019; Jensen & Buch, 2015; Turner et al., 2009; Vandenbulcke et al., 2014). Cross-sectional methods compare the safety performance of intersections with (and sometimes without) roundabouts during one general time period. Although they can potentially utilise more (and more recent) data and are necessary when before data are unavailable, cross-sectional studies are less useful for determining causality and quantifying safety effectiveness resulting from roundabout conversions, since they rely on between-location differences to infer an implied treatment effect.

Most studies utilising statistical analyses of crash data involving cyclists have come from northern Europe, where there are more cyclists and roundabouts. This highlights a fundamental challenge for objective analysis of actual safety outcomes in most places: there is often insufficient data – few bicycle crashes, few roundabouts, limited number of years, lack of bicycle exposure data, lack of information on roadway characteristics – for a robust bicycle safety analysis (DiGioia, Watkins, Xu, Rodgers, & Guensler, 2017). Most US and Australian/New Zealand studies can do no more than basic descriptive/comparative statistics with their crash data (Arnold et al., 2010; Aumann et al., 2017; Campbell et al., 2006; Cumming, 2011a, 2011b; Ferguson et al., 2019; Rodegerdts et al., 2007; Tan et al., 2019; Wilke et al., 2014). A recent US study estimated that, at current rates of usage and crashes, there may even not be enough roundabouts in the entire country to estimate robust pedestrian- and bicycle-specific safety performance functions for roundabouts (Ferguson et al., 2019). We could find only one study that has conducted a meta-analysis of bicycle safety studies at roundabouts, combining studies from Denmark, Sweden and the Netherlands that encompass 1,156 cyclist crashes (Jensen, 2013a, as cited in Jensen, 2015).

Two studies have modelled the severity of bicycle crashes at roundabouts, which allows the study of factors beyond just geometric/operational characteristics, including socio-demographics and meteorological conditions. Akgün et al. (2018) analysed cyclist crash severity (serious versus slight) using binary logistic regression, whereas Shen et al. (2020) used a partial proportional odds (ordered logit) regression model; both studies were conducted in the UK. A few other studies have investigated bicycle crash severity without the use of such regression models (Cumming, 2012; Daniels et al., 2008; Jensen, 2013b).

Video data (or manual observations) and analyses of road user behaviours/conflicts

In the absence of a sufficient number of crashes, proxy or surrogate safety measures can be collected, often (now) using video technology. Data (e.g. speeds, trajectories, actions) collected from GPS devices and video/in-person observations can be used, for instance, to classify conflicts and near misses (Chin & Quek, 1997). A common definition of a conflict is if the time to collision – the time at which road users, with no change to speed and/or direction, would come into contact – is below some reference time (usually a few seconds). Overall, field observations of cyclist behaviours and interactions help inform how users react in real situations and can include some degree of experimental control (e.g. tracking cyclists on predefined routes, navigating through different infrastructure).

Several studies have used observations to examine interactions between motor vehicle drivers and people cycling: conflicts, driver (and cyclist) yielding, driver looking, and driver gap acceptance at entrances, exits, and within roundabouts (Bahmankhah et al., 2019; Herslund & Jørgensen, 2003; Hourdos et al., 2012; Hydén & Várhelyi, 2000; Jonsson et al., 2007; Räsänen & Summala, 2000; Sadeq & Sayed, 2016; Sakshaug et al., 2010; Saul et al., 2017; Silvano et al., 2015; Tan et al., 2019). Other observational studies have focused more on cyclist behaviours, including lane positioning, trajectories, and path choices (Arnold et al., 2010; Berthaume & Knodler, 2013; Cumming, 2012; Harkey & Carter, 2006; Kircher et al., 2018; Rodegerdts et al., 2007; Schreiber et al., 2014; Wilke et al., 2014). Overall, this type of research can generate important behavioural insights into potential safety issues, most notably "looked-but-failed to see" conflicts between circulating cyclists and entering drivers (Herslund & Jørgensen, 2003; Sakshaug et al., 2010).

Although video-based conflict analysis and behavioural observations can help to mitigate the data challenges associated with statistical crash data analysis, this method is not without its own limitations. Surrogate safety measures are just that: a replacement for actual safety outcomes. Sites with more conflicts may indeed eventually see more crashes, but this relationship requires more study (Zheng, Ismail, & Meng, 2014). Also, these methods only tell us how cyclists and drivers *behave* when navigating a roundabout. They cannot provide insights into how cyclists *feel* when traversing roundabouts and interacting with vehicles, and (importantly) they cannot capture most avoidance behaviours due to cyclists' safety perceptions.

Survey data or interviews about safety perceptions and preferences

Information on subjective safety perceptions and design preferences can also be useful for understanding bicycle safety at roundabouts. Perceptions of risk, safety, and comfort could significantly affect the nature with which cyclists will use (or avoid) certain intersections or roadways, and designs can signal or nudge road users toward intended behaviours. Unfortunately, there is not much literature on cyclist safety perceptions of roundabouts. The eight studies we identified used questionnaires (or interviews) to investigate cyclists' perceived comfort, danger, risk, and avoidance of roundabouts (Arnold et al., 2010; Campbell et al., 2006; Hydén & Várhelyi, 2000; Jensen, 2013c; Macioszek & Lach, 2019; Møller & Hels, 2008; Parkin et al., 2007; Tan et al., 2019). For example, Møller and Hels (2008) stopped around 1,000 cyclists at roundabouts in Denmark and asked 12 questions about perceived crash risks in different situations (e.g., entering the roundabout, circulating while a car exits).

One advantage of questionnaires and interviews is that researchers can investigate perceptions and preferences for roundabouts and characteristics that do not yet exist or that users do not regularly experience. Experiments asking cyclists to select or rate potential roundabout designs and intended trajectories could be useful to determine cyclists' preferences – and have been used to examine safety perceptions of other bicycle infrastructure (e.g. McNeil, Monsere, & Dill, 2015) – but, to our knowledge, only Parkin et al. (2007) and Jensen (2013c) have tried anything similar. Both studies showed people different video clips of bicycling through roundabouts and asked them to rate their perceived risk or satisfaction.

Factors influencing the safety of bicyclists at roundabouts

Many studies in Table 1 investigated factors associated with the safety performance of roundabouts for cyclists. We summarise these findings in three subsections: operational and design characteristics, the presence and type of bicycle facilities, and road user behaviours.

Operational and design characteristics

As measures of exposure that increase the chance of collisions, traffic volumes are a critical factor affecting intersection safety performance, including for cyclists at roundabouts. In five cross-sectional studies (Brüde & Larsson, 2000; Daniels et al., 2010, 2011; Hels & Orozova-Bekkevold, 2007; Turner et al., 2009), both motor vehicle volumes and bicycle volumes were positively associated with crash frequencies. However, a "safety in numbers" effect for bicycling – in which bicycle crash rates (counts per volume) decreased with increasing bicycle volumes (Jacobsen, Ragland, & Komanoff, 2015) – has been identified in several cross-sectional studies (Daniels et al., 2010, 2011; Turner et al., 2009) that also controlled for motor vehicle volumes. In two perception studies, roundabouts with more bicycle traffic were perceived to be less dangerous (Møller & Hels, 2008), while roundabouts with higher motor vehicle volumes were perceived to be more dangerous (Møller & Hels, 2008) and decreased the perceived satisfaction for cycling at roundabouts (Jensen, 2013c).

Research generally suggests that situations with higher motorised vehicle operating speeds are deleterious for bicycle safety at roundabouts. Higher speeds have been associated with higher crash frequencies (Hels & Orozova-Bekkevold, 2007; Turner et al., 2009) or severities (Akgün et al., 2018); although, these studies calculated speeds in different ways. In Akgün et al. (2018) and Hels and Orozova-Bekkevold (2007), deflection in the roadway (entry path radius) was used as a proxy for vehicle operating speed; alternatively, Akgün et al. (2018) also used speed limit and Turner et al. (2009) measured entering vehicle speeds. Slower approach speeds have also been associated with increased driver yielding to cyclists in one observational study (Räsänen & Summala, 2000). In a perception study (Møller & Hels, 2008), around 66% of cyclists thought lower-speed roundabouts were safer. However, some studies find a counterintuitive relationship with vehicle speed. Cumming (2012) classified bicycle crashes by speed and severity, finding that serious injury crashes made up a slightly higher share of crashes at lower-speed roundabouts (28% for 30–50 km/hr; 21% for +60 km/hr). Based on data from Jensen (2013b), crashes involving cyclists increased (by around 100%) when roundabouts were installed at lower-speed intersections (40–50 km/hr) but decreased (by around 40%) at higher-speed locations (+60 km/hr).

It could be that the safety impacts of speed appear in other ways. Roundabouts installed in urban areas (where approach speeds tend to be lower) experienced greater increases in bicycle crash frequencies compared to roundabouts installed in more rural locations (Daniels et al., 2008; Jensen, 2017), although the severity of those crashes may be lower at roundabouts than at other types of intersections (Kaplan & Prato, 2013). Multilane roundabouts – which facilitate higher motor vehicle volumes and perhaps higher speeds, but certainly more potential conflict points – have been found to have more frequent (Brüde & Larsson, 2000; Ferguson et al., 2019) as well as more severe (Akgün et al., 2018) bicycle crashes than single lane roundabouts. Cyclists also perceive multilane roundabouts as more dangerous, uncomfortable, and an obstacle to be avoided (Arnold et al., 2010; Campbell et al., 2006); although a study in Poland (Macioszek & Lach, 2019) found that cyclists rated two-lane roundabouts safer than did drivers.

Other geometric design parameters have also been investigated. Roundabouts having central islands with larger radii (>10 m), heights (>2 m), and apron widths may be safer for cyclists (Brüde & Larsson, 2000; Jensen, 2017; Hels & Orozova-Bekkevold, 2007; Hollenstein et al., 2019), perhaps because they can check circulation speed and focus the attention of entering vehicle drivers (Jensen, 2017). Preference for large central islands over small ones and for roundabouts with narrower circulating lanes were demonstrated by respondents of a video stated preference survey (Jensen, 2013c). But, roundabouts with larger inscribed circle radii are thought to not be as safe for bicycling (Jensen, 2013c; Tang, 2018), since large roundabouts can allow for higher motor vehicle speeds. Driver yielding to cyclists at crossings was higher when the crossing was closer to the roundabout (Räsänen & Summala, 2000). Although the number of legs/arms/approaches might increase the number of conflict points, this variable has been significant in only one study of small roundabouts (Hollenstein et al., 2019). Roundabouts that replaced intersections with signals had greater increases in injury crashes than roundabouts that replaced unsignalized intersections (Daniels et al., 2008, 2009).

Bicycle facility presence and type

The provision of (any and types of) bicycle facilities at roundabouts is a critical design consideration that warrants its own summary of findings. There are typically four options (with variations): (1) no bicycle facilities (cyclists are expected to “take the lane” and ride in mixed traffic, or else use the sidewalk); (2) an on-roadway bicycle lane within the roundabout (along the outside edge of the roadway, adjacent to the circulating lane(s)); (3) a shared-use path combined with the sidewalk (often with bicycle ramps leading to/from the roadway); or (4) a separated cycle path (separate from both the sidewalk and roundabout lanes), often with set-back bicycle crossings (sometimes called a "protected roundabout"). The second option is not recommended by most design guidance (Aumann et al., 2017; CROW, 2007; Rodegerdts et al., 2010) but still exists in some countries; the bike lane is usually delineated with pavement markings or coloured pavement, or it may be slightly elevated above the rest of the roadway. In some cases, the fourth option may have two-way bicycle traffic, and crossing cyclists may or may not have priority over entering/exiting motor vehicle traffic. (Grade-separated cycle paths with over- or under-crossings are another, not always feasible, option.) Figure 2 shows examples of these different bicycle facility types at roundabouts.

Research results are consistent in finding adverse bicycle safety impacts associated with having on-roadway bike lanes within (around the edge of) roundabouts. Two sets of robust crash data modelling studies in Belgium (Daniels et al., 2009) and Denmark (Jensen, 2013b, 2017) concluded that roundabouts with on-roadway bike lanes performed worse and had greater increases in bicycle crashes (of +100% or more) than roundabouts with separated cycle paths or no bicycle facilities. Both sets of studies used before-after analysis with comparison groups (to correct for general trends and regression-to-the-mean) and controlled for roundabout location and geometry but not bicycle or motor vehicle traffic volumes. Several follow-up (cross-sectional) crash data studies in Belgium (Daniels et al., 2010, 2011; Polders et al., 2015; Vandenbulcke et al., 2014) confirmed that cyclist crash frequencies were higher and more likely at roundabouts with bike lanes, especially compared to sites with separated cycle paths. Also, a meta-analysis of crashes at roundabouts with different bicycle facilities (Jensen, 2013a, as cited in Jensen, 2015) found that marked bike lanes within the roundabout increased bicycle crashes by 33%, while a separate cycle path (with no priority for cyclists) reduced crashes by 84%, in comparison to roundabouts with no bicycle facilities. These findings match earlier research (Brüde & Larsson, 2000; Dijkstra, 2004; Schoon & van Minnen, 1993); although, one study (Hels & Orozova-Bekkevold, 2007) found no significant association between bicycle crashes and the presence of bicycle facilities.

Some interesting results can be seen regarding the safety of different cyclist priority rules at separated path crossings. In three different northern European studies utilising crash data (Dijkstra, 2004; Jensen, 2013b; Jensen & Buch, 2015), there were fewer crashes or crashes decreased where cyclists did not have priority at separated cycle path crossings, and instead had to yield to roadway users. An observational study at 10 German roundabouts found that cyclists were more assertive at roundabout crossings with priority but more defensive and attentive at crossings without priority (Schreiber et al., 2014). Findings may be related to priority rules in different countries: several European countries give cyclists priority at roundabout crossings in urban areas but not at rural roundabouts (Aumann et al., 2017).

Cyclists, through their perceptions and preferences, appear to be somewhat aware of the increased crash risk posed by on-roadway bike lanes. In a UK study (Parkin et al., 2007), cyclists perceived a greater adverse risk for roundabouts with bike lanes (compared to those with no bicycle facilities), but the authors speculated that the presence of facilities might suggest to cyclists a greater risk for bicycling (p. 369). Danish cyclists perceived roundabouts without cycle facilities to be more dangerous, and most thought that building a cycle facility in such locations would improve safety (Møller & Hels, 2008). It was unclear from the article whether respondents considered "cycle facilities" to be bike lanes and/or separated cycle paths. Similarly, in a Danish video stated preference survey (Jensen, 2013c), the satisfaction level for cyclists was increased when the video included riding on a cycle path or cycle track in comparison to a cycle lane (along the perimeter) or while taking the roadway. After converting a roundabout in Australia that had in-road bicycle lanes to one with protected cycle lanes, cyclists' perceptions of safety improved (Tan et al., 2019).

Driver and cyclist behaviours and interactions

Observations of cyclist behaviours – particularly lane positioning and path selection – can inform our understanding of the safety of different bicycle facility types and other roundabout design considerations. When a shared-use or separated cycle path is provided at a roundabout, most cyclists choose to use that route rather than travel on the roadway (Arnold et al., 2010). In the absence of bicycle facilities, most cyclists seem to choose one of a few different paths. Some may avoid the roundabout altogether, choosing to using the sidewalk; this was especially common (18–50%) in the US (Berthaume & Knodler, 2013; Harkey & Carter, 2006; Rodegerdts et al., 2007). Although designers may intend for most cyclists to "take the lane" and operate as a vehicle in these cases, not all cyclists do: less than 20% in one study of single-lane roundabouts in Massachusetts (Berthaume & Knodler, 2013). An observational study of small roundabouts in one Swedish city found that 70% of drivers overtook circulating cyclists, contrary to the intended sharing of the lane (Hydén & Várhelyi, 2000).

A common behaviour (that minimises displacement and maximises speed) is "straight-lining," in which cyclists enter (and exit) on the outer edge of the roundabout but sweep towards the centre island while circulating. The other common behaviour is "edge-riding" or "creating a bike lane" by circulating along the outer edge or shoulder of the roundabout, likely due to discomfort. In several studies (Cumming, 2012; Harkey & Carter, 2006; Rodegerdts et al., 2007), the former was frequently observed (>50%) while the latter was also fairly prevalent: ~25%, even >50% (Arnold et al., 2010). But even when on-roadway bike lanes are present, many cyclists may not use them: only 10–60% in Australian studies (Cumming, 2012; Wilke et al., 2014). Wrong-way riding has also been observed at roundabouts (Berthaume & Knodler, 2013; Harkey & Carter, 2006; Rodegerdts et al., 2007; Schreiber et al., 2014). Hydén and Várhelyi (2000) observed five different "inappropriate" path choices that 20–34% of cyclists took to navigate roundabouts. Tracking of 41 cyclists making a turn at one roundabout in Sweden identified 10 different paths taken, including some people who stopped and walked and others who rode against traffic (Kircher et al., 2018).

Investigating and observing driver–cyclist interactions, conflicts, and common crash types can also shed light on safe bicycle facilities at roundabouts. For separated cycle paths, safety concerns most likely arise at crossings. At two locations in Sweden, drivers yielded to cyclists less often when exiting (versus entering) the roundabout (Jonsson et al., 2007). Other studies found that at entrances, driver yielding was lower when there were no vehicles in the roundabout and when cyclists approached from the opposite direction of travel (Räsänen & Summala, 2000; Sakshaug et al., 2010); most drivers did not look opposite to the direction of traffic when cyclists were not present, but up to 15% did not look even when cyclists were approaching (Räsänen & Summala, 2000). Yet at exits, driver yielding was lower when cyclists approached from the same direction of travel (Sakshaug et al., 2010). These two situations were also the most common crash types in one Swedish study (Sakshaug et al., 2010). Driver yielding to cyclists at crossings might increase with bicycle volumes, although it may not be as high as yielding for pedestrians (Hourdos et al., 2012; Jonsson et al., 2007).

For roundabouts with on-roadway bike lanes or no bicycle facilities, the primary safety concern appears to be between entering (or exiting) motor vehicles and circulating cyclists. In several studies of crash data (Aumann et al., 2017; Campbell et al., 2006; Cumming, 2011a, 2011b; Sakshaug et al., 2010), these "entering–circulating" crashes were overwhelmingly (67–82%) the most common type of bicycle-involved crash. They were also the most frequent serious conflict (Sakshaug et al., 2010), and conflicts with entering or exiting vehicles were perceived to be the most dangerous and risky (Campbell et al., 2006; Møller & Hels, 2008) or observed to be the most common (Saul et al., 2017). Given that roundabout rules require yielding to traffic (including cyclists) in the roundabout, the fault seems to be placed on driver behaviour (Aumann et al., 2017). Drivers have been observed to accept a smaller time gap when only a bicycle was present than when both a bicycle and a motor vehicle were present (Herslund & Jørgensen, 2003).

Discussion and conclusions

As roundabouts become an increasingly popular intersection design solution, and as many communities promote healthy and sustainable bicycle use, the safety of bicyclists at roundabouts is of major concern. Through our literature search, we reviewed 49 different documents: most studies were in northern Europe, some took place in Australia or New Zealand, and only a few were from the US and Canada. We considered various study methodologies – statistical modelling and analysis of longitudinal or cross-sectional crash data, observations of cyclist and driver behaviours and interactions, and surveys of road users' safety perceptions – and summarised evidence of factors potentially influencing bicycle safety, including operational and design characteristics (volume, speed, etc.), the presence and type of bicycle facilities, and road user behaviours.

In the remaining sections, we detail our paper's key findings, consider the implications for roundabout design and operation, and discuss knowledge gaps and opportunities for future research. To summarise our findings and contributions:

- Roundabouts do not improve safety for cyclists as much as for drivers, and may actually increase bicycle crashes, especially for roundabouts with on-roadway bike lanes or no bicycle facilities.
- Roundabouts that appear to be safer for bicycling have: lower motor vehicle volumes and speeds, one lane, and are smaller in size but have larger/higher central islands.
- Separated cycle paths are much better, and on-roadway bike lanes are much worse, for bicycle safety at roundabouts.

- Critical situations and behaviours are: visibility and yielding at separated cycle path crossings, and conflicts between entering/exiting vehicles and circulating cyclists.
- Future research should investigate more varied factors, study roundabouts outside of Europe, and utilise naturalistic methods and stated choice experiments.

Key findings and roundabout design and operational considerations

In general, although the conversion of an intersection to a roundabout likely reduces crashes overall, it may actually increase the frequency or rate of crashes involving cyclists. Moreover, bicycle safety performance appears to be worse for multilane roundabouts, those in urban areas, and/or previously signalised intersections. Research lends support to recommendations (Arnold et al., 2010; Aumann et al., 2017; Patterson, 2010; Rodegerdts et al., 2010; Wilke et al., 2014) that roundabouts (particularly multilane ones) may not be the best intersection design in all situations, especially in places where moderate-to-high bicycle volumes are expected or planned. Reducing the speed and volume of motor vehicle traffic at roundabouts seems likely to yield fewer bicycle crashes.

Research findings are clear regarding the relative safety of specific bicycle facilities at roundabouts: Providing in-roadway bike lanes through roundabouts leads to worse safety performance and more crashes for cyclists. Design guidance from Europe, the United States, Australia, and New Zealand (Aumann et al., 2017; CROW, 2007; Rodegerdts et al., 2010) is consistent in recommending against bike lanes. Instead, providing separated cycle paths around the roundabout seems to be the preferred and safer solution (short of grade-separation). Separated facilities are likely to be especially important at locations with higher traffic speeds and volumes, multiple lanes approaching or through the roundabout, and many cyclists, or when there is a desire to encourage "interested but concerned" cyclists (Dill & McNeil, 2013). Given the increase in protected bicycle facilities in the US over the last 10 years (FHWA, 2015; People for Bikes, n.d.) – including protected intersections, which act like bicycle roundabouts superimposed on traditional intersections – there is a need to revise US roundabout design recommendations (Rodegerdts et al., 2010) to account for newer bicycle planning, selection, and design guidance (NACTO, 2019; Schultheiss et al., 2019). For instance, the Massachusetts DOT provides general guidelines for "protected roundabouts" with separated bike lanes (MassDOT, 2015).

When using separated cycle paths at roundabouts, care should be taken to design bicycle crossings far enough away from the roundabout to provide a queuing area and sufficient perception/reaction time for drivers to yield or stop, and alignments (and signage) to encourage entering and exiting drivers to look for crossing cyclists (or vice versa, in locations with different driver/cyclist priority rules). Other potential design/operational features include: splitter islands for long crossings, separate through/turn lanes (and separate bicycle/pedestrian crossings) for intersections with high bicycle volumes, and even traffic signals or actuated rectangular rapid flashing beacons at crossings.

When no bicycle facilities are provided at roundabouts, research is also clear about the most critical safety concern: entering (and to a lesser degree, exiting) drivers colliding with circulating cyclists. Researchers call this the "looked-but-failed-to-see" phenomena, in which a driver looks in the direction but fails to notice the bicycle already in the roundabout. They speculate that drivers entering roundabouts become used to primarily looking for other motor vehicles (and for potential dangers to themselves), and so fail to notice smaller, slower-moving, and less threatening cyclists (Herslund & Jørgensen, 2003). Indeed, there are more conflict points for people bicycling in a traditional roundabout than in a protected design with a separated cycle path (Stanek, 2018). Although signage and pavement markings could help to encourage cyclists to "take the lane," it is likely that many will still ride along the outer edge, at the risk of being passed or overlooked by drivers. High central islands could help to focus entering drivers' attention on circulating road users – blocking views of the far side of the roundabout – but cannot address the expectation bias issue related to the smaller size and different speed of people bicycling (compared to motor vehicles). Some other geometric design features of roundabouts (wider central islands, greater deflection, narrower circulatory roadway widths) could help improve bicycle safety, especially those features that reduce speeds for (entering, circulating, and exiting) vehicles down to typical bicycling speeds. Despite all this, if the design user is the "interested but concerned" cyclist (Dill & McNeil, 2013), then roundabouts with no bicycle facilities are likely not an appropriate design unless motor vehicle speeds and volumes are very low (<20–25 mph and <2,000–3,000 ADT, borrowed from Schultheiss et al., 2019, p. 23). Otherwise, separated shared-use or cycle paths may be required to provide adequate levels of comfort and safety.

Research limitations and opportunities for future work

As with other fields and topics, the major limitation to better understanding bicycle safety at roundabouts is data availability. Roundabouts are still fairly new in many places, limiting our capabilities to perform before/after safety studies, which tell us more about causal relationships than cross-sectional analyses. The installation of roundabouts is more systematic than random, raising questions surrounding the comparability of control group intersections when evaluating safety effectiveness. Lower numbers of cyclists and bicycle crashes (compared to other transportation modes) further complicates this line of research, as does the underreporting of crashes involving cyclists and the relative lack of bicycle exposure data (DiGioia et al., 2017; Shinar et al., 2018). Smaller sample sizes in crash data modelling means that fewer significant factors associated with bicyclist safety can be found.

Given the limitations of safety data, there will be a continued need for observational analyses of cyclist behaviours and interactions/conflicts with motor vehicles. Automated video-based analysis is promising for larger-scale studies, but limitations remain regarding the reliability of the analysis along with the proper positioning of the cameras. Most video observations have been collected for a relatively short period of time at few sites, again raising potential concerns about the representativeness and comprehensiveness of the nature of conflicts studied. As previously noted, the linkage between traffic conflicts and collisions is still not clearly defined (Sadeq & Sayed, 2016; Zheng et al., 2014), and observations only pick up current cyclists, not people who avoid cycling through roundabouts due to safety concerns.

Additional research limitations make more detailed and universal conclusions about bicycle safety at roundabouts difficult. As we have noted, various countries may have different experiences and roundabout bicycle safety issues due to variations in traffic laws, geometric design philosophies, mode shares, and driver/bicyclist behaviours and road etiquette. Furthermore, some studies are now decades old, which raises potential questions about their relevance. Overall, both of these issues are the result of a general lack of robust empirical research on bicycle safety at roundabouts. Such limitations can most directly be mitigated by additional investigations.

After reviewing the literature, we see some areas which have not yet been researched or which require further exploration. Few geometric design characteristics have been investigated in more than one or two crash data or observational studies. We found almost no studies investigating the effects of lighting and weather conditions on cycling safety, nor considerations of land use and built environment conditions near roundabouts. Future research could study additional cyclist interactions at roundabouts – including with pedestrians and with heavy vehicles – and other road user behaviours, such as driver acceleration actions (or passing clearances) when encountering cyclists and the effects of sight distance on driver looking and yielding. Research on attention and vision could provide insight into human factors (e.g. gaze allocation, visibility, obstructions) that influence the safety outcomes of road user interactions. The safety performance of roundabouts may partially depend upon socio-demographic characteristics of road users, which studies have not explored beyond age and gender (likely because demographic attributes are difficult to obtain from crash reports and observations). Moreover, questions regarding the validity of knowledge transferred from one context to another – especially northern European findings to places like the US with fewer cyclists and roundabouts, or to places in Asia or Africa – calls for the study of such demographic and cross-cultural comparisons.

We also highlight some underutilised methodologies. To our knowledge, few naturalistic studies (we know of one: Räsänen & Summala, 2000) and no driving simulator studies of driver–cyclist interactions have been undertaken, which seem like promising areas of research. There have also been few studies about cyclists' safety perceptions of roundabouts, which could be used to develop quality-of-service ratings (Jensen, 2013c), investigate avoidance behaviours and route choices, and account for awareness and experience with roundabouts. Particularly, stated choice experiments could help to understand the comfortability of users for adding new bicycle facilities, which design features cyclists prefer, which types of roundabouts they would avoid, etc. Such experiments, particularly those using videos or even augmented/virtual reality, could provide semi-realistic (and currently non-existent) situations for people to experience and rate. Overall, there are many opportunities to improve our knowledge regarding the safety impacts of roundabouts for people bicycling.

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