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INVESTIGATING BICYCLIST SAFETY PERCEPTIONS AND BEHAVIORS AT ROUNDABOUTS

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16. Abstract

As roundabouts become increasingly popular, and as many communities promote bicycle use, the safety of roundabouts for people bicycling is of major concern. In this project, we studied bicyclists' safety perceptions of and preferences for roundabouts with different characteristics. First, we performed a systematic literature review on bicycle safety at roundabouts, reviewing 49 different resources with empirical findings. Next, we developed a 20-minute online questionnaire to collect data from up to 613 U.S. adult bicyclists. The survey presented respondents with hypothetical roundabouts with various controlled design and operational attributes, represented using text and simulated images. We then analyzed cyclist preferences from a discrete choice experiment and bicycle perceptions of comfort. Overall, U.S. bicyclists prefer roundabouts with smaller central islands, fewer travel lanes, lower traffic volumes, lower speed limits, and separated bicycle lanes. The most comfortable roundabouts for bicycling had many of the same characteristics. Notably, women and "interested but concerned" cyclists had stronger preferences for separated bicycle lanes. We suggest updating U.S. roundabout design guidelines to include "protected roundabouts" allowing these separated bicycle lanes. Considering bicycle preferences and perceived comfort at roundabouts can help encourage cycling for people of all ages and abilities.

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Investigating Bicyclist Safety Perceptions and Behaviors at Roundabouts

Patrick A. Singleton
Associate Professor
Civil and Environmental Engineering
Utah State University

Niranjan Poudel
Graduate Research Assistant
Civil and Environmental Engineering
Utah State University

March 2024

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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. In this project, we studied bicyclists' safety perceptions of and preferences for roundabouts with different characteristics. First, we performed a systematic literature review on bicycle safety at roundabouts, reviewing 49 different resources with empirical findings. Next, we developed a 20-minute online questionnaire to collect data from up to 613 U.S. adult bicyclists. The survey presented respondents with hypothetical roundabouts with various controlled design and operational attributes, represented using text and simulated images. We then analyzed cyclist preferences from a discrete choice experiment and bicycle perceptions of comfort. Overall, U.S. bicyclists prefer roundabouts with smaller central islands, fewer travel lanes, lower traffic volumes, lower speed limits, and separated bicycle lanes. The most comfortable roundabouts for bicycling had many of the same characteristics. Notably, women and "interested but concerned" cyclists had stronger preferences for separated bicycle lanes. We suggest updating U.S. roundabout design guidelines to include "protected roundabouts" allowing these separated bicycle lanes. Considering bicycle preferences and perceived comfort at roundabouts can help encourage cycling for people of all ages and abilities.

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EXECUTIVE SUMMARY

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. The overarching goal of this research project was to characterize and evaluate how bicyclists view the safety of roundabouts. There were two specific objectives: (1) to characterize bicyclists' safety perceptions of roundabouts and roundabout elements, and (2) to identify bicyclists' preferences for various roundabout elements. To achieve these objectives, we developed a multifaceted research approach involving literature synthesis, survey data collection with a stated choice experiment, and robust data analysis of preferences and perceptions.

First, we performed a systematic literature review on bicycle safety at roundabouts, reviewing 49 different resources with empirical findings (most from Europe, some from Australia/New Zealand, and a few from the United States). Many studies analyze (limited) bicycle crash data or observe driver/cyclist behaviors 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.

Next, we developed a 20-minute online questionnaire to collect data from U.S. adult bicyclists about their preferences for roundabouts with various design and operational attributes, as well as their perceptions of comfort and other elements. The survey included a discrete choice experiment to understand stated preferences for roundabouts with different design and operational characteristics: central island size, number of circulating lanes, bicycle facility type, motor vehicle volumes, and approach speed limit. For each respondent, the experiment included six (from among 18) choices between two roundabouts with different attributes, represented using text and simulated images. In the online questionnaire, we also presented respondents with renderings of one hypothetical roundabout and asked a series of questions about perceived comfort.

We then analyzed preference data from 613 respondents using panel mixed multinomial logit models with random and systematic preference heterogeneity due to respondent characteristics. Overall, U.S. bicyclists seem to prefer roundabouts with smaller central islands, fewer travel lanes, lower traffic volumes, lower speed limits, and separated bicycle lanes; however, shared lane bicycle markings and signs were also preferred over bicycle ramps to the sidewalk or no bicycle facilities. Additionally, there were significant variations in preferences for bicycle facilities at roundabouts. Women, infrequent cyclists, and "interested but concerned" cyclists had stronger preferences for separated bicycle lanes, but "strong and fearless" and/or "enthused and confident" cyclists had significantly weaker preferences for these more protected facilities.

We also analyzed data from 568 respondents on perceptions of comfort, using an integrated set of ordered probit regression models to analyze comfort outcomes (overall and in five situations) against roundabout attributes, while controlling for personal socio-demographics and cycling characteristics (including type of cyclist). Although most current U.S. adult cyclists (71%) reported some degree of comfort bicycling at roundabouts, around a third (29%) felt somewhat or very uncomfortable. Roundabouts perceived to be more comfortable for bicycling had one (rather than two) lanes, lower traffic volumes, more bicycle facilities—especially separated bicycle lanes (a "protected roundabout")—and a larger central island. The

most comfortable situations were entering and exiting the roundabout, while the least comfortable situations were riding on the sidewalk or in the crosswalk. Circulating within the roundabout was the situation rated most similar to ratings of overall comfort. “Strong and fearless” cyclists were generally more comfortable at roundabouts than “interested but concerned” cyclists, except for sidewalk riding.

Overall, our study provided key insights into what kinds of roundabouts people bicycling prefer and feel more comfortable using, as well as some personal differences in these preferences and perceptions. The results offer several recommendations for roundabout design, operations, and planning and policy. For instance, there is a need to revise U.S. roundabout design guidance to allow for “protected roundabouts” with separated bicycle lanes, which were preferred and perceived to be the most comfortable by current U.S. cyclists, especially the “interested but concerned” majority. Roundabouts (particularly multilane ones) may not be the best intersection design in all cases, especially where moderate-to-high bicycle volumes are expected or planned. In order to encourage bicycling for all ages and abilities, we suggest separated shared-use paths or cycle tracks may be required when motor vehicle speeds are higher than 20-25 mph and volumes are higher than 2,000-3,000 AADT. We also offer suggestions for future research, including exploring a wider variety of roundabout attributes, studying these issues in other countries and cultures, and utilizing research methods such as virtual reality, naturalistic studies, and combinations of surveys, observations, and physiological sensors. Overall, future work can continue to advance knowledge and improve safety for people bicycling at roundabouts.

1. INTRODUCTION

The modern roundabout is a commonly used intersection design treatment in the United States, increasing from zero in the early 1990s to more than 4,200 estimated in 2016 (Rodegerdts, 2017). Agencies may install or convert an existing intersection to a roundabout for two primary reasons: to improve traffic flow by eliminating stop signs or signals, and to improve safety by reducing the number of conflict points. The roundabout is a proven safety countermeasure (FHWA, 2017) that has been shown to reduce all crashes by roughly 40% and substantially reduce injury and other severe crashes (by 50% or more) in both U.S. and international studies (Elvik, 2003; Persaud et al., 2001; Rodegerdts et al., 2007).

Despite this safety success, questions remain regarding the safety performance of roundabouts for specific road users, particularly people cycling. Research from Europe—where roundabouts are more common and have been used longer—suggests that roundabouts have mixed results for bicycling safety (depending on design characteristics) and even may yield an overall increase in vehicle-bicycle crashes. Observational before-after studies of roundabouts in Belgium and Denmark found increases in total crashes, injury crashes, and fatal/serious injury crashes involving bicyclists (Daniels et al., 2008; Jensen, 2013). Regarding roundabout designs, European studies suggest that multilane, higher-speed roundabouts and those with bicycle lanes have more frequent and perhaps more severe bicycle crashes, while roundabouts with separated cycle paths and medium-sized central islands may perform better for bicyclists (Daniels et al., 2011; Hels et al., 2007; Jensen, 2017; Polders et al., 2015).

Unfortunately, corresponding evidence for the bicyclist safety performance of roundabouts in U.S. contexts is extremely limited and remains an important research need. One challenge of safety analyses that rely upon historical crash data is that bicycle-vehicle collisions are relatively rare events, and bicycle crashes at roundabouts are even less common (Ferguson et al, 2019). Instead, a few U.S. studies have relied on surrogate safety measures collected via video-based analyses of road conflicts between motor vehicles and bicycles at roundabouts (Arnold et al., 2010; Berthaume et al., 2015; Rodergerdts et al., 2007; Shen et al., 2000). Although conflict analysis can identify some of the fundamental road user behaviors and site conditions that may contribute to potential bicycle collisions, it is unable to account for potential avoidance and other behaviors by cyclists who may have negative perceptions of roundabout safety.

Collecting and analyzing qualitative safety perceptions can be a useful method of safety analysis, especially when quantitative safety outcomes (crash frequencies) are sparse. Several studies have investigated cyclists' safety perceptions of various bicycle facilities (e.g., Foster et al., 2015; Monsere et al., 2012; Sanders, 2016), but only a few have investigated roundabouts. Møller and Hels (2008) interviewed over 1,000 Danish cyclists about their perceptions of risk in different traffic scenarios at roundabouts. They found that cyclists perceived the highest risk situation as being a collision with a vehicle exiting the roundabout; perceptions of safety increased with the presence of a separated bicycle facility. Focus groups of 36 cyclists held by Arnold et al. (2010) in California and Maryland reported changing their behavior at roundabouts (such as riding on the sidewalk or avoiding roundabouts altogether) and perceived roundabouts to be less safe than other intersection types.

Understanding the safety-driven motivations for certain bicyclist behaviors at or near roundabouts can offer a complementary and sometimes deeper knowledge about the safety of specific roundabout characteristics. Furthermore, bicyclists' perceptions of safety, comfort, and how to navigate roundabouts have important implications for designing roundabouts so that they are both safe and attractive for people on bicycles, thus helping to improve healthy and sustainable transportation mode usage. There is a clear and important need for additional qualitative research on bicyclists' safety at U.S. roundabouts.

1.1 Research Objectives

This study has two primary research objectives:

1. Characterize bicyclists' safety perceptions of roundabouts and roundabout elements.
2. Identify bicyclists' preferences for various roundabout elements.

The overarching goal of this research project is to characterize and evaluate how bicyclists view the safety of roundabouts. In this regard, we identify bicyclists' preferences for and perceptions of the safety and comfort of specific design and operational elements of roundabouts (e.g., number of lanes, crossing treatments, options for taking the lane vs. joining the sidewalk), as well as how bicyclists would navigate through various types of roundabouts. Such information can inform the future design and operation of safe roundabouts for bicycling.

1.2 Research Approach and Overview

To achieve these objectives, we developed a multifaceted research approach involving literature synthesis, survey data collection with a stated choice experiment, and robust data analysis of preferences and perceptions. The procedures of each step are summarized in the following report overview and detailed in the subsequent chapters of this research report.

- Chapter 2 "Bicycle safety at roundabouts: A systematic literature review" presents a systematic literature review summarizing evidence regarding bicycle safety performance at roundabouts.
- Chapter 3 "Data collection" describes the process of developing and deploying an online survey to collect data about bicyclists' roundabout preferences and perceptions.
- Chapter 4 "Preferences for roundabout attributes among U.S. bicyclists: A discrete choice experiment" reports the results of an analysis of bicyclist preferences for roundabouts with various design and operational attributes.
- Chapter 5 "Bicycling comfort at roundabouts: Effects of design and situational factors" reports the results of an analysis of bicyclist perceptions of comfort at roundabouts with different characteristics.
- Chapter 6 "Conclusion" summarizes the key findings of this research study, and highlights recommendations and opportunities for future work.

Note that Chapters 2, 4, and 5 have been previously published as peer-reviewed manuscripts in academic journals. They are being reprinted here with permission from the publishers.

2. BICYCLE SAFETY AT ROUNDABOUTS: A SYSTEMATIC LITERATURE REVIEW

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2.1 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 U.S.). Many studies analyze (limited) bicycle crash data or observe driver/cyclist behaviors 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 utilize naturalistic methods, driving simulators, and stated choice experiments.

2.2 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 U.S. showed that the installation of a roundabout was associated with a 30% to 50% reduction in the number of traffic injuries and an even larger, 50% to 70%, reduction in traffic fatalities (Elvik, 2003). Similarly, within the U.S., the conversion of two-way stop-controlled intersections and signalized 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 U.S. 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 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 and a larger increase (>40%) in fatal and serious injury crashes involving bicyclists (Daniels et al., 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 with other modes and different intersection types (Allot & Lomax, 1991, as cited in Räsänen & Summalla, 2000; Jørgensen & Jørgensen, 2002, as cited in Møller & Hels, 2008; Cumming, 2011a, 2011b; Wilke et al., 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 et al., 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 behaviors 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 U.S. national research project, Ferguson et al. (2019) proposed to create robust roundabout crash prediction models for vehicle–bicycle crashes but concluded that there was 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 utilized in different countries (Aumann et al., 2017).

Overall, there is a relative lack of research on bicycle safety at roundabouts and a need to summarize and consolidate various research findings and identify knowledge gaps, especially in places where roundabouts are becoming a popular design solution. Studying the relationship between roundabouts and safety for people bicycling is also important as cities seek to promote cycling for transportation. For instance, in the U.S. since around 2000, bicycling has increased by roughly 2% or more per year according to national-level survey data and traffic counts (Le et al., 2019). Bicycle injuries and fatalities in the U.S. have also been increasing since 2009 (Buehler & Pucher, 2021), and cyclists now represent more than 2% of all road user fatalities (NHTSA, 2018).

With this literature review, **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 behaviors, since behavior responds to design and design should accommodate expected behaviors. By examining and classifying existing knowledge on this topic, our work provides guidance for future researchers wishing to study bicycle safety at roundabouts and 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 behaviors and safety perceptions, which we will highlight.

The next section details the literature search strategy. The subsequent section describes the various types of methodologies used to examine bicyclist safety, focusing on crash data, video recordings, and user perceptions. The large subsequent section summarizes the many factors associated with roundabout safety, including geometric, design, operational, behavioral, 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.

2.3 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 behaviors). We considered peer-reviewed academic journal articles as well as grey literature, including published reports, conference presentations, and student theses/dissertations.

Figure 2.1 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 2.1.

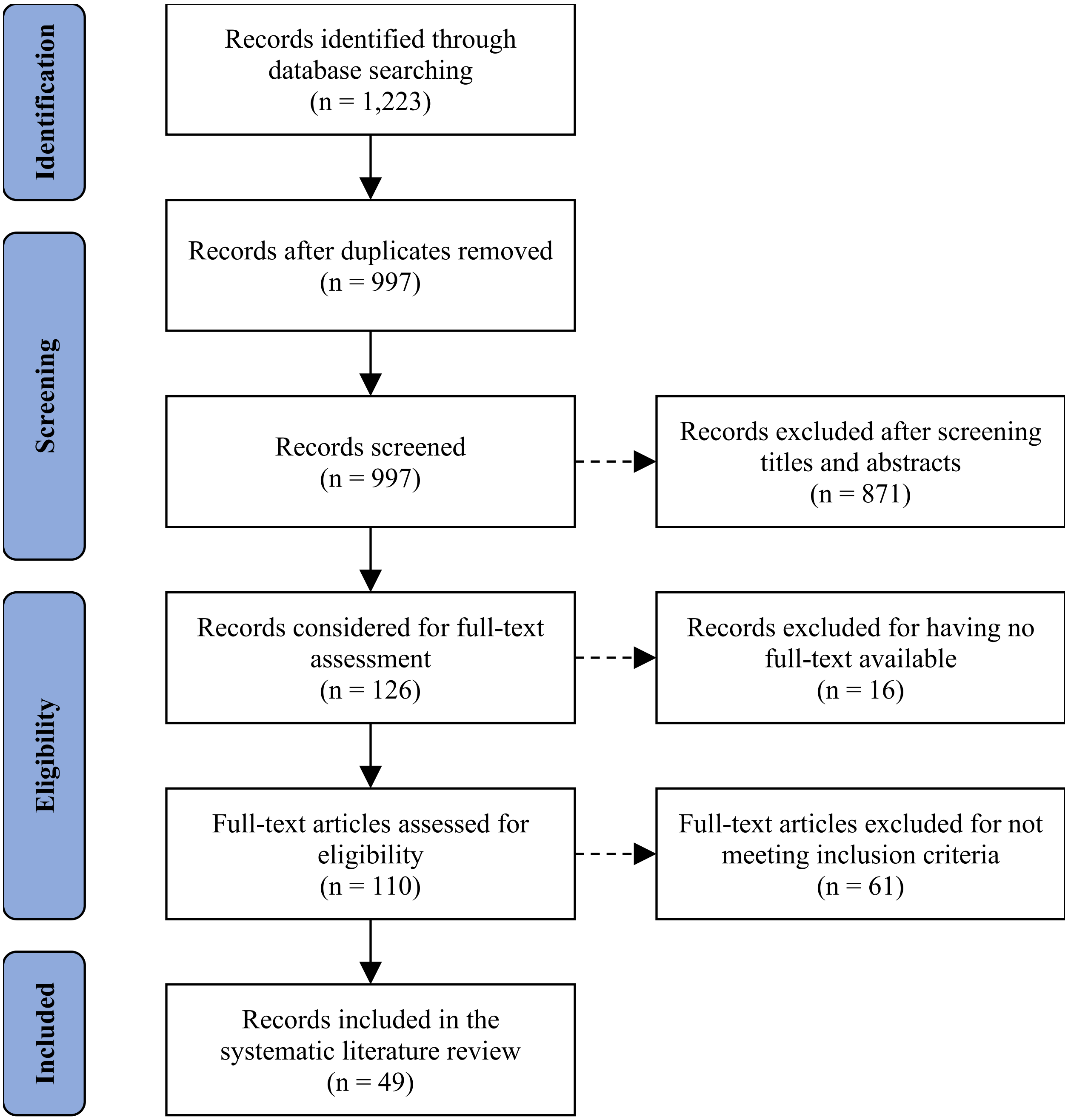

Figure 2.1 PRISMA flow diagram for the systematic literature review of bicycle safety at roundabouts

Table 2.1 Studies on bicycle safety at roundabouts

Citation	*Location*	*Sample size*	*Methodology*	*Associations with factors and other findings*
Akgün et al., 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 signalized 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 et al., 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 & Knodler, 2013	Massachusetts, US	9 roundabouts, 64 cyclists	Observations (in-person)	Most common cyclist behaviors were: using the sidewalk, and creating a bicycle lane. A few cyclists rode the wrong way.
Brüde & Larsson, 2000	Sweden	72 roundabouts, 67 crashes	Crash data	Crash frequency: motor vehicle volume (+), bicycle volume (+), multiple lanes (+), central radius > 10m (–), special bicycle crossing (–).
Campbell et al., 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; Cumming, 2011b	Victoria, Australia	497 crashes	Crash data	Roundabout crashes disproportionately involved cyclists. Most bicycle-vehicle crashes were entering-circulating.
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 signalized intersections in rural areas.
Daniels et al., 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 (+).

Citation	*Location*	*Sample size*	*Methodology*	*Associations with factors and other findings*
Daniels et al., 2010	Flanders, Belgium	90 roundabouts, 280 crashes	Crash data (Poisson, gamma regression)	Crash frequency: motor vehicle volume (+), bicycle volume (+), moped volume (+), bike lane (+).
Daniels et al., 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 & 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 & 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 & 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 et al., 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 et al., 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.
Hydén & 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.

Citation	*Location*	*Sample size*	*Methodology*	*Associations with factors and other findings*
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 (<2m) especially in urban areas, and bike lanes. Crashes decreased for high central islands (>2m) and separated cycle paths.
Jensen & 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.
Jonsson et al., 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 & 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 et al., 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 & 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 & 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 et al., 2007	Bolton, UK	10 intersections (5 roundabouts), 144 commuters	Questionnaire (video clips, logistic regression)	Perceived risk: roundabout (+), bike lane (+), male (+).
Polders et al., 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 & 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 (–).
Rodegerdts et al., 2007	US (various)	39 roundabouts, 8 crashes	Crash data	Bicycle crashes were too infrequent to analyze or yield conclusions.

Citation	*Location*	*Sample size*	*Methodology*	*Associations with factors and other findings*
Sadeq & 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 et al., 2010	Lund, Sweden	2 roundabouts, 1,440 interactions	Observations (in-person, video)	With a 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, 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 et al., 2017	Berlin, Germany	1 roundabout, 3,451 cyclists, 252 conflicts	Observations (video)	Cyclist conflicts with motor vehicles were associated with motor vehicle volumes. Conflicts between exiting vehicles and circulating cyclists were frequent.
Schoon & van Minnen, 1993[a]	The Netherlands	201 roundabouts	Crash data (before/after)	Crashes were reduced by 30%.
Schoon & 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 et al., 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 signalized intersections (15%). Bicycle volume and bicycle × motor vehicle volume were both positively associated with bicycle crashes.
Schreiber et al., 2014	Germany	10 roundabouts	Observations	For roundabouts with mixed traffic, high traffic volumes increase chances 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 et al., 2015; Silvano et al., 2016	Stockholm, Sweden	1 roundabout, 187 interactions	Observations (video) (binary logit regression)	Yielding: distance of cyclist to crossing (–), speed (–).
Shen et al., 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 roundabouts with in-road bike lanes to (bicycle) protected roundabout, increased safety perceptions among cyclists.
Tang, 2018	Norrköping, Sweden	4 roundabouts, 39 crashes	Crash data	Roundabouts with the fewest cyclists and highest motor vehicle volumes had the most crashes, injuries, and fatalities.

Citation	*Location*	*Sample size*	*Methodology*	*Associations with factors and other findings*
Turner et al., 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 et al., 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).

2.4 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 categorize based on the predominant type of data analyzed: reported crashes (before and after analysis, regression analysis), observations of road user behaviors/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 eight 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.

2.4.1 Crash Data and Statistical Modeling of Observed Crashes

Statistical modeling 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 (Persaud et al., 2001; Elvik, 2003) 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 intersection safety performance (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 utilizing 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. Jensen (2013b, 2017) analyzed 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, geometrics, 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 utilize 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 utilizing 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 et al., 2017). Most U.S. 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 U.S. 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 modeled 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) analyzed 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).

2.4.2 Video Data (or Manual Observations) and Analyses of Road User Behaviors/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, e.g., 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 behaviors 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 behaviors, 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 behavioral 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 behavioral 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 et al., 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 behaviors due to cyclists' safety perceptions.

2.4.3 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 behaviors. Unfortunately, there is not much literature on cyclists' 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 about perceived crash risks in different situations.

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 et al., 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.

2.5 Factors Influencing the Safety of Bicyclists at Roundabouts

Many studies in Table 2.1 investigated factors associated with the safety performance of roundabouts for cyclists. We summarize these findings in three subsections: operational and design characteristics, the presence and type of bicycle facilities, and road user behaviors.

2.5.1 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 et al., 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 motorized 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 with 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). Roundabouts with larger inscribed circle radii are thought to be not as safe for bicycling (Jensen, 2013c; Tang, 2018) since large roundabouts can allow for higher motor vehicle speeds. The number of drivers 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).

2.5.2 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 colored 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 2.2 shows examples of these different bicycle facility types at roundabouts.

Figure 2.2 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 (licensed CC BY-SA 2.0); (bottom right) by Dan Burden (used with permission).

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 modeling 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 with 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 utilizing 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 with 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 with 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).

2.5.3 Driver and Cyclist Behaviors and Interactions

Observations of cyclist behaviors—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 use the sidewalk; this was especially common (18%–50%) in the U.S. (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 behavior (that minimizes displacement and maximizes speed) is "straight-lining," in which cyclists enter (and exit) on the outer edge of the roundabout but sweep toward the center island while circulating. The other common behavior 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; Cumming, 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., 2018). Given that roundabout rules require yielding to traffic (including cyclists) in the roundabout, the fault seems to be placed on driver behavior (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).

2.6 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 U.S. and Canada. We considered various study methodologies—statistical modeling and analysis of longitudinal or cross-sectional crash data, observations of cyclist and driver behaviors and interactions, and surveys of road users' safety perceptions—and summarized 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 behaviors.

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

- Roundabouts do not improve safety for cyclists as much as for drivers and may actually increase bicycle crashes.
- 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 behaviors 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 utilize naturalistic methods and stated choice experiments.

2.6.1 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 signalized 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 U.S. 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 U.S. roundabout design recommendations (Rodegerdts et al., 2010) to account for newer bicycle planning, selection, and design guidance (Schultheiss et al., 2019; NACTO, 2019). For instance, the Massachusetts DOT provides general guidelines for "protected roundabouts" with separated bike lanes (MassDOT, 2015).

When using protected 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, 2017). 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 speeds of bicycles (compared with 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 FHWA, 2019, p. 23). Otherwise, separated shared-use or cycle paths may be required to provide adequate levels of comfort and safety.

2.6.2 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 with 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 modeling 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 behaviors 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 behaviors 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 that have not yet been researched or require further exploration. Few geometric design characteristics have been investigated in more than one or two crash data or observational studies. We found very few studies investigating the effects of lighting and weather conditions on cycling safety, or 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 behaviors, 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 countries like the U.S. 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 underutilized 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—and these 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 behaviors 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.

3. DATA COLLECTION

Recall our study's research objectives: first, to characterize bicyclists' safety perceptions of roundabouts and roundabout elements; and second, to identify bicyclists' preferences for various roundabout elements. In order to achieve these objectives, we designed an online questionnaire and collected data from US adult bicyclists about their roundabout preferences and safety perceptions. In this chapter, we describe the design of the survey, how participants were recruited, and where others can access the data we collected.

This study was reviewed and approved by the Utah State University Institutional Review Board, protocol #11319.

3.1 Survey Overview and Design

Based on the findings of the literature review (Chapter 2), we developed a 20-minute online questionnaire. This survey had several parts:

- *Start*: Informed consent document. Questions to determine eligibility.
- *Introduction*: Knowledge of roundabouts. Frequency of mode use, before and during the COVID-19 pandemic. Frequency of encountering roundabouts. How roundabouts affect travel behavior.
- *Choice experiment*: Choices (for bicycling preference) between hypothetical roundabouts with different characteristics, presented with simulated images.
- *Comfort*: One hypothetical roundabout. Comfort bicycling overall, and in different situations. Path choice and lane positioning. Comfort driving overall, and in different situations.
- *Bicycling*: Bicycle crash experience. Recent bicycling for transportation and recreation. Preference for bicycling more. Reasons for bicycling or not bicycling. Comfort bicycling in different places. Mode liking and perceptions. Helmet and seat belt use.
- *Personal information*: Home location. Household income. Bicycle and car ownership. Household adults and children. Age, gender, race/ethnicity, and educational attainment. Student and worker status.
- *End*: Optional entry into a gift card drawing. Other comments.

Whenever possible, questions were borrowed from previous studies and surveys to ensure that results could be compared if desired. For example, the "Bicycling" section contained questions about bicycling comfort that were borrowed exactly from Dill and McNeil (2016), which allowed us to follow those authors' procedures for constructing four categories representing "types of cyclists" (no way no how, interested but concerned, enthused and confident, and strong and fearless).

A key element of this study was the construction of hypothetical roundabouts with different characteristics, which were presented to respondents to assess their bicycling preferences and perceptions. Informed by the results of the literature review, we selected five attributes that were among the most important in influencing (perceived or actual) bicycle safety at roundabouts. We then selected two or three levels that these attributes could take, reflecting a carefully controlled variety of conditions that could apply to generic roundabouts, mostly in a U.S. context.

- *Central island diameter*: Small (80 ft) central island, large (120 ft) central island.
- *Circulating travel lanes*: One travel lane, two travel lanes.
- *Bicycle facility type*: No bicycle facilities, shared lane bicycle markings & signs, bicycle ramps to the sidewalk, separated bicycle lanes.
- *Traffic volume*: Low traffic volumes (rarely have to yield to and interact with other vehicles), medium traffic volumes (sometimes have to yield to and interact with other vehicles), high traffic volumes (usually have to yield to and interact with other vehicles).

- *Approach speed limit*: 25 mph speed limit on adjacent roads (25 mph or less in the roundabout), 35 mph speed limit on adjacent roads (25 mph or less in the roundabout).

We considered but eventually did not include other characteristics—bicycle/pedestrian volumes, the presence of trucks, circulating lane widths, crossing types and signalization options, two-way cycle tracks, lighting, adjacent land uses, urban form, and other factors—in order to reduce the variation and effort involved to develop hypothetical roundabouts. Future research could consider the effects of these factors on bicyclists' roundabout preferences and perceptions.

To increase the salience of the hypothetical roundabouts to participants taking the online survey, we supplemented text descriptions with simulated images of each hypothetical roundabout. We developed two different images: one was an eye-height view of a bicyclist approaching the roundabout, and another was a tilted overhead view of the roundabout and its approaches. To increase the images' realism while retaining our ability to depict different characteristics consistently, we designed roundabouts using Lumion, a 3D rendering software used for architectural visualization. The setting for all roundabouts was a low-to-medium density residential urban neighborhood with no terrain. See Figure 3.1 for examples of these photorealistic simulated images.

Figure 3.1 Example images of a hypothetical roundabout

Although there were 96 possible unique combinations of the levels of the five roundabout attributes, we only developed 21 different hypothetical roundabouts (sets of images). This reduced the effort of creating different roundabout designs in Lumion, while ensuring that there was sufficient variety of each level of each attribute (and combinations thereof).

The heart of the survey was a stated choice (or discrete choice) experiment, in which respondents viewed a series of pairs of hypothetical roundabouts and picked which they would prefer for bicycling. The design of such an experiment relies on obtaining a maximum amount of information about preferences from a minimum number of questions or choice scenarios. We used a commonly used choice experiment design software (Ngene) to generate what is called an orthogonal design that recommended 24 choice scenarios to represent the most informative tradeoffs between various roundabout attributes and levels. Of these, we removed six scenarios because there were "dominating" alternatives that would have been chosen almost always. We then split the remaining 18 scenarios into three blocks of six questions each, trying to balance attribute levels within each block. In the end, each respondent was presented with one randomly selected block, so they saw and made six randomly ordered choices between simulated roundabouts.

In July 2020, an initial draft of the survey was developed and shared with five transportation academics and professionals who had experience with surveys, bicycling, and/or roundabouts. These professionals reviewed the survey and provided feedback on overall structure, question wording, experimental design, and other areas. Based on this feedback, several survey questions/sections that were not central to the study's objectives or analyses were removed in order to shorten the length.

For the full list of final survey questions, as well as all of the hypothetical roundabouts that were simulated, see our project's open data repository (Singleton & Poudel, 2022).

3.2 Participant Recruitment

The study's target population included U.S. resident adults (age 18+) who ride a bicycle for any purpose at least occasionally. In order to reach a wide audience, we used convenience sampling. Specifically, we distributed an informative link to the online survey via multiple methods to a variety of platforms. This included social media (LinkedIn, Twitter, Facebook), transportation list-serves (e.g., Association of Pedestrian and Bicycle Professionals discussion forum, Pedestrian and Bicycle Information Center Messenger e-newsletter), and several national/state/local bicycle organizations. Attempts were made to obtain a variety of geographies and social groups. To incentivize participation, respondents who completed the survey were offered an opportunity to enter a drawing to receive one of ten $50 gift cards.

Data collection occurred in fall 2020, between mid-August and late-November, although most responses were received from late-August through mid-October. A total of 744 people started the survey, but not everyone completed the survey due to attrition. As noted in Chapter 4, up to 613 (82%) of responders answered enough questions to be included in the analyses.

3.3 Data Availability

Descriptive statistics for the survey data and respondent characteristics are included in tables within Chapter 4 and 5. Full access to the complete (cleaned and anonymized) dataset and associated documentation is available on the project's open data repository (Singleton & Poudel, 2022), hosted by Zenodo: https://doi.org/10.5281/zenodo.5107737.

4. PREFERENCES FOR ROUNDABOUT ATTRIBUTES AMONG US BICYCLISTS: A DISCRETE CHOICE EXPERIMENT

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4.1 Abstract

As roundabouts have become increasingly common, there is very limited research about bicycle safety at roundabouts and, specifically, a lack of information about preferences for roundabouts among people bicycling. To address this gap, we conducted a discrete choice experiment involving an online survey of 613 U.S. adult bicyclists to understand stated preferences for roundabouts with different design and operational characteristics: central island size, number of circulating lanes, bicycle facility type, motor vehicle volumes, and approach speed limit. For each respondent, the experiment included six (from among 18) choices between two roundabouts with different attributes, represented using text and simulated images. We analyzed these data using panel mixed multinomial logit models with random and systematic preference heterogeneity due to respondent characteristics. Overall, U.S. bicyclists seem to prefer roundabouts with smaller central islands, fewer travel lanes, lower traffic volumes, lower speed limits, and separated bicycle lanes; however, shared lane bicycle markings and signs were also preferred over bicycle ramps to the sidewalk or no bicycle facilities. Additionally, there were significant variations in preferences for bicycle facilities at roundabouts. Women, infrequent cyclists, and "interested but concerned" cyclists had stronger preferences for separated bicycle lanes, but "strong and fearless" and/or "enthused and confident" cyclists had significantly weaker preferences for these more protected facilities. This research offers insights into bicycling preferences that may help to create roundabouts that are safer and more attractive for people bicycling of all ages and abilities.

4.2 Introduction

Globally, the modern roundabout is an increasingly common alternative to a traditional stop-controlled or signalized intersection. For instance, in the United States, the number of roundabouts went from zero in the early 1990s to more than 4,200 in 2016 (Rodegerdts, 2017). One reason for roundabouts' popularity is that they have been associated with large overall reductions in severe crashes and traffic injuries and fatalities (Elvik, 2003; FHWA, 2017). Nevertheless, the safety effects of roundabouts for people bicycling are more ambiguous. Before and after studies from Belgium (Daniels et al., 2008) and Denmark (Jensen, 2013a) have found increases in bicycle injuries and fatal/serious injury crashes after converting traditional intersections to roundabouts. Other research (from Denmark, the United Kingdom [UK], and Australia) also suggests that crashes involving people bicycling are overrepresented at roundabouts in comparison with other modes and types of intersections (Allot & Lomax, 1991, as cited in Räsänen & Summalla, 2000; Jørgensen & Jørgensen, 2002, as cited in Møller & Hels, 2008; Cumming, 2011a, 2011b; Wilke et al., 2014).

We recently investigated these topics surrounding bicycle safety at roundabouts by conducting a systematic review of 49 empirical resources (Poudel & Singleton, 2021). Summarizing evidence from studies utilizing crash data analysis, observational analyses of behaviors and conflicts, and user perception surveys, we identified several factors associated with bicycle safety performance at roundabouts. Specifically, bicycle safety outcomes seem to be worse at larger roundabouts with multiple circulating lanes, in the presence of higher motor vehicle volumes and speeds, and when there are no bicycle facilities or only on-road bicycle lanes provided (separated cycle paths appear to be safer). Further, conflicts between entering/exiting motor vehicles and circulating cyclists (at roundabouts with no bicycle facilities), as well as visibility and yielding at crossings (at roundabouts with separated cycle paths), are the most critical situations and behaviors.

In our literature review (Poudel & Singleton, 2021), we cautioned that these findings are based on a limited number of studies, mostly from northern Europe and utilizing models of crash data. Safety performance may vary across socio-demographic groups or geographies and may depend in part upon cultural and legal contexts, all of which makes it difficult to directly transfer findings from one place to another. There is little evidence about bicycle safety at U.S. roundabouts, largely due to a lack of sufficient data (Ferguson et al., 2019), including too few roundabouts, years, and bicycle crashes. While such limitations cannot be mitigated in the near future, we suggested conducting more studies—including stated choice experiments—on cyclists' safety perceptions of roundabouts (and roundabout attributes) as a way to overcome limited bicycle crash data (Poudel & Singleton, 2021). Measuring cyclist preferences can help to understand whether safety perceptions match evidence on safety outcomes, explain bicycle user behaviors at roundabouts (including route choices, sidewalk riding, and other avoidance behaviors), and design roundabouts that feel (and are) safer to traverse while bicycling. Improving the bicycling quality of roundabouts can help to create a more equitable transportation environment and might even encourage more healthy, active travel.

The overall objective of our present study is to understand preferences among U.S. adult bicyclists (with different socio-demographic characteristics and cycling abilities) related to multiple roundabout design and operational attributes or characteristics affecting bicycle safety at roundabouts. To accomplish this goal, we first conducted a stated choice experiment consisting of six scenarios, each with two unlabeled alternatives representing (through text and simulated images) varying roundabout attributes. We then analyzed results from 613 respondents (using a panel mixed multinomial logit model) to understand relative preferences for those attributes. Further, heterogeneous preferences were explored using personal socio-demographic and cycling characteristics. The remaining sections of the chapter briefly summarize the literature, report the study design, describe the data and analysis methods, present the results, and discuss key findings and implications.

4.3 Literature Review

Only a handful of studies have investigated roundabout preferences and perceptions among people bicycling. Our literature review paper (Poudel & Singleton, 2021) found only eight such studies (Arnold et al., 2010; Campbell et al., 2006; Hydén & Várhelyi, 2000; Jensen, 2013b; Macioszek & Lach, 2019; Møller & Hels, 2008; Parkin et al., 2007; Tan et al., 2019). For example, Jensen (2013b) showed video clips of 20 roundabouts to 180 people in Denmark and associated perceived satisfaction with various roundabout characteristics. Parkin et al. (2007) conducted a similar study with five roundabouts and 144 commuters in the UK. Møller & Hels (2008) stopped about 1,000 cyclists at roundabouts and asked them about risk perceptions. Using questionnaires of 300 cyclists in Poland, Macioszek and Lach (2019) found a preference for single-lane over two-lane roundabouts. Overall, these studies have tended to investigate perceptions of comfort, danger, or risk with roundabouts in general, rather than preferences for different roundabout design or operational elements. In other bicycle perception research (Jensen, 2013b; Parkin et al., 2007), roundabouts are not the primary focus. Another limitation of perception/preference studies that use video clips of (or stop cyclists at) real-world roundabouts is that they are unable to adequately consider preferences regarding rare or non-existent roundabout characteristics, such as the "protected roundabout" (a roundabout with separated cycle paths) in the U.S.

Stated choice surveys are a leading method for understanding respondent preferences for various alternatives and attributes of those alternatives. Such surveys typically include choice experiments that present respondents with multiple hypothetical scenarios (carefully designed by the analyst) and ask respondents to choose their preferred option in each scenario. Through discrete choice analysis of survey data, relative preferences for various attributes and attribute levels can be determined. Some advantages of these choice experiments are the low cost of data collection, the ability to avoid multicollinearity of attributes (e.g., high-volume roundabouts having multiple lanes), and having predefined choice sets (Abraham et al., 2002; Stinson & Bhat, 2003). These advantages strongly benefit our study, as we are trying to understand cyclists' preferences for various design and operational attributes of roundabouts. It is practically difficult to find roundabouts with specific combinations of characteristics, let alone recruit respondents who (in real life) have faced all the attributes we wish to examine. One of the disadvantages of stated choice surveys is potential lack of realism or unfamiliarity with some of the attributes or alternatives presented, but clear instructions and explanation while presenting scenarios can reduce some of these hypothetical biases.

Stated choice surveys and analyses have been conducted to understand cyclists' preferences for other bicycle facilities and in other situations. Stated choice experiments have commonly been conducted to understand preferences surrounding bicycle route choices (e.g., Stinson & Bhat, 2003; Sener et al., 2009; Vedel et al., 2017). To our knowledge, no prior research has used stated choice methods to understand cyclist preferences in the context of roundabouts.

4.4 Study Design, Data, and Methods

The following subsections detail this study's experimental design, data collection and weighting process, and methods of analysis. For more information on our study design and to view our questionnaire, survey data, and analysis scripts, please visit this project's open data repository (Singleton & Poudel, 2022).

4.4.1 Experimental Design

In order to achieve our study objective, we conducted a stated or discrete choice experiment (DCE). When designing such an experiment, important decisions include the number of choice scenarios presented to respondents (questions), the number of alternatives (options), the number and types of attributes of the alternatives (characteristics of options), the levels of these attributes, the arrangement of attributes and alternatives across the choice scenarios, and the manner in which alternatives and attributes are presented/shown to respondents (Hensher et al., 2005; Hensher, 2006). In this study, we used two unlabeled alternatives, both depicting roundabouts with various characteristics.

Our recent literature review on bicycle safety at roundabouts (Poudel & Singleton, 2021) guided our selection of attributes and levels, as well as a desire to avoid burdening respondents with too many or confusing attributes. We decided to focus on five attributes (covering both design and operational characteristics) shown to have a potential influence on roundabout bicycle safety: central island size, number of circulating lanes, bicycle facility type, motor vehicle volumes, and approach speed limit. Research finds that higher-volume, higher-speed, and multilane roundabouts tend to see more bicycle crashes and are perceived as less safe or less comfortable, likely due to increased exposure, potential conflicts, and more severe injury outcomes. A few studies have found that more separated bicycle facilities, such as off-street cycle paths, are preferred and result in higher perceptions of safety and fewer bicycle crashes. Central island size was included because of conflicting evidence in the literature. Larger islands allow for higher motor vehicle speeds but were preferred by cyclists in one study (Jensen, 2013b). See Poudel and Singleton (2021) for more details about research regarding these relationships.

The five alternative attributes and their levels are shown in Table 4.1. Levels were selected to cover a variety of commonly experienced conditions while ensuring a feasible experimental design. For bicycle facilities, four types were considered: none, shared lane markings and signs, bicycle ramps leading from bike lanes to wide shared sidewalks, and separated bicycle lanes. Although there is no information about the prevalence of different bicycle facility treatments at roundabouts in the U.S., we suspect that most roundabouts do not include any bicycle facilities. When included, the most common roundabout bicycle facilities in the U.S. are likely bicycle ramps to/from sidewalks since they are the only bicycle treatment shown in the U.S. roundabout design guide (Rodegerdts et al., 2010). Shared lane markings and separated bicycle lanes in roundabouts, while currently rare, may become more popular in the future due to newer bicycle design guidance (MassDOT, 2015).

Other attributes were considered—including central island height, number of approach lanes, circulating lane width, bicycle facility type on the approaches, bicycle and pedestrian volumes, bicyclist movement (left, thru, right), circulating speed, and area type (urban, suburban, rural)—but rejected due to the difficulty of communicating such information to respondents or their overlap with attributes already included in the DCE. Instead, these other attributes were fixed for all alternatives, e.g., same number of approach lanes as circulating lanes, circulating speeds of 25 mph or less, and low-to-medium density residential land uses.

Table 4.1 Roundabout attributes and levels used in the discrete choice experiment

Attribute	*Levels*
Central island diameter	Small (80 ft) central island
	Large (120 ft) central island
Circulating travel lanes	One travel lane
	Two travel lanes
Bicycle facility type	No bicycle facilities
	Shared lane bicycle markings & signs
	Bicycle ramps to the sidewalk
	Separated bicycle lanes
Traffic volume	Low traffic volumes (rarely have to yield to and interact with other vehicles)
	Medium traffic volumes (sometimes have to yield to and interact with other vehicles)
	High traffic volumes (usually have to yield to and interact with other vehicles)
Approach speed limit	25 mph speed limit on adjacent roads (25 mph or less in the roundabout)
	35 mph speed limit on adjacent roads (25 mph or less in the roundabout)

The next decision was about the number of choice scenarios and the arrangement of attributes and alternatives across those choice scenarios. There are various techniques to construct an efficient design (Rose & Bliemer, 2009) for a DCE, with the goal of obtaining a maximum amount of information about preferences from a minimum number of questions. In the absence of prior knowledge about parameter estimates, the literature suggests that an orthogonal design with the removal of dominant alternatives may be as or more efficient than other designs (Walker et al., 2019). Thus, we used Ngene software (ChoiceMetrics, 2018) to generate an orthogonal design with 24 choice scenarios, and we removed six scenarios with a dominating alternative (assuming preferences for lower speeds and volumes, fewer lanes, and more separated bicycle facilities). The remaining 18 choice scenarios were distributed into three blocks, each containing six choice scenarios, with the objective of balancing the frequency of different attribute levels; each attribute level appeared at least three times in each block. Within each block, the order of the six choice scenarios was randomized. Within each choice scenario, the order of the alternatives (left, right) was also randomized. Each respondent saw one of the three blocks.

In order to increase the realism of the DCE choice task for respondents, the attributes of alternatives were presented in both text and visual formats. The text of each attribute level, as shown in Table 4.1, was included in a table. Additionally, two simulated images of the hypothetical roundabout—one shown at eye height of a bicyclist approaching the roundabout, the other a tilted overhead view of the roundabout and its approaches—were shown above the text table. Respondents could click on the images to view larger versions. These photorealistic renderings were created using Lumion, a 3D rendering software used for architectural visualization. All roundabout attributes (except for approach speed limit) were represented visually through different geometric designs or traffic control devices. Traffic volumes were represented by two to four cars for low, six to eight cars for medium, and 10 to12 cars for high volume situations. Figure 4.1 shows an example choice scenario presented to respondents. The full set of images and choice scenarios can be viewed online (Singleton & Poudel, 2022).

Which roundabout would you prefer for bicycling?

Small (80ft) central island	**Large** (120ft) central island
Two travel lanes	**One** travel lane
Shared lane bicycle markings & signs	**Bicycle ramps** to the sidewalk
Medium traffic volumes (**sometimes** have to yield to and interact with other vehicles)	**High** traffic volumes (**usually** have to yield to and interact with other vehicles)
35mph speed limit on adjacent roads (25mph or less in the roundabout)	**25mph** speed limit on adjacent roads (25mph or less in the roundabout)

Figure 4.1 Example choice scenario between two roundabout alternatives

4.4.2 Data Collection and Weighting

The target population for this study included adult U.S. residents who ride a bicycle for any purpose at least occasionally. The DCE was included within a self-administered online survey built in Qualtrics. To obtain a wide range of respondents, we used convenience sampling but with a broad focus. In fall 2020, we distributed an informational link to the survey via multiple methods, including social media (LinkedIn, Twitter, Facebook), transportation list-serves (e.g., Association of Pedestrian and Bicycle

Professionals discussion forum, Pedestrian and Bicycle Information Center Messenger e-newsletter), and several national/state/local bicycle organizations. Although the survey was open from mid-August through late-November, most responses were received from late-August through mid-October. Study methods were approved by the Utah State University Institutional Review Board, Protocol #11319.

Although 744 respondents started the survey, only 613 respondents are included in this analysis: those who completed the DCE and answered relevant demographic questions. (This 82% completion rate was reasonable given the length of the survey: median 15 minutes, interquartile range 10–22 minutes.) Descriptive statistics for this sample are shown in Table 4.2. Most of these respondent characteristics are socio-demographic in nature, such as age, gender, race/ethnicity, education, student/employment status, and household income. Other questions included the frequency of bicycling and encountering roundabouts when bicycling, crash experiences with bicycling and roundabouts, and how roundabouts affect bicycle route choice.

Table 4.2 Descriptive statistics for sample ($N = 613$)

Variable	*#*	*%*	*Mean*	*SD*
Age				
18 to 24 years	25	4.08		
25 to 34 years	116	18.92		
35 to 44 years	112	18.27		
45 to 54 years	106	17.29		
55 to 64 years	132	21.53		
65 years or above	99	16.15		
Other (prefer not to answer, or missing)	23	3.75		
Gender				
Male	382	62.32		
Female	203	33.12		
Other (prefer to self-describe, prefer not to answer, or missing)	28	4.57		
Race/ethnicity				
White only	503	82.06		
Other (Hispanic or Latino, Asian, Black or African American, American Indian or Alaska Native, Native Hawaiian or other Pacific Islander, prefer to self-describe, prefer not to answer, or missing)	110	17.94		
Education level				
Less than a high school diploma, or High school diploma or equivalent (e.g., GED)	32	5.22		
Bachelor's or associate degree	273	44.54		
Master's degree, doctorate degree, or professional degree beyond bachelor's degree	281	45.84		
Other (prefer not to answer, or missing)	27	4.40		
Student status				
Yes	52	8.48		
No	544	88.74		
Missing	17	2.77		
Worker status				
Yes	462	75.37		
No	135	22.02		
Missing	16	2.61		
Household income				
Less than $49,999	65	10.60		
$50,000 to $74,999	83	13.54		
$75,000 to $99,999	92	15.01		

Variable	#	%	*Mean*	*SD*
$100,000 to $149,999	141	23.00		
$150,000 or more	145	23.65		
Other (Don't know, prefer not to answer, or missing)	87	14.19		
Number of bicycles available at home [a]			3.55	1.51
Missing	15	2.45		
Number of motor vehicles available at home [a]			1.92	1.03
Missing	15	2.45		
Number of adults (age 18+) in household [a]			2.21	0.88
Missing	16	2.61		
Number of children (age 0 to 17) in household [a]			0.50	0.98
Missing	15	2.45		
Bicycle use frequency [b]				
Never [c]	17	2.77		
Less than once a week	84	13.70		
1 to 3 days a week	196	31.97		
4 or more days a week	316	51.55		
Type of cyclist				
Strong and fearless	42	6.85		
Enthused and confident	112	18.27		
Interested but concerned	441	71.94		
Missing	18	2.94		
Crash experience while bicycling at a roundabout				
Hit, or nearly hit	151	24.63		
No, or missing	462	75.37		
Frequency of encountering roundabouts when bicycling				
Never	50	8.16		
Sometimes	254	41.44		
Often	185	30.18		
Always	112	18.27		
Missing	12	1.96		
Roundabouts affect bicycling route choice				
Yes, I avoid roundabouts if at all possible.	32	5.22		
Yes, I avoid roundabouts only when there is a reasonably convenient alternative route.	108	17.62		
Yes, I prefer routes with roundabouts.	105	17.13		
No, roundabouts don't affect my choice of route.	357	58.24		
Missing	11	1.79		
Roundabouts affect bicycling mode choice				
Yes, I bicycle less because of roundabouts.	34	5.55		
Yes, I bicycle more because of roundabouts.	34	5.55		
No, roundabouts don't affect my choice to bicycle or not.	540	80.09		
Missing	5	0.82		

[a] These variables were originally measured on a categorical scale {0,1,2,3,4,5+}, and recoded for descriptive statistics and modeling (5+ = 5 and Missing = 0).
[b] The survey took place during the COVID-19 pandemic. This question asked about "normal conditions (or last year)" to try to avoid any impacts of different travel patterns.
[c] We retained these observations in the analysis because: (i) some of these respondents reported bicycling under "current conditions" but not "normal conditions (or last year)," and (ii) in an earlier question, they all reported being physically able to and knowing how to ride a bicycle.

We also included survey questions that allowed us to determine the type of cyclist for each respondent, using the same questions and categorization method developed by Dill and McNeil (2016)[1]. Excluding "no way, no how" cyclists (since our survey was targeted at current cyclists) and missing responses, our sample contained about 7% "strong and fearless" cyclists, 19% "enthused and confident" cyclists, and 74% "interested but concerned" cyclists. This breakdown by cyclist type is close to the shares reported nationally (first number) (Dill & McNeil, 2016) or in Portland, Oregon (second number) (Dill & McNeil, 2013): 11%/6% "strong and fearless" cyclists, 8%/13% "enthused and confident" cyclists, and 81%/81% "interested but concerned" cyclists. Thus, we feel confident that our sample included a sufficiently representative variety of bicycling comfort levels.

Nevertheless, our sample was not necessarily representative of the U.S. adult population. Likely due to the convenience sampling recruitment method, our survey under-sampled young adults, people identifying as female, people identifying as non-white, and people in lower-income households, among other attributes. To attempt to adjust for this, we created a weighted dataset based on U.S. adult population information for age, gender, race/ethnicity, and household income, taken from the 2019 American Community Survey (US Census Bureau, n.d.). We could not weight on education level because our sample contained too few people having less than a bachelor's or associate degree.

"Other" responses (Prefer to self-describe, prefer not to answer, or missing) complicated the weighting procedure; therefore, we first split the 613 respondents into three groups: 516 with complete responses for all four weighting variables, 64 with "other" responses for household income only, and 33 with "other" responses for age or gender. Weights for the first group were based on all four weighting variables; weights for the second group were based on age, gender, and race/ethnicity; the third group received a weight of 1.00. The weighting process was conducted using the "anesrake" package (Pasek & Pasek, 2018) in R, which makes use of the raking method to achieve the targeted weights (default maximum weight of 5). Table 4.3 shows the results of the weighting procedure, with percentages excluding "other" responses (except for race/ethnicity). Weighted data were used in some (but not all) of the analyses.

[1] Respondents who would be "very comfortable" bicycling on "a major urban or suburban street with 4 lanes, on-street parking, traffic speeds of 30-35 mph, and no bike lane" were considered to be "strong and fearless" cyclists. Other respondents who would be "very comfortable" bicycling on "the same major street, but with a striped bike lane" were considered to be "enthused and confident" cyclists. Other respondents who "don't know how" or are "physically unable" to ride a bicycle or were "very uncomfortable" bicycling on "a path or a trail separate from the street" were considered to be "no way, no how" cyclists. However, those in the "no way, no how" group but who reported most recently bicycling "for transportation" or "for recreation" in the last week or in the last month were re-classified as "interested but concerned" cyclists. All other respondents were considered to be "interested but concerned" cyclists.

Table 4.3 Descriptive statistics for sample before and after weighting

	Un-weighted		*Weighted*		*Target*
Variable	*#*	*%*	*#*	*%*	*%*
Age					
18 to 24 years	25	4.24	68.99	11.69	11.89
25 to 34 years	116	19.66	108.51	18.39	17.85
35 to 44 years	112	18.98	97.57	16.54	16.48
45 to 54 years	106	17.97	93.65	15.87	15.97
55 to 64 years	132	22.37	98.45	16.69	16.63
65 years and above	99	16.78	122.84	20.82	21.18
Other	23	–	23.00	–	–
Gender					
Male	382	65.30	283.25	48.42	48.66
Female	203	34.70	301.75	51.58	51.34
Other	28	–	28.00	–	–
Race/ethnicity					
White only	503	82.06	435.90	71.11	73.60
Other	110	17.94	177.10	28.89	26.40
Household income					
Less than $49,999	65	12.36	162.61	30.92	30.35
$50,000 to $74,999	83	15.78	89.68	17.05	17.38
$75,000 to $100,000	92	17.49	74.13	14.09	14.17
$100,000 to $149,999	141	26.81	96.28	18.31	18.47
$150,000 or more	145	27.57	103.30	19.64	19.63
Other	87	–	87.00	–	–

4.4.3 Analysis Methods

Given the nature of the DCE and the objective of this study, we estimated five different discrete choice models on the data. All were based on a multinomial logit (MNL) model with no alternative-specific constants (given the unlabeled alternatives), and where attribute levels were considered to be categorical variables (dummy coding). The five models were:

1. MNL, using unweighted data
2. MNL, using weighted data
3. Panel mixed MNL, using unweighted data
4. Panel mixed MNL, using weighted data
5. Panel mixed MNL, using unweighted data, with systematic preference heterogeneity due to respondent characteristics in Table 4.1.

Each of the 613 respondents answered one block of six choice scenarios, yielding 3,678 choices in each model. Estimation of parameters for the panel mixed MNL models used 1,000 draws, Monte Carlo integration, and normally distributed random parameters. Estimating a full preference heterogeneity model with many random parameters can be very resource-intensive and time-consuming. Therefore, estimation of the fifth model tested different characteristics in separate models before bringing only the marginally significant ($p < 0.10$) variables together into one final model. All models were estimated using Pandas Biogeme in Python (Bierlaire, 2020).

4.5 Results

Table 4.4 presents the results of the first four models: MNL unweighted, MNL weighted, panel mixed MNL unweighted, and panel mixed MNL weighted. Given the same null model log-likelihood, models can be compared using the final model log-likelihood, or the Akaike or Bayesian information criteria (AIC or BIC). The less negative log-likelihoods and smaller AIC/BIC values for the panel mixed models indicate that they are better fits to the data than the MNL models, and that there is unobserved preference heterogeneity. McFadden pseudo-R2 values are 0.12 for the MNL models and 0.21–0.22 for the panel mixed MNL models. Additionally, although the specific parameter estimates differ across the different models, their direction and significance remain mostly the same. Therefore, in the following paragraphs we focus our attention on results from the panel mixed MNL models.

Model results highlight preferences among bicyclists for certain types of roundabouts. Central islands with small diameters (80 ft) are preferred over large (120 ft) ones, although this attribute was not significant in the MNL models. One circulating travel lane is strongly preferred over two travel lanes. Having medium and especially high traffic volumes at roundabouts is less preferred among cyclists than having low traffic volumes. There is a preference against 35 mph approach speed limits in favor of 25 mph speed limits (not significant in Model 1). Overall, cyclists expressed the strongest preference (compared with no bicycle facilities) for separated bicycle lanes, followed by shared lane markings and signs. Results for bicycle ramps were equivocal; there was no difference with no bicycle facilities using unweighted data, but there was a slight preference for bicycle ramps in the weighted MNL model (not significant in the weighted panel mixed MNL model).

For the panel mixed MNL models, significance tests of the estimated random parameter standard deviations help to identify roundabout attributes for which the sample exhibits heterogeneous preferences. In general, there appears to be preference heterogeneity for number of lanes, speed limit, and bicycle facilities. The standard deviation for central island size is not significant, nor is it for traffic volumes (except high traffic volumes in the unweighted model).

Table 4.4 Results of the MNL and panel mixed MNL models (unweighted and weighted) ($N = 613 \times 6$)

	1. MNL, unweighted			*2. MNL, weighted*			*3. Panel mixed MNL, unweighted*			*4. Panel mixed MNL, weighted*		
Attributes levels	*Est.*	*SE*	*p*	*Est.*	*SE*	*p*	*Est.*	*SE*	*p*	*Est.*	*SE*	*p*
Central island diameter												
Small (80ft) central island	-0.0521	0.0692	0.452	0.00797	0.0689	0.908	0.341	0.133	0.0103	0.391	0.124	0.0016
Standard deviation	–	–	–	–	–	–	0.279	0.425	0.512	0.00809	0.294	0.978
Large (120ft) central island (ref.)	0.000	–	–	0.000	–	–	0.000	–	–	0.000	–	–
Circulating travel lanes												
One travel lane	0.579	0.0682	<0.001	0.605	0.0691	<0.001	1.36	0.195	<0.001	1.20	0.167	<0.001
Standard deviation	–	–	–	–	–	–	1.79	0.239	<0.001	1.60	0.207	<0.001
Two travel lanes (ref.)	0.000	–	–	0.000	–	–	0.000	–	–	0.000	–	–
Bicycle facility type												
No bicycle facilities (ref.)	0.000	–	–	0.000	–	–	0.000	–	–	0.000	–	–
Shared lane bicycle markings & signs	0.758	0.0820	<0.001	0.917	0.0837	<0.001	1.46	0.210	<0.001	1.61	0.194	<0.001
Standard deviation	–	–	–	–	–	–	1.53	0.339	<0.001	0.739	0.458	0.107
Bicycle ramps to the sidewalk	-0.0608	0.0890	0.495	0.182	0.0900	0.0433	-0.373	0.245	0.128	0.0981	0.219	0.654
Standard deviation	–	–	–	–	–	–	3.50	0.424	<0.001	3.20	0.368	<0.001
Separated bicycle lanes	0.985	0.0852	<0.001	1.24	0.0873	<0.001	2.38	0.294	<0.001	2.59	0.265	<0.001
Standard deviation	–	–	–	–	–	–	4.04	0.424	<0.001	3.31	0.318	<0.001
Traffic volume												
Low traffic volumes (ref.)	0.000	–	–	0.000	–	–	0.000	–	–	0.000	–	–
Medium traffic volumes	-0.424	0.0722	<0.001	-0.354	0.0732	<0.001	-0.744	0.146	<0.001	-0.583	0.130	<0.001
Standard deviation	–	–	–	–	–	–	0.0161	0.555	0.977	0.0908	0.299	0.762
High traffic volumes	-0.847	0.0597	<0.001	-0.852	0.0602	<0.001	-1.90	0.193	<0.001	-1.75	0.163	<0.001
Standard deviation	–	–	–	–	–	–	0.745	0.316	0.0184	0.484	0.316	0.126
Approach speed limit												
25mph speed limit (ref.)	0.000	–	–	0.000	–	–	0.000	–	–	0.000	–	–
35mph speed limit	-0.0810	0.0561	0.149	-0.180	0.0569	0.0015	-0.444	0.116	<0.001	-0.526	0.109	<0.001
Standard deviation	–	–	–	–	–	–	0.837	0.228	<0.001	0.843	0.189	<0.001
Goodness-of-fit												
Null model log-likelihood	-2549.40			-2549.40			-2549.40			-2549.40		
Final model log-likelihood	-2248.72			-2230.74			-1984.39			-2015.58		
Akaike information criterion	4513.44			4477.48			4000.77			4063.17		
Bayesian information criterion	4563.12			4527.16			4071.47			4133.86		

Notes: MNL = multinomial logit, ref. = reference level, Est. = estimate, SE = standard error, p = p-value.

Table 4.5 presents the results of the fifth model: panel mixed MNL unweighted with systematic preference heterogeneity. Compared with the regular panel mixed MNL model 3, model 5 with preference heterogeneity due to respondent characteristics offers a noticeable improvement in fit (less negative log-likelihood, smaller AIC/BIC values), and a larger McFadden pseudo-R2 value of 0.27. In this model, the parameter estimates of the attributes can be thought of as intercepts, while the parameter estimates for respondent characteristics are differences in preferences for that attribute (vs. the reference) and for that group vs. all other respondents. Results indicated similar overall preferences (as in Table 4.4) for smaller central islands, fewer travel lanes, lower traffic volumes, slower speed limits, and separated bicycle lanes. Yet, there was significant heterogeneity in many of these preferences.

Regarding central island size, people with more cars had a weaker preference for a small central island diameter (80 ft). (There was a marginally significant standard deviation for this parameter.) Preferences for one travel lane over two circulating lanes were stronger for people with more bicycles and fewer cars, while "strong and fearless" cyclists appeared to prefer two lanes over one lane. Considering approach speeds, respondents who have been involved in a collision (or nearly hit) while bicycling at a roundabout were less deterred by a 35-mph speed limit over a 25-mph speed limit. The same was true for people with more children and those who bicycle only a couple of days per week. (The standard deviations for the lane and speed parameters were both still significant, indicating additional unobserved preference heterogeneity.)

Some similar characteristics were significant in explaining preference heterogeneity for traffic volumes. People who experienced crashes and those who bicycled less frequently were less deterred than others by medium or high traffic volumes vs. low traffic volumes. The same was true for respondents with a bachelor's or associate degree, implying that people with a graduate or higher degree (above a bachelor's) have a stronger aversion to higher-volume roundabouts. Older and middle-aged adults (65+ and 45-54) were less deterred (compared with younger adults), while people with incomes $75,000 to $100,000 were more deterred (compared with people who have lower or higher incomes) by medium traffic volumes; however, there were no significant income or age differences in the relative deterrence of high traffic volumes, and all groups still preferred low traffic volumes. Women disliked high traffic volumes more than men, while "strong and fearless" cyclists and those who reported bicycling more because of roundabouts were less deterred by high traffic volumes than other respondents.

Many respondent characteristics explained variations in preferences for different types of bicycle facilities at roundabouts, compared with no bicycle facilities. First, although shared lane markings/signs were preferred to no bicycle facilities (on average), respondents who never encounter roundabouts while bicycling did not share this preference. Also, those who reported avoiding roundabouts when convenient alternatives exist and those who reported bicycling more because of roundabouts expressed less positive preferences for shared lanes. Second, while there was no overall preference for bicycle ramps to sidewalks (compared with no bicycle facilities), some groups expressed a preference for or against this type of bicycle facility. Those who bicycle less than once a week strongly preferred bicycle ramps over no facilities, while "enthused and confident" cyclists and those who prefer routes with roundabouts preferred no facilities over bicycle ramps. Third, several other respondent characteristics affected the strength of the overall preference for separated bicycle lanes (compared with no facilities). Women, students, people aged 35-44, those who cycle less than once a week, those who avoid routes with roundabouts, and those who bicycle less because of roundabouts had stronger preferences for separated bicycle lanes. Conversely, people who always encounter roundabouts when cycling and both "strong and fearless" and "enthused and confident" cyclists had weaker preferences for separated bicycle lanes. In fact, all else being equal, "strong and fearless" cyclists had no preference for separated bicycle lanes compared with no bicycle facilities. Variations remain (in terms of significant standard deviations) in preferences for different kinds of bicycle facilities at roundabouts.

Table 4.5 Results of the panel mixed MNL model with systematic preference heterogeneity (unweighted) (N = 613×6)

Attributes levels and interactions	*5. Panel mixed MNL, unweighted, preference heterogeneity* *Est.*	*SE*	*p*
Central island diameter			
Small (80ft) central island	0.808	0.251	0.0013
Number of motor vehicles available at home	-0.207	0.102	0.0412
Standard deviation	0.596	0.328	0.0691
Large (120ft) central island (ref.)	0.000		–
Circulating travel lanes			
One travel lane	0.885	0.408	0.0299
Number of bicycles available at home	0.386	0.105	<0.001
Number of motor vehicles available at home	-0.338	0.145	0.0194
Type of cyclist: Strong and fearless	-1.14	0.580	0.0497
Standard deviation	1.82	0.262	<0.001
Two travel lanes (ref.)	0.000	–	–
Bicycle facility type			
No bicycle facilities (ref.)	0.000	–	–
Shared lane bicycle markings & signs	2.03	0.288	<0.001
Frequency of encountering roundabouts: Never	-1.67	0.577	0.0038
Roundabouts affect route choice: Yes, avoid only when alternative	-1.06	0.417	0.0112
Roundabouts affect mode choice: Yes, bicycle more	-1.38	0.686	0.0438
Standard deviation	1.73	0.373	<0.001
Bicycle ramps to the sidewalk	-0.125	0.287	0.664
Bicycle use frequency: Less than once a week	3.02	0.663	<0.001
Type of cyclist: Enthused and confident	-1.97	0.598	0.0010
Roundabouts affect route choice: Yes, prefer roundabouts	-2.18	0.622	<0.001
Standard deviation	3.43	0.434	<0.001
Separated bicycle lanes	2.35	0.383	<0.001
Gender: Female	1.09	0.454	0.0160
Student status: Yes	1.92	0.780	0.0140
Bicycle use frequency: Less than once a week	1.61	0.646	0.0128
Type of cyclist: Strong and fearless	-2.45	0.848	0.0038
Type of cyclist: Enthused and confident	-1.52	0.545	0.0053
Frequency of encountering roundabouts: Always	-1.27	0.523	0.0152
Roundabouts affect route choice: Yes, avoid if at all possible	2.09	1.02	0.0403
Roundabouts affect mode choice: Yes, bicycle less	2.51	1.14	0.0279
Standard deviation	3.98	0.462	<0.001
Traffic volume			
Low traffic volumes (ref.)	0.000	–	–
Medium traffic volumes	-1.53	0.275	<0.001
Age: 45 to 54 years	0.661	0.302	0.0285
Age: 65 years or above	0.848	0.303	0.0051
Education level: Bachelor's or associate degree	0.565	0.241	0.0190
Household income $75,000 to $99,999	-0.580	0.317	0.067
Bicycle use frequency: 1 to 3 days a week	0.629	0.270	0.0199
Crash experience: Hit, or Nearly hit	0.616	0.278	0.0265
Standard deviation	0.322	0.356	0.365
High traffic volumes	-2.66	0.321	<0.001
Gender: Female	-0.536	0.234	0.0222
Education level: Bachelor's or associate degree	0.368	0.118	0.0019
Bicycle use frequency: Never	1.54	0.627	0.0141
Bicycle use frequency: 1 to 3 days a week	0.903	0.265	<0.001
Type of cyclist: Strong and fearless	0.703	0.411	0.0874

Roundabouts affect mode choice: Yes, bicycle more	0.910	0.445	0.0410
Roundabouts affect mode choice: Missing	2.91	1.14	0.0105
Standard deviation	0.479	0.374	0.201
Approach speed limit			
25mph speed limit (ref.)	0.000	–	–
35mph speed limit	-0.970	0.185	<0.001
Number of children (age 0 to 17) in household	0.339	0.115	0.0033
Bicycle use frequency: 1 to 3 days a week	0.687	0.234	0.0034
Crash experience: Hit, or Nearly hit	0.499	0.243	0.0402
Standard deviation	0.948	0.257	<0.001
Goodness-of-fit			
Null log-likelihood	-2549.50		
Final log-likelihood	-1863.57		
Akaike information criterion	3827.13		
Bayesian information criterion	4048.05		

Notes: MNL = multinomial logit, ref. = reference level, Est. = estimate, SE = standard error, p = p-value.

4.6 Discussion and Conclusion

This study's goal was to understand preferences for various roundabout design and operational attributes among U.S. adult bicyclists. To achieve this objective, we conducted a discrete choice experiment involving various choice scenarios of two simulated roundabouts, each with different characteristics on five important attributes identified in our prior literature review (Poudel & Singleton, 2021). We made use of panel mixed MNL models of data from 613 respondents to understand the relative preferences and both random and systematic heterogeneity (due to personal characteristics) with respect to roundabout attributes. Our study addresses gaps in the literature surrounding roundabout cyclist preferences, providing evidence especially useful for a U.S. setting. To our knowledge, this is the first study using stated choice methods to examine cyclists' preferences about roundabouts. Assuming that these preferences are motivated primarily by safety and comfort considerations, we believe that our findings regarding preferences (and variations in those preferences) for different operational and design characteristics provide significant knowledge toward creating roundabouts that are more comfortable (and perhaps feel safer) for people bicycling.

Overall, model results (Table 4.4) suggest that U.S. bicyclists prefer roundabouts with the following characteristics:

- Central island diameter: A small (80 ft) central island is preferred over a large (120 ft) central island.
- Circulating travel lanes: One travel lane is preferred over two travel lanes.
- Bicycle facility type: Separated bicycle lanes are preferred over shared lane bicycle markings and signs, which are both preferred over bicycle ramps to the sidewalk or no bicycle facilities.
- Traffic volume: Low traffic volumes are preferred over medium traffic volumes, which are both preferred over high traffic volumes.
- Approach speed limit: A 25-mph speed limit is preferred over a 35-mph speed limit.

Example simulated images visualizing this "bicyclist-preferred" roundabout are shown in Figure 4.2. Generally, these results match findings from literature (Poudel & Singleton., 2021) that show smaller roundabouts with separated cycle paths, lower motor vehicle traffic volumes and speeds, and fewer lanes appear to be safer for bicycling. In summary, it seems as if U.S. cyclists' preferences for roundabout attributes are mostly in line with empirical evidence about safety performance. This matches other research suggesting that traffic safety concerns motivate choices and preferences around bicycling in the U.S. (Dill & McNeil, 2013, 2016; Pucher & Buehler, 2012).

Figure 4.2 Simulated images of a roundabout with bicyclist-preferred characteristics (small central island, one travel lane, separated bicycle lanes, lower speeds and traffic volumes)

Despite these overall preferences for various roundabout elements, our results also suggest significant variations in those preferences across the bicycling population. The panel mixed MNL models (Table 4.4) found significant preference heterogeneity for bicycle facility type, circulating travel lanes, and approach speed limits, with the magnitude (standard deviation greater than the mean) indicating that some respondents may have preferences in a different direction or order. When weighting the data (to make it more representative of the U.S. adult population), the coefficient on bicycle ramps to the sidewalk switched from negative to positive, although it was still not significantly different from no bicycle facilities. This suggests that when giving greater weight to preferences among women, people of non-white race/ethnicity, or those in lower income households (all of whom were underrepresented in the unweighted dataset), different preferences can result than if focusing on only existing cyclists.

Other results examining systematic preference heterogeneity due to personal characteristics (Table 4.5) shed additional light on these variations in cyclist roundabout preferences. Notable differences by cyclist type were found for bicycle facility type. Specifically, “strong and fearless” cyclists did not prefer separated bicycle lanes, while “enthused and confident” cyclists disliked bicycle ramps to the sidewalk and had weaker preferences for separated bicycle lanes (compared with other cyclists, and compared with no bicycle facilities). These cyclists, who are comfortable riding in most road conditions (Dill & McNeil, 2016), seem to prefer roundabouts that allow them to navigate like motor vehicles, whether due to desires for minimizing out-of-direction travel, maintaining higher speeds, or avoiding conflicts with pedestrians. On the other hand, the strong preference for separated bicycle lanes seems to have been driven by “interested but concerned” cyclists, who made up the largest share of the sample and constitute the majority of the population (Dill & McNeil, 2016). These findings mirror other stated preference research about bicycle facility types, in which “interested but concerned” cyclists report greater increases in comfort with more physical separation from motor vehicles over standard bike lanes or mixing zones (McNeil et al., 2015; Monsere et al., 2020).

Similar patterns were found for other personal characteristics and different roundabout attributes. Women had stronger preferences (than men) for separated bicycle lanes and against high traffic volumes, matching other research that finds gender differences in traffic safety concerns (Rahman et al., 2021). Infrequent cyclists (who cycled less than once a week) exhibited even stronger preferences than the rest of the sample for more separated bicycle facilities (separated lanes and sidewalk ramps), potentially because these cyclists are less experienced at interacting with motor vehicles. Conversely, “strong and fearless” cyclists were less deterred by high traffic volumes, exhibiting their confidence with sharing the road. Responses to questions about the stated effects of roundabouts on bicycle mode choice and route choice matched these preferences regarding bicycle facility types and motor vehicle volumes.

On the other hand, some preference heterogeneity results (Table 4.5) were unexpected, counterintuitive, or defy easy explanation. For example, we would have expected people who experienced a crash or near-miss to have been more concerned about safety, not less deterred by medium traffic volumes and higher speeds. Perhaps these cyclists ride more frequently (greater exposure) and are more comfortable interacting with motor vehicle traffic despite their experiences. We were also surprised to see that people who only cycle one to three days per week were less deterred (than those who cycle more or less frequently) by medium and high traffic volumes and higher approach speed limits. Perhaps this group contains more recreational cyclists who ride on the weekends at times and in locations where traffic volumes and patterns are different (than for those who ride on weekdays). Regarding findings related to income, education, and children, we have no strong prior hypotheses or potential explanations. Given the large number of variables tested, it is possible that some of these significant associations are spurious and may not hold up in a different sample or study.

In summary, the results from our analysis offer suggestions for bicycle-friendly roundabout design, operation, planning, and policymaking. Because cyclist preferences seem to be focused on safety-related elements, doing everything possible to reduce vehicle speeds, volumes, and conflicts would make more preferred roundabouts for the general population. In order to encourage bicycling for people of all ages and abilities (including among potential cyclists), providing separated bicycle lanes (cycle paths) around the roundabout (MassDOT, 2015) is essential unless motor vehicle speeds and volumes are very low. In our literature review (Poudel & Singleton, 2021, p. 20), we suggest borrowing from Schultheiss et al.

(2019, p. 23) and using 20 or 25 mph and 2,000 to 3,000 AADT as the upper limits for roundabouts with no bicycle facilities. Bicycle ramps to sidewalks—a current design option in U.S. guidance (Rodegerdts et al., 2010)—do not seem to be preferred by anyone but infrequent cyclists, and they lead to potential conflicts with pedestrians and at crossings. In these cases, "strong and fearless" or "enthused and confident" cyclists who may not prefer the separated lanes or ramps could still choose to "take the lane" and operate with motor vehicles. In areas where right-of-way constraints prohibit the construction of separated bicycle lanes, it may be worth considering shared lane bicycle markings and signs as an alternative since this treatment was preferred over no markings/signs (although less so than separated bicycle lanes). Given that roundabouts are increasingly common in cities and communities, this study's findings—coupled with our prior literature review (Poudel & Singleton, 2021)—can help decision-makers create roundabouts that are safer and more attractive for people bicycling of all ages and abilities.

As previously mentioned, there is a lack of empirical research on cyclist preferences about roundabouts, and this was an initial step toward filling that gap. Future research could address several study limitations. Although we included the design and operational characteristics most commonly associated with safety performance in the literature (Poudel & Singleton, 2021), additional factors potentially affecting preferences could be considered in future studies, including bicycle and pedestrian volumes, circulating speeds, central island height, landscaping of non-paved areas, pavement markings, crossing types and signalization options, bicyclist movements (left, thru, right), weather conditions, adjacent land uses, area type (urban, suburban, rural), etc. Respondents interacted with the alternatives in a passive way (viewing static images and text); using virtual reality or other active and experiential means of engaging respondents in the choice process could lead to more realistic stated preferences. Fitch and Handy (2018) found that imagined perceptions of bicycling comfort and safety (from watching video clips) were somewhat (10%–15%) more negative than comfort/safety ratings from people who actually rode the same routes; this could suggest that the strong preferences for separated bicycle lanes from our stated choice experiment may be slightly different in reality. Our choice experiment used only two unlabeled roundabout alternatives; future state choice experiments could add a non-roundabout alternative to understand cyclist preferences as compared with traditional stop-controlled or signalized intersections, which could inform bicycle route choices. The impact of different roundabout elements on perceived comfort, bicyclist lane positioning within roundabouts, or cyclist route choices should also be further investigated to understand the alignment of bicycle preferences, perceptions, and behaviors at roundabouts. Although we attempted to correct for some non-representativeness among our sample, a larger and more representative sample could highlight even more variations in preferences across the population. Finally, we should reiterate that our study surveyed the preferences of current cyclists, not the larger population of potential cyclists. People who are not bicycling for reasons related to safety will likely be just as, if not more, sensitive as the "interested but concerned" group to bicycle facility type and other roundabout features.

5. BICYCLING COMFORT AT ROUNDABOUTS: EFFECTS OF DESIGN AND SITUATIONAL FACTORS

This chapter is reprinted from *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 94, P. A. Singleton & N. Poudel, "Bicycling comfort at roundabouts: Effects of design and situational factors," 227-242, Copyright 2023, with permission from Elsevier. To cite, please use this reference:

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5.1 Abstract

As roundabouts replace traditional intersections, there are concerns regarding the safety of roundabouts for bicycling. Given the limitations of crash data, this study informs an understanding of bicycle safety at roundabouts in the U.S. through an analysis of cyclists' perceptions of comfort regarding different roundabout design and operational attributes and different bicycling situations (e.g., entering, exiting, circulating) at roundabouts. In an online questionnaire, we presented 568 U.S. adult bicyclists with renderings of a hypothetical roundabout and asked a series of questions about perceived comfort. We then used an integrated set of ordered probit regression models to analyze comfort outcomes (overall and in five situations) against roundabout attributes, while controlling for personal socio-demographics and cycling characteristics (including type of cyclist). Although most current cyclists (71%) reported some degree of comfort bicycling at roundabouts, around a third (29%) felt somewhat or very uncomfortable. Roundabouts perceived to be more comfortable for bicycling had one (rather than two) lanes, lower traffic volumes, more bicycle facilities—especially separated bicycle lanes (a "protected roundabout")—and a larger central island. The most comfortable situations were entering and exiting the roundabout, while the least comfortable situations were riding on the sidewalk or in the crosswalk. Circulating within the roundabout was the situation rated most similar to ratings of overall comfort. "Strong and fearless" cyclists were generally more comfortable at roundabouts than "interested but concerned" cyclists, except for sidewalk riding. These results offer implications for how to make roundabouts more comfortable for people bicycling of all abilities and levels of confidence.

5.2 Introduction

5.2.1 Motivation

Globally, modern roundabouts are replacing traditional stop-controlled and signalized intersections. For instance, as of early 2023 there were more than 9,000 roundabouts in the United States, up from less than 1,000 in 2003 (Kittelson & Associates, 2023). This growth in popularity can be attributed to the improvement in overall safety performance for roundabouts compared with traditional intersections. A meta-analysis of studies from outside the U.S. found that the installation of a roundabout resulted in a 30%–50% reduction in the number of road traffic injuries and an even greater (50%–70%) reduction in fatalities (Elvik, 2003). Similarly, in the U.S., reductions in severe crashes by 82% and 78% were observed for conversion of two-way stop-controlled and signalized intersections (respectively) to roundabouts (FHWA, 2017), considering mostly motor vehicle only crashes (Rodegerdts et al., 2007). Amidst the increasing popularity and overall safety improvements of roundabouts, their effects on safety for cyclists are less clear, with some research (mostly in Europe and Australia) suggesting negative impacts, including increases in bicycle crashes after the installation of roundabouts, and an overrepresentation of bicycle crashes at roundabouts compared with other types of intersections (Daniels et al., 2008; Jensen, 2013b; Allot & Lomax, 1991; Cumming, 2011a, Cumming 2011b; Wilke et al., 2014).

In our recent systematic literature review (Poudel & Singleton, 2021), we investigated the bicycle safety implications of roundabouts, reviewing 49 different empirical sources to better understand these concerns. The authors summarized evidence from studies utilizing crash data analysis, observational analyses of behaviors and conflicts, and user perception surveys. Among key findings are worse safety outcomes for cyclists at roundabouts with multiple circulating lanes, higher motor vehicle volumes, higher speeds, and when in-road bicycle lanes are provided but with no physical separation. Also, situations at roundabouts with higher chances of bicycle–motor vehicle conflicts or collisions include a motor vehicle entering/exiting across the path of a circulating cyclist, a cyclist traveling along the outer edge of the circulating lane(s), and at a crossing (when riding on a separated path or the sidewalk). The authors concluded, "Providing separated cycle paths around the roundabout seems to be a lower-risk and more comfortable design solution [for cyclists], although care must be taken to encourage appropriate [driver] yielding at crossings" (Poudel & Singleton, 2021).

One limitation identified through the literature review was the lack of research outside of the European context. For example, only a few bicycle roundabout studies have been conducted in the U.S., mostly using observations or questionnaires (Arnold et al., 2010; Berthaume & Knodler, 2013; Harkey and Carter, 2006, Hourdos et al., 2012; Poudel & Singleton, 2022) because of limited crash data (Rodegerdts et al., 2007). Thus, it is not clear whether findings (mostly from Europe) translate to the U.S. or other areas with different geographies, laws, road designs, and traffic cultures. A major challenge to replicating European roundabout bicycle safety studies—many of which used before/after analysis on crash data—is the limited number of roundabout bicycle crashes in places like the U.S. (Ferguson et al., 2019), due to comparatively low rates of cycling and few roundabouts.

To overcome limited crash data, some research (reviewed below) has turned to studying cyclists' perceptions of safety and comfort; we also recommended this in our recent literature review (Poudel & Singleton, 2021). Studying such perceptions—and interpreting them to make recommendations about transportation design and operations—assumes that people's perceptions of safety match objective safety outcomes and that comfort is driven largely by safety concerns. In the U.S., other research identifies safety concerns as primary motivators of choices, preferences, and perceptions of bicycling (Dill & McNeil, 2013, 2016; Pucher & Buehler, 2012). This suggests another implication of making roundabouts that are perceived as safe and comfortable for bicycling: they may be used more by cyclists of all ages and abilities. Additional to the greater ease of measuring cyclists' perceptions and insights into potential use, such research can also systematically examine a range of hypothetical situations, designs, etc. that may not exist in reality. Thus, the primary motivation of our study is to inform an understanding of bicycle safety at roundabouts in the U.S. through an analysis of cyclists' perceptions of comfort.

5.2.2 Literature Review

Using perceptions of comfort and safety to evaluate the suitability of transportation infrastructure is common in bicycle research literature. (For a recent literature review, see Watkins et al. [2020]. Representative examples of this literature are mentioned here.) McNeil et al. (2015) used perceptions of comfort to inform recommended bike lane buffer types. They surveyed cyclists and neighborhood residents near newly installed protected bike lanes in five U.S. cities, asking about perceived comfort with hypothetical bicycle facilities and bike lane buffer types as well as with the installed protected bike lane. Monsere et al. (2020) used comfort ratings of video clips to assess the suitability of various intersection treatments associated with separated bike lanes. Similarly, Foster et al. (2015) used cyclists' comfort ratings of video clips to create a level-of-service rating for protected bike lanes based on buffer type and motor vehicle volumes and speeds. Cyclists' perceptions have also been used to investigate comfort associated with motor vehicle passing distance (Apasnore et al., 2017) and bicycle infrastructure (Watkins et al., 2020), as well as satisfaction associated with traffic conditions and road characteristics (Liu et al., 2020), among other topics.

Not much research has investigated the safety perceptions of cyclists regarding roundabouts; our recent literature review (Poudel & Singleton, 2021) identified just eight such studies (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). Through intercept surveys of 87 cyclists in the U.S. (Arnold et al., 2010), around a third (32%) felt uncomfortable traveling through a roundabout. Macioszek & Lach (2019) surveyed 300 Polish cyclists and found they perceived single-lane roundabouts to be much safer than two-lane roundabouts. Campbell et al. (2006) surveyed 195 cyclists in New Zealand, who perceived multilane roundabouts as more dangerous than single-lane roundabouts. Cyclists' biggest situational concerns were conflicts with motor vehicles at entry or exit points. Møller & Hels (2008) intercepted 1,019 cyclists at five roundabouts in Denmark and asked about perceived risk overall and in 11 situations. The situation perceived to be the most dangerous was a conflict between a circulating cyclist and an exiting car. Perceived risk was better for roundabouts with a bicycle facility but worse for higher motor vehicle traffic volumes. Jensen (2013c) studied the satisfaction of cyclists with roundabout attributes by showing video clips of 20 roundabouts to 180 people in Denmark. Perceived satisfaction was higher for roundabouts with a separated cycle track, a highly marked cycle crossing, and a larger central island, but lower for shared roadways or unprotected bike lanes and as motor vehicle traffic volumes increased. In the United Kingdom, Parkin et al. (2007) also showed 10 video clips (including five roundabouts) to 144 commuters. Perceived risk was worse for roundabouts (vs. other intersection types) as well as when an on-street bike lane was provided.

Despite these disparate studies using different methods (intercept surveys, questionnaires, video clips), some commonalities can be found. Cyclists tend to perceive roundabouts as being less safe than other types of intersections. The situation about which cyclists are most concerned involves conflicts with entering and exiting motor vehicles when circulating within the roundabout. Cyclists' perceptions seem to be worse for multilane roundabouts and when motor vehicle volumes increase, but adding a separated bicycle facility (but not an on-street bike lane) might help improve cyclists' perceptions of safety and comfort. Nevertheless, there are several limitations of existing research. Different measures of perception (safety, comfort, risk, danger) were asked, which may complicate comparisons between studies. Not all studies related perceptions to roundabout attributes, and only a few studies investigated cyclists' perceptions in different situations. Also, person-sample-sizes tended to be low—with the exception of Møller & Hels (2008)—and only one study was conducted in the U.S. (Arnold et al., 2010). There is a need for larger-sample research on cyclists' perceptions of comfort and safety at roundabouts in the U.S.

5.2.3 Study Objectives and Overview

The overarching goal of this study is to understand perceptions of comfort among bicyclists regarding roundabouts. Towards this goal, our work has two specific objectives:

1. To understand how the perceived comfort of cyclists at roundabouts varies with different design and operational characteristics; and
2. To understand how overall bicycling comfort relates to perceived comfort with several common situations at roundabouts, such as when entering, circulating, and exiting.

To achieve these objectives, we presented 568 U.S. adult bicyclists with a hypothetical roundabout and asked a series of questions about perceived comfort. The design attributes, operational characteristics, and situations were taken from some of the major findings of our systematic literature review (Poudel & Singleton, 2021). We then analyzed these comfort outcomes, situations, and roundabout attributes using an integrated set of ordered probit regression models while controlling for personal socio-demographics and cycling characteristics (including type of cyclist). The remaining sections of the chapter describe the data and methodology of the study, present the results of our analysis, and discuss the implications of our study findings.

5.3 Data and Methods

5.3.1 Data Collection

Data were collected from a target population of U.S. adult residents. Our screening criteria included being a U.S. resident and at least 18 years old—due to limitations on consent and payment of incentives—and reporting knowing how and being physically able to ride a bicycle. We allowed for participants who had bicycled for any purpose, even if it had been many years since their last ride, in order to capture a wide range of perceptions, including from potential bicyclists who may currently be deterred due to safety concerns. Data collection took place in fall 2020, where an informational link to self-administered Qualtrics online survey was distributed via multiple methods: social media (LinkedIn, Twitter, Facebook), transportation list-serves (e.g., Association of Pedestrian and Bicycle Professionals discussion forum, Pedestrian and Bicycle Information Center Messenger e-newsletter), and several national/state/local bicycle organizations. Following ethical principles of research involving human subjects, we did mention that the study was about "perceptions, preferences, and behaviors related to bicycling at roundabouts." The specific recruitment language used was as follows:

> *Researchers at Utah State University are looking for adult residents of the US to participate in a research study about bicycling at roundabouts. Specifically, we are interested in learning about perceptions, preferences, and behaviors related to bicycling at roundabout intersections.*
>
> *You are invited to complete a 20-minute survey about your transportation and bicycling behaviors, preferences for bicycling at roundabouts with different designs, perceptions of comfort and safety at roundabouts, and personal characteristics.*
>
> *No matter if you ride a bicycle every day or haven't been on a bike in several years, we want to hear from you!*

To incentivize participation, participants were offered the chance to win one of ten $50 gift cards. The study approach was approved by the Utah State University Institutional Review Board, Protocol #11319.

For this analysis, relevant data came from a section of the survey where each respondent was randomly shown one hypothetical roundabout (from a set of 21) with specific design and operational attributes. The five attributes and their possible levels are shown in Table 5.1. These attributes—central island size, number of circulating lanes, bicycle facility type, motor vehicle volumes, and approach speed limit—were among the most important factors in the recent literature review on bicycle safety at roundabouts (Poudel & Singleton, 2021). Each hypothetical roundabout was described with text but also using a simulated GIF that alternated between two simulated images: an eye-height view of a bicyclist approaching the roundabout, and a tilted overhead view of the roundabout and its approaches. To increase the realism of the questions, these photorealistic renderings were created with Lumion, a 3D rendering software used for architectural visualization. Figure 5.1 shows a typical roundabout as displayed to the respondents.

Table 5.1 Roundabout attributes, their levels, and their frequency of appearance

Attributes	*Levels of each attribute*	#
Central island diameter	Small (80 ft) central island	11
	Large (120 ft) central island	10
Circulating travel lanes	One travel lane	10
	Two travel lanes	11
Bicycle facility type	No bicycle facilities	5
	Shared lane bicycle markings & signs	6
	Bicycle ramps to the sidewalk	5
	Separated bicycle lanes	5
Traffic volume	Low traffic volumes (rarely have to yield to and interact with other vehicles)	8
	Medium traffic volumes (sometimes have to yield to and interact with other vehicles)	6
	High traffic volumes (usually have to yield to and interact with other vehicles)	7
Approach speed limit	25 mph speed limit on adjacent roads (25 mph or less in the roundabout)	11
	35 mph speed limit on adjacent roads (25 mph or less in the roundabout)	10

Small (80ft) central island
Two travel lanes
No bicycle facilities
High traffic volumes (usually have to yield to and interact with other vehicles)
35mph speed limit on adjacent roads (25mph or less in the roundabout)

Figure 5.1 Example hypothetical roundabout

Although there are 96 unique possible combinations of the five attributes, we only created 21 different hypothetical roundabouts. One reason is that we reused roundabouts originally developed for a discrete choice experiment—18 choice scenarios, each with two alternatives (Poudel & Singleton, 2022)—that was presented immediately before the comfort/behavior section of the survey. This decision significantly reduced the effort of creating photorealistic renderings. To reduce bias, each attribute level appeared roughly an equal number of times (as shown in Table 5.1), and each of the 21 roundabouts appeared roughly the same number of times across the sample (minimum 23, median 27, maximum 29). As a reminder, each respondent saw just one of these roundabouts. For a full description of the 21 hypothetical roundabouts, see the survey questions in our open data repository (Singleton & Poudel, 2022).

Immediately after displaying the hypothetical roundabout, respondents were asked a series of questions about their comfort with bicycling through the roundabout, overall and in five specific situations. All comfort questions used a four-point scale (very uncomfortable, somewhat uncomfortable, somewhat comfortable, very comfortable); these comfort questions comprised the dependent variables in this study. The specific questions were:

1. Overall, how comfortable would you feel bicycling through this roundabout?
2. How comfortable would you feel bicycling through this roundabout in following situations…
    a. Entering the roundabout
    b. Circulating within the roundabout
    c. Exiting the roundabout
    d. On the sidewalk
    e. In the crosswalk

A total of 744 respondents started the survey, although only 568 provided responses to all comfort questions. Table 5.2 below shows the descriptive statistics for the sample. Socio-demographic characteristics included age, gender, race/ethnicity, education, student/employment status, and household income. Additional survey questions asked about the frequency of bicycling and encountering roundabouts when bicycling, crash experiences with bicycling and roundabouts, and how roundabouts affect bicycle route and mode choice. Due to the convenience sampling recruitment method, our sample was not necessarily representative of the U.S. adult population. Specifically, our survey likely under-sampled young adults, people identifying as female, people identifying as non-white, people in lower-income households, and people who do not frequently ride a bicycle, among other attributes.

We were also able to determine the "type of cyclist" for each respondent, using the same questions and categorizations developed by Dill and McNeil (2016)[2]. After excluding "no way, no how" cyclists (not in the target population), our sample contained about 7% "strong and fearless" cyclists, 18% "enthused and confident" cyclists, and 74% "interested but concerned" cyclists. These shares of types of cyclists closely match those reported nationally (first number) (Dill & McNeil, 2016) or in Portland, Oregon, (second number) (Dill & McNeil, 2013): 11%/6% "strong and fearless" cyclists, 8%/13% "enthused and confident" cyclists, and 81%/81% "interested but concerned" cyclists. Thus, we believe our data sufficiently represent a range of comfort levels among (current) cyclists.

[2] Respondents who would be "very comfortable" bicycling on "a major urban or suburban street with 4 lanes, on-street parking, traffic speeds of 30-35 mph, and no bike lane" were considered to be "strong and fearless" cyclists. Other respondents who would be "very comfortable" bicycling on "the same major street, but with a striped bike lane" were considered to be "enthused and confident" cyclists. Other respondents who "don't know how" or are "physically unable" to ride a bicycle or were "very uncomfortable" bicycling on "a path or a trail separate from the street" were considered to be "no way, no how" cyclists. However, those in the "no way, no how" group but who reported most recently bicycling "for transportation" or "for recreation" in the last week or in the last month were re-classified as "interested but concerned" cyclists. All other respondents were considered to be "interested but concerned" cyclists.

Table 5.2 Descriptive statistics of respondents ($N = 568$)

Variables	*#*	*%*	*Mean*	*S.D*
Age				
18 to 24 years	23	4.05		
25 to 34 years	111	19.54		
35 to 44 years	107	18.84		
45 to 54 years	101	17.78		
55 to 64 years	124	21.83		
65 years or above	92	16.20		
Other (prefer not to answer, or missing)	10	1.76		
Gender				
Male	362	63.73		
Female	192	33.80		
Other (prefer to self-describe, prefer not to answer, or missing)	14	2.46		
Race/ethnicity				
White only	476	83.80		
Other (Hispanic or Latino, Asian, Black or African American, American Indian or Alaska Native, Native Hawaiian or other Pacific Islander, prefer to self-describe, prefer not to answer, or missing)	92	16.20		
Education level				
Less than a high school diploma, or High school diploma or equivalent (e.g., GED)	29	5.11		
Bachelor's or associate degree	258	45.42		
Master's degree, doctorate degree, or professional degree beyond bachelor's degree	267	47.01		
Other (prefer not to answer, or missing)	14	2.46		
Student status				
Yes	50	8.80		
No	514	90.49		
Missing	4	0.70		
Worker status				
Yes	438	77.11		
No	127	22.36		
Missing	3	0.53		
Household income				
Less than $49,999	63	11.09		
$50,000 to $74,999	78	13.73		
$75,000 to $99,999	88	15.49		
$100,000 to $149,999	136	23.94		
$150,000 or more	135	23.77		
Other (Don't know, prefer not to answer, or missing)	68	11.97		
Number of bicycles available at home [a]			3.60	1.44
Missing	2	0.35		
Number of motor vehicles available at home [a]			1.95	1.00
Missing	2	0.35		
Number of adults (age 18+) in household [a]			2.23	0.89
Missing	3	0.53		
Number of children (age 0 to 17) in household [a]			0.51	0.98
Missing	2	0.35		
Bicycle use frequency [b]				
Never [c]	15	2.64		
Less than once a week	79	13.91		
1 to 3 days a week	177	31.16		
4 or more days a week	297	52.29		
Type of cyclist				
Strong and fearless	38	6.69		

Enthused and confident	103	18.13
Interested but concerned	423	74.47
Missing	4	0.70
Crash experience while bicycling at a roundabout		
Hit, or nearly hit	144	25.35
No, or missing	424	74.65
Frequency of encountering roundabouts when bicycling		
Never	48	8.45
Sometimes	231	40.67
Often	175	30.81
Always	104	18.31
Missing	10	1.76
Roundabouts affect bicycling route choice		
Yes, I avoid roundabouts if at all possible.	32	5.63
Yes, I avoid roundabouts only when there is a reasonably convenient alternative route.	98	17.25
Yes, I prefer routes with roundabouts.	97	17.08
No, roundabouts don't affect my choice of route.	333	58.63
Missing	8	1.41
Roundabouts affect bicycling mode choice		
Yes, I bicycle less because of roundabouts.	31	5.46
Yes, I bicycle more because of roundabouts.	31	5.46
No, roundabouts don't affect my choice to bicycle or not.	504	88.73
Missing	2	0.35

[a] These variables were originally measured on a categorical scale {0,1,2,3,4,5+}, and recoded for descriptive statistics and modeling (5+ = 5 and Missing = 0).
[b] The survey took place during the COVID-19 pandemic. This question asked about "normal conditions (or last year)" to try to avoid any impacts of different travel patterns.
[c] We retained these observations in the analysis because: (i) some of these respondents reported bicycling under "current conditions" but not "normal conditions (or last year)," and (ii) in an earlier question, they all reported being physically able and knowing how to ride a bicycle.

5.3.2 Analysis Methods

Recall our study objectives: to understand relationships among perceived comfort of bicycling at a roundabout (overall and in five different situations) with design and operational attributes, while controlling for personal and cycling characteristics. We had six dependent variables (comfort) measured on an ordinal scale, thus we employed ordered probit regression. Independent variables were roundabout attributes (Table 5.1) and respondent characteristics (Table 5.2). We also wanted to test how some dependent variables (comfort by situation) affected another dependent variable (overall comfort). Also, ordered probit regression involves estimating relationships with an unobserved (latent) continuous dependent variable, which is mapped to the observed ordered categorical dependent variable through to-be-estimated threshold values. Therefore, we decided to employ structural equation modeling, which accommodates multiple simultaneous and interconnected regressions as well as latent variables.

Figure 5.2 shows the conceptual framework for data analysis. Six latent dependent variables—comfort, overall, and for five situations (connected to observed ordinal comfort with an ordered probit link)—were regressed on roundabout attributes and personal characteristics, while the overall comfort model also included latent situational comfort as predictor variables. Additionally, correlations between the five situational comfort variables were allowed to allow for correlated effects of unobserved factors. Modeling was conducted using the "lavaan" package in R (Rosseel, 2012). Given the ordinal outcome variables, the package used the "WLSMV" estimator: diagonally weighted least-squares for parameter estimation, robust standard errors from the full weight matrix, and a mean- and variance-adjusted test statistic.

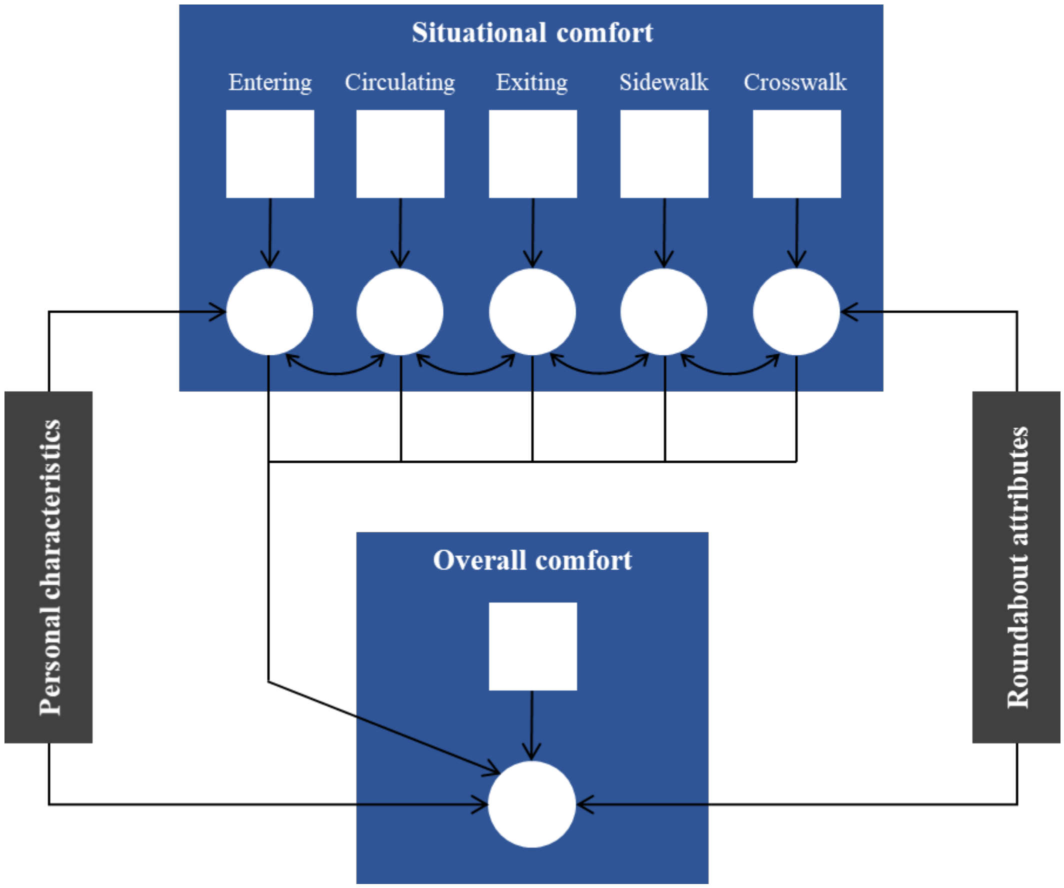

Figure 5.2 Conceptual analytical framework[3]

Given the six regressions and many possible respondent characteristics, we employed an iterative model specification process:

1. Estimate model with all paths (and correlations) among comfort dependent variables, plus roundabout attributes. Keep all roundabout attributes and comfort paths (and correlations), even if not significant ($p > 0.10$).
2. For each situational comfort dependent variable:
   a. Test each personal characteristic in Table 5.2, one at a time.
   b. Combine all variables/levels that were potentially marginally significant ($p > 0.15$).
   c. Using backwards elimination, remove least-significant variable until all are marginally significant ($p < 0.10$).
3. Combine specifications for all situational comfort dependent variables. Use backwards elimination again on personal characteristics.
4. Repeat step 3, but for the overall comfort dependent variable.
5. Evaluate the entire model and use backwards elimination once more until all personal characteristics in the model are at least marginally significant.

Results from this modeling process are presented in the following section. The data and scripts for this analysis are available on the project's open data repository (Singleton & Poudel, 2022).

[3] Squares/rectangles are measured variables, circles are latent variables, large straight arrows are regressions, and small curved arrows are correlations; all paths are not shown for clarity.

5.4 Results

Figure 5.3 shows the distribution of perceived comfort with bicycling at the roundabout overall as well as for various situations. More than two-thirds (71%) of respondents felt at least somewhat comfortable overall, while approximately another third (29%) were uncomfortable. Aggregated responses about circulating within the roundabout had a very similar comfort distribution, indicating that this situation may be on respondents' minds when thinking about the roundabout overall. Entering and exiting the roundabout were perceived to be the most comfortable situations (around 50% reported being very comfortable), while riding on the sidewalk or in the crosswalk were the least comfortable situations (although around 50% reported being at least somewhat comfortable).

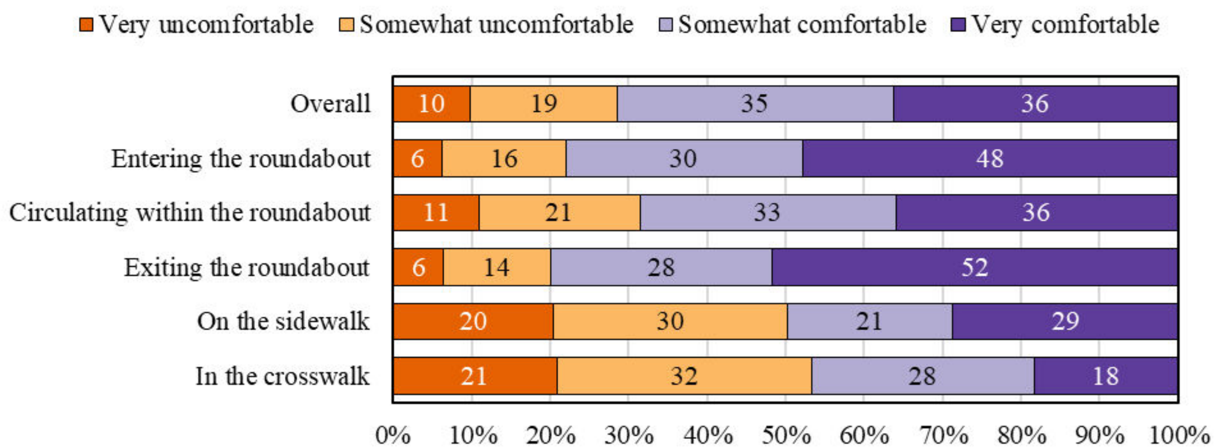

Figure 5.3 Distribution of perceived comfort (overall and by situation)

Figure 5.4 shows the distribution of perceived comfort (overall) across the design and operational attributes of roundabouts. Some broad observations are possible about roundabout attributes perceived to be more comfortable: larger central island diameters, fewer travel lanes, bicycle facilities that are more visible and separate from motor vehicle traffic, lower traffic volumes, and lower approach speed limits. Several of these differences were not large; the regression models will determine if the differences were statistically significant.

Figure 5.5 shows the distribution of perceived comfort (overall) by type of cyclist. Perceived comfort generally increased from "interested but concerned" cyclists to "strong and fearless" cyclists, although the latter group idiosyncratically reported more discomfort than "enthused and confident" cyclists.

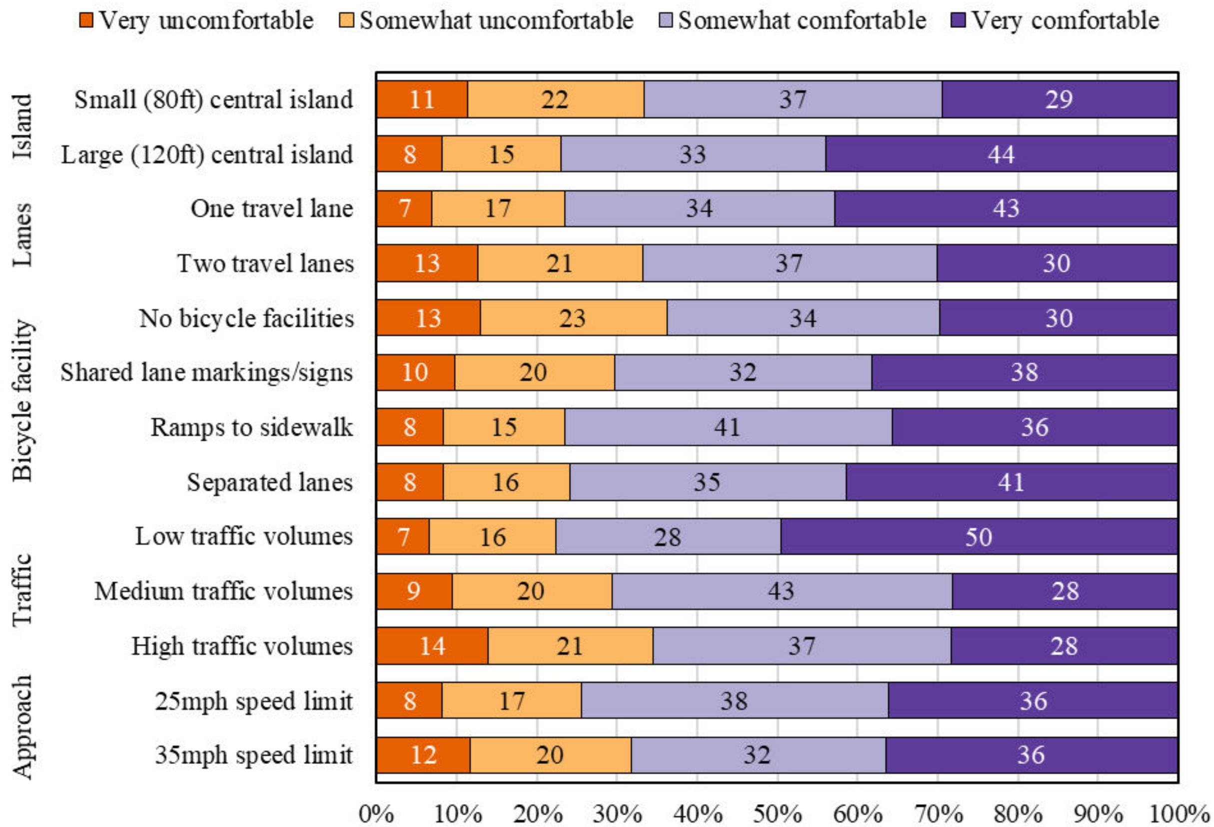

Figure 5.4 Distribution of perceived comfort (overall), by roundabout attribute

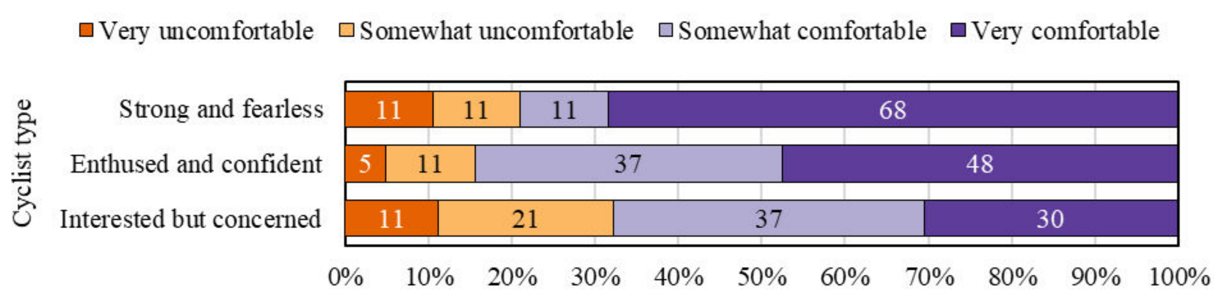

Figure 5.5 Distribution of perceived comfort (overall), by type of cyclist

Table 5.3 summarizes estimated coefficients from the final structural equation model involving ordered probit regressions of perceived comfort with bicycling at roundabouts. Estimates for threshold parameters are not shown. There were several significant correlations among the latent situational comfort variables: entering and circulating (0.583), entering and exiting (0.656), entering and crossing (0.195), circulating and exiting (0.642), circulating and crossing (0.224), exiting and crossing (0.213), and sidewalk and crossing (0.675). The variance of the latent overall comfort variable was 0.386; all other variances were fixed at 1 for identifiability.

Table 5.3 Results of ordered probit regressions of perceived comfort with bicycling at roundabouts (N = 568)

	Overall (R^2 0.712)			*Entering (R^2 0.224)*			*Circulating (R^2 0.223)*			*Exiting (R^2 0.211)*			*Sidewalk (R^2 0.161)*			*Crosswalk (R^2 0.124)*		
Variables	*Est.*	*S.E.*	*p*	*Est.*	*S.E.*	*p*	*Est.*	*S.E.*	*p*	*Est.*	*S.E.*	*p*	*Est.*	*S.E.*	*p*	*Est.*	*S.E.*	*p*
Comfort scenarios																		
Entering the roundabout	0.349	0.042	<0.01	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Circulating within the roundabout	0.424	0.039	<0.01	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Exiting the roundabout	0.087	0.048	0.07	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
On the sidewalk	-0.073	0.068	0.28	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
In the crosswalk	0.125	0.067	0.06	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Roundabout attributes																		
Central island diameter																		
Small (80 ft) central island	-0.151	0.070	0.03	-0.184	0.103	0.08	-0.245	0.098	0.01	-0.143	0.104	0.17	-0.255	0.098	<0.01	-0.295	0.096	<0.01
Large (120 ft) central island (ref.)	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—
Circulating travel lanes																		
One travel lane	0.076	0.079	0.34	0.365	0.106	<0.01	0.475	0.103	<0.01	0.357	0.106	<0.01	-0.100	0.099	0.31	0.093	0.099	0.35
Two travel lanes (ref.)	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—
Bicycle facility type																		
No bicycle facilities (ref.)	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—
Shared lane bicycle markings & signs	0.163	0.107	0.13	0.220	0.144	0.13	-0.008	0.143	0.95	0.076	0.147	0.60	0.136	0.135	0.31	0.125	0.134	0.35
Bicycle ramps to the sidewalk	0.156	0.120	0.19	0.259	0.151	0.09	0.130	0.154	0.40	-0.086	0.154	0.58	0.268	0.144	0.06	-0.114	0.141	0.42
Separated bicycle lanes	0.162	0.132	0.22	0.846	0.158	<0.01	0.150	0.148	0.31	0.224	0.158	0.16	0.195	0.144	0.18	-0.052	0.141	0.72
Traffic volume																		
Low traffic volumes (ref.)	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—
Medium traffic volumes	-0.220	0.099	0.03	-0.133	0.131	0.31	-0.207	0.129	0.11	-0.252	0.130	0.05	-0.234	0.123	0.06	-0.214	0.122	0.08
High traffic volumes	-0.216	0.093	0.02	-0.498	0.119	<0.01	-0.417	0.116	<0.01	-0.398	0.121	<0.01	-0.236	0.111	0.03	-0.287	0.109	<0.01
Approach speed limit																		
25-mph speed limit (ref.)	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—	0.000	—	—
35-mph speed limit	-0.054	0.075	0.47	-0.072	0.102	0.48	-0.090	0.100	0.37	0.026	0.103	0.80	0.072	0.097	0.46	0.001	0.095	0.99
Personal characteristics																		
Age: 65 years or above	—	—	—	—	—	—	—	—	—	-0.491	0.162	<0.01	—	—	—	—	—	—
Gender: Female	—	—	—	-0.287	0.122	0.02	—	—	—	—	—	—	—	—	—	—	—	—
Gender: Other	—	—	—	-0.701	0.375	0.06	—	—	—	—	—	—	—	—	—	—	—	—
Education level: Less than a bachelor's or associate degree	0.410	0.229	0.07	—	—	—	—	—	—	0.652	0.299	0.03	—	—	—	0.390	0.221	0.08
Student status: Yes	—	—	—	—	—	—	—	—	—	—	—	—	0.333	0.174	0.06	—	—	—
Worker status: No	—	—	—	—	—	—	—	—	—	—	—	—	-0.231	0.126	0.07	—	—	—
Household income: Less than $49,999	—	—	—	—	—	—	-0.561	0.186	<0.01	-0.508	0.198	0.01	—	—	—	—	—	—
Number of bicycles available at home	—	—	—	—	—	—	—	—	—	—	—	—	-0.120	0.036	<0.01	—	—	—
Number of adults (age 18+) in household	—	—	—	—	—	—	—	—	—	-0.173	0.056	<0.01	0.144	0.057	0.01	—	—	—

Variables	*Overall (R^2 0.712)* Est.	*S.E.*	*p*	*Entering (R^2 0.224)* Est.	*S.E.*	*p*	*Circulating (R^2 0.223)* Est.	*S.E.*	*p*	*Exiting (R^2 0.211)* Est.	*S.E.*	*p*	*Sidewalk (R^2 0.161)* Est.	*S.E.*	*p*	*Crosswalk (R^2 0.124)* Est.	*S.E.*	*p*
Bicycle use frequency: Less than 4 days a week	—	—	—	—	—	—	—	—	—	—	—	—	0.257	0.098	<0.01	0.356	0.101	<0.01
Type of cyclist: Strong and fearless	—	—	—	0.517	0.196	<0.01	0.575	0.183	<0.01	0.348	0.190	0.07	-0.417	0.189	0.03	—	—	—
Type of cyclist: Enthused and confident	—	—	—	0.350	0.137	0.01	0.404	0.131	<0.01	0.582	0.148	<0.01	-0.225	0.117	0.06	—	—	—
Crash experience: Hit, or nearly hit	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	-0.332	0.115	<0.01
Roundabouts affect route choice: Yes, avoid	-0.207	0.110	0.06	-0.586	0.129	<0.01	-0.702	0.122	<0.01	-0.618	0.142	<0.01	—	—	—	-0.347	0.138	0.01
Roundabouts affect mode choice: Yes, bicycle less	0.486	0.287	0.09	—	—	—	—	—	—	—	—	—	0.540	0.229	0.02	—	—	—
Roundabouts affect mode choice: Yes, bicycle more	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.436	0.220	0.05

Notes: ref. = reference level, Est. = estimate, S.E. = standard error, p = p-value. Threshold estimates not shown.

Because of the nature of the structural equation model (Figure 5.2), the "effects" of roundabout attributes on overall comfort can arise in multiple ways: directly in the model of overall comfort, or indirectly through the situational comfort models. Thus, in Table 5.4, we also calculated the direct, indirect, and total effects of each roundabout attribute on perceived comfort, overall.

Table 5.4 Indirect, direct, and total effects of roundabout attributes on overall comfort

	Direct	*Indirect*	*Total*		
Roundabout attributes	*Est.*	*Est.*	*Est.*	*S.E.*	*p*
Central island diameter					
Small (80 ft) central island	-0.151	-0.199	-0.350	0.100	<0.01
Large (120 ft) central island (ref.)	0.000	0.000	0.000	—	—
Circulating travel lanes					
One travel lane	0.076	0.379	0.455	0.103	<0.01
Two travel lanes (ref.)	0.000	0.000	0.000	—	—
Bicycle facility type					
No bicycle facilities (ref.)	0.000	0.000	0.000	—	—
Shared lane bicycle markings & signs	0.163	0.086	0.248	0.147	0.09
Bicycle ramps to the sidewalk	0.156	0.104	0.260	0.151	0.09
Separated bicycle lanes	0.162	0.357	0.519	0.158	<0.01
Traffic volume					
Low traffic volumes (ref.)	0.000	0.000	0.000	—	—
Medium traffic volumes	-0.220	-0.166	-0.385	0.129	<0.01
High traffic volumes	-0.216	-0.404	-0.620	0.116	<0.01
Approach speed limit					
25-mph speed limit (ref.)	0.000	0.000	0.000	—	—
35-mph speed limit	-0.054	-0.066	-0.121	0.102	0.24

Notes: ref. = reference level, Est. = estimate, S.E. = standard error, p = p-value.

Together, the variables explained a large portion of variation in overall comfort (R2 = 0.712), and a meaningful but not particularly large portion of variation in the situational comfort variables (R2 = 0.124–0.224). Below, we summarize results by variable type.

- *Comfort scenarios*: Reported comfort for four of the five scenarios (not sidewalk) were significantly and positively associated with overall comfort; circulating and entering were strongest, while crosswalk and exiting were weaker.

- *Roundabout attributes*:
  - *Central island diameter*: Overall and for each situation, respondents reported feeling less comfortable with smaller (vs. larger) central islands.
  - *Circulating travel lanes*: For entering, circulating, and exiting the roundabout (and for total effects on overall comfort), one lane was more comfortable than two lanes. The number of lanes was not significantly associated with comfort for the sidewalk and crosswalk situations.
  - *Bicycle facility type*: In most situations, all types of bicycle facilities were perceived to be slightly more comfortable than no bicycle facilities, but few differences were statistically significant when controlling for other attributes and personal characteristics. When entering the roundabout, separated bicycle lanes were perceived to be much more comfortable, with bicycle ramps to the sidewalk somewhat more comfortable. Comfort on the sidewalk was increased for roundabouts with bicycle ramps. While direct effects on overall comfort were not significant, total effects were the following: separated bike lanes were much more comfortable, and the greater comfort for bicycle ramps and shared lane signs/markings (over no facilities) was marginally significant.
  - *Traffic volume*: In general—for most scenarios and total effects overall—comfort decreased with increasing traffic volumes. However, the coefficient for medium traffic

volumes was not significant for the entering and circulating scenarios. Also, the medium and high traffic volume coefficients had similar estimates for comfort in the sidewalk situation.
    - *Approach speed limit*: Regarding vehicle speeds, although 35 mph was slightly less comfortable than 25 mph, the difference was not statistically significant.

- *Personal characteristics*:
    - *Socio-demographics*: Older adults (age 65+) reported lower comfort exiting the roundabout. Women were less comfortable than men with entering the roundabout. People without a college degree reported greater comfort overall and for the exiting and crosswalk situations. Students and workers reported greater and lesser comfort (respectively) for sidewalk riding. Those in the lowest income category were less comfortable circulating and exiting the roundabout. Having more adults in one's household was negatively associated with exiting comfort and positively associated with sidewalk comfort.
    - *Cycling characteristics*: People with more household bicycles were less comfortable riding on the sidewalk. Non-daily cyclists (riding less than four times per week) were more comfortable on the sidewalk or in the crosswalk. Those who experienced a roundabout bicycle crash were less comfortable in the crosswalk. Respondents for whom roundabouts deter bicycling reported greater comfort overall and for sidewalk riding, while those for whom roundabouts encourage cycling reported greater comfort in the crosswalk. People who reported choosing routes to avoid roundabouts were less comfortable overall and with almost every situation (except sidewalks).
    - *Type of cyclist*: Compared with "interested but concerned" cyclists, "enthused and confident" cyclists were more (and "strong and fearless" cyclists were much more) comfortable entering and circulating within the roundabout. Both groups were more comfortable exiting, too, but "enthused and confident" cyclists were more comfortable than "strong and fearless" cyclists. Both types were also less comfortable riding on the sidewalk than "interested but concerned" cyclists, especially the "strong and fearless" group.

5.5 Discussion

5.5.1 Findings About Study Objectives

Recall our study's overarching goal: to understand perceived comfort of roundabouts among U.S. cyclists. Overall, most (current) cyclists (71%) are at least somewhat comfortable with bicycling through a roundabout, while around a third (29%) are somewhat or very uncomfortable (Figure 5.3). This matches other results from Arnold et al. (2010) that around a third (32%) of U.S. cyclists were uncomfortable bicycling at a roundabout. Despite these findings, there are opportunities to make roundabouts more comfortable for bicycling, as described in the next paragraph.

Our first specific objective was to understand how comfort varied with different roundabout design and operational characteristics. Based on our findings (Figure 5.4, Table 5.3, Table 5.4), we conclude that roundabouts with the following characteristics are perceived to be more comfortable for bicycling:

- *Central island diameter*: A large (120-ft) central island is more comfortable than a small (80-ft) central island.
- *Circulating travel lanes*: One travel lane is more comfortable than two travel lanes.

- *Bicycle facility type*: Separated bicycle lanes are most comfortable, followed by both bicycle ramps to the sidewalk and shared lane bicycle markings and signs. All are more comfortable than with no bicycle facilities.
- *Traffic volume*: Comfort decreases with increasing motor vehicle traffic volumes.
- *Approach speed limit*: There was not a significant comfort difference for speed limits of 25 mph vs. 35 mph on the approach to the roundabout.

These findings about roundabout attributes and comfort tend to align with results from the limited number of studies on bicycle safety perceptions at roundabouts. Jensen (2013c) also found higher satisfaction for roundabouts with larger central islands. Two different studies (Campbell et al., 2006; Macioszek & Lach, 2019) also found that single-lane roundabouts were perceived to be safer and less dangerous than multilane roundabouts. Another two studies found greater satisfaction and lower perceived risk for roundabouts with (separated) bicycle facilities (Jensen, 2013c; Møller & Hels, 2008). Jensen (2013c) also found a negative relationship between satisfaction and motor vehicle traffic volumes. No studies found links of perceptions with approach speeds.

These findings regarding perceived comfort are also generally in line with previous research investigating cyclists' preferred roundabouts, which suggests that comfort is a major driver of preferences. In the same study, we also modeled preferences collected from a discrete choice experiment (Poudel & Singleton, 2022). Cyclists' preferred roundabout had many of the same attributes as the most comfortable roundabout, albeit with some exceptions. Bicycle ramps were not preferred over no bicycle facilities, and lower speeds were preferred over higher speeds. Notably, in contrast to our findings of comfort, smaller islands were preferred over larger islands. We are not entirely sure of the causes of these differences. It could be that preferences and perceptions diverge for these attributes. For instance, cyclists may prefer smaller islands because they allow less time spent in the roundabout, but cyclists think larger islands are more comfortable perhaps because they provide greater visibility to entering motorists. In another instance, bicycle ramps may be perceived as a comfortable design but not preferred because their use results in greater out-of-direction travel and potential delays when encountering other sidewalk users.

Our second specific objective was to examine relations between comfort overall and in several common situations. The most comfortable situations were entering and exiting the roundabout (78%–80% reported being somewhat or very comfortable), while the least comfortable situations were riding on the sidewalk or in the crosswalk (still, 46%–50% reported being somewhat or very comfortable) (Figure 5.3). Comfort in all of the situations (except for sidewalk riding) were positively associated with overall comfort, although the link was strongest for circulating within the roundabout, followed by entering the roundabout (Table 5.3). It appears that circulating is front-of-mind when cyclists consider overall comfort questions, perhaps because most time is spent in this situation or because this is when the most conflicts (with entering/exiting motor vehicles) occur. These results are in line with situational concerns found in past perceptual research (Campbell et al., 2006; Møller & Hels, 2008), and they match findings from crash data and behavioral observations that the most common crashes and most serious conflicts were between circulating cyclists and entering or exiting motor vehicles. In other words, current cyclists correctly perceive the most significant risks involved with bicycling through roundabouts.

Although personal and cycling characteristics were not the primary focus of this study, interpreting results for these control variables is illustrative. Of special interest are those relating to cycling characteristics such as the type of cyclist. As expected, compared with "interested but concerned" cyclists, "strong and fearless" cyclists were most comfortable riding with traffic (entering and circulating) and least comfortable on the sidewalk, while "enthused and confident" cyclists fell in the middle. One exception was the greater comfort reported by the middle "enthused and confident" group regarding exiting the roundabout; perhaps "strong and fearless" cyclists exit roundabouts differently or have worse experiences than "enthused and confident" cyclists. Unsurprisingly, the 6% of cyclists who avoid routes with roundabouts rated them less comfortably. The groups who rated sidewalk riding more comfortably—those who do not cycle every day and those who reported bicycling less because of roundabouts—also make sense. Overall, these results suggest important personal differences in comfort ratings that align with previous research, in which less frequent and less confident cyclists (who, it should be noted, are the majority of the adult population) are less comfortable with roundabouts, especially "taking the lane" and riding with motor vehicle traffic. These findings have implications for the design and operation of transportation infrastructure, as discussed in the next section.

5.5.2 Study Implications

Our study's findings—along with related and prior research (Poudel & Singleton, 2021, 2022)—offer implications for making bicycle-friendly roundabouts in the U.S. Single-lane roundabouts, with low motor vehicle traffic volumes, and with separated bicycle lanes or cycle paths around the roundabout—sometimes called a "protected roundabout" or a "Dutch roundabout"—are preferred and perceived to be most comfortable by current U.S. cyclists. It is likely that non-cyclists would have even stronger preferences and perceptual differences about these roundabouts, given that cyclists' preference and comfort ratings seem motivated by safety concerns. A significant share of our sample (23%) reported avoiding roundabouts when they bicycle.

In order to encourage more bicycling among people of all ages and abilities, intersections and roundabouts need to be perceived as comfortable. Existing U.S. roundabout design guidance (Rodegerdts et al., 2010) could include more options beyond bicycle ramps to the sidewalk, including separated bicycle lanes (MassDOT, 2015) to minimize conflicts with both motor vehicle and pedestrian traffic. In locations where bicycles are expected or encouraged to be, separated bike lanes (with well-signed/marked crossing treatments) are recommended, especially when motor vehicle traffic volumes are higher and multilane roundabouts are being considered. Such designs allow "strong and fearless" cyclists to take the lane and ride with motor vehicle traffic while also providing the protection sought by "interested but concerned" cyclists. However, some of these recommendations may require changes to local/state traffic laws and/or the Manual on Uniform Traffic Control Devices (MUTCD) regarding right-of-way for bicyclists on paths at roundabout crossings. Also, treatments like separated bicycle lanes or shared-used sidewalks/paths require bicyclists to use roundabout crossings, which may be uncomfortable situations (see Figure 5.3) on an otherwise more comfortable path through the intersection (compared with "taking the lane"). Additionally, when roundabouts are first installed in an area, educational efforts focused on both cyclists and drivers are recommended to teach all road users about intended behaviors and ways of safely interacting at roundabouts.

5.5.3 Limitations and Future Work

This work was not without some limitations that could be addressed through future work. First, the data were not fully representative of the potential adult cycling population. The convenience sampling approach (and recruitment language) helped create a sample that underrepresented certain groups and may not adequately reflect non-cyclists who may ride in the future but are deterred by lack of perceived safety or comfort. Additionally, by not weighting the dataset to correct for sample bias in this study, comfort results may not be completely comparable to the companion preference results (Poudel & Singleton, 2022). Future work should attempt to collect a wider and more representative (and somewhat larger) sample.

Second, our comfort variables had no neutral option, forcing a choice between somewhat comfortable or uncomfortable. While this may be beneficial in discouraging ambivalent or inattentive responses, it also results in a potential loss of precision compared with a 7- or 10-point comfort scale. Future work should test different scales to find the best balance between precision and respondent burden.

Third, our hypothetical roundabouts only represented a limited number of levels (two to four) for just five attributes. For instance, the simulations did not vary the urban context, excluded medium- and heavy-duty trucks, and kept bicycle and pedestrian volumes low enough to avoid congestion or conflicts between active mode users. Future work could examine perceived comfort in relation to additional attributes, including bicycle/pedestrian volumes, the presence of trucks, circulating lane widths, crossing types and signalization options, two-way cycle tracks, lighting, adjacent land uses, urban form, or other factors. Relatedly, to reduce respondent burden, we only showed each participant one roundabout, which limited our ability to distinguish the impact of personal characteristics from the role of roundabout attributes (and interaction effects) on perceived comfort. Also, our reuse of the 21 hypothetical roundabouts from the stated preference experiment may have affected our results in unanticipated ways. Having participants consider several roundabouts—with carefully constructed varying attributes—would improve future research insights (and potentially avoid the unexpected results we found for central island size and approach speed limit).

Fourth, respondents passively and imaginatively "experienced" the hypothetical roundabout through viewing static images and text. We assumed that respondents were familiar enough with roundabouts (through their own encounters, or via brief informational materials in the online survey) in order to make a realistic judgment about their own perceptions. Placing respondents in a bicycle simulator or immersing them in a 3D virtual environment may provide more accurate perceptions of comfort; research has found some differences between video-informed comfort and comfort from intercept studies (Fitch & Handy, 2018). With sufficient resources and facilities, it could even be possible to have participants cycle through a real roundabout (in live traffic, or in a controlled test-track environment) and supplement questionnaires about comfort with eye tracking software and/or physiological sensor measurements related to stress (Caviedes & Figliozzi, 2018; Fitch et al., 2020).

Despite these limitations, we believe our study contributes valuable knowledge about how current cyclists perceive the comfort of bicycling in different situations and for different roundabout designs.

6. CONCLUSION

Recall the two objectives of this research study:

1. Characterize bicyclists' safety perceptions of roundabouts and roundabout elements.
2. Identify bicyclists' preferences for various roundabout elements.

To achieve these objectives, we conducted a systematic literature review, collected survey data from U.S. adult bicyclists, and analyzed those data to extract insights about bicyclists' preferences and perceptions of hypothetical roundabouts with a variety of carefully controlled design and operational characteristics. In this concluding chapter, we summarize the study's key findings, highlight recommendations for design and policy, and offer suggestions for future research.

6.1 Key Findings

Regarding the second objective, our analysis in Chapter 4 suggests that U.S. bicyclists prefer roundabouts with the following characteristics:

- *Central island diameter*: A small (80-ft) central island is preferred over a large (120-ft) central island.
- *Circulating travel lanes*: One travel lane is preferred over two travel lanes.
- *Bicycle facility type*: Separated bicycle lanes are preferred over shared lane bicycle markings & signs, which are both preferred over bicycle ramps to the sidewalk or no bicycle facilities.
- *Traffic volume*: Low traffic volumes are preferred over medium traffic volumes, which are both preferred over high traffic volumes.
- *Approach speed limit*: A 25-mph speed limit is preferred over a 35-mph speed limit.

Generally, these results match findings from the literature (Chapter 2) that smaller roundabouts with separated cycle paths, lower motor vehicle traffic volumes and speeds, and fewer lanes appear to be safer for bicycling. In summary, it seems as if U.S. cyclists' preferences for roundabout attributes are mostly in line with empirical evidence about safety performance. This matches other research suggesting that traffic safety concerns motivate choices and preferences around bicycling in the U.S.

Regarding the first objective, our analysis in Chapter 5 suggests that U.S. bicyclists perceive roundabouts with the following characteristics to be more comfortable:

- *Central island diameter*: A large (120-ft) central island is more comfortable than a small (80-ft) central island.
- *Circulating travel lanes*: One travel lane is more comfortable than two travel lanes.
- *Bicycle facility type*: Separated bicycle lanes are most comfortable, followed by both bicycle ramps to the sidewalk and shared lane bicycle markings and signs. All are more comfortable than with no bicycle facilities.
- *Traffic volume*: Comfort decreases with increasing motor vehicle traffic volumes.
- *Approach speed limit*: There was not a significant comfort difference for speed limits of 25 mph vs. 35 mph on the approach to the roundabout.

These findings about roundabout attributes and comfort tend to align with results from the limited number of studies on bicycle safety perceptions at roundabouts (Chapter 2). These findings are also generally in line with previous research investigating cyclists' preferred roundabouts, which suggests that comfort is a major driver of preferences. However, in contrast to our findings of comfort, smaller islands were preferred over larger islands. We are not entirely sure of the causes of these differences. It could be that preferences and perceptions diverge for these attributes. For instance, cyclists may prefer smaller islands because they allow less time spent in the roundabout, but cyclists think larger islands are more comfortable perhaps because they provide greater visibility to entering motorists. In another instance, bicycle ramps may be perceived as a comfortable design but not preferred because their use results in greater out-of-direction travel and potential delays when encountering other sidewalk users.

Our two sets of analyses (in Chapters 4 and 5) also highlighted some key differences in roundabout preferences and comfort perceptions for different population groups and situations. For preferences, notable differences by cyclist type were found. Specifically, "strong and fearless" cyclists did not prefer separated bicycle lanes, while "enthused and confident" cyclists disliked bicycle ramps to the sidewalk and had weaker preferences for separated bicycle lanes (compared with other cyclists, and compared with no bicycle facilities). On the other hand, the strong preference for separated bicycle lanes seems to have been driven by "interested but concerned" cyclists, who made up the largest share of the sample and constitute the majority of the population. "Strong and fearless" cyclists were less deterred by high traffic volumes, exhibiting their confidence with sharing the road. On the other hand, women had stronger preferences (than men) for separated bicycle lanes and against high traffic volumes, matching other research finding gender differences in traffic safety concerns.

For comfort, as expected, compared with "interested but concerned" cyclists, "strong and fearless" cyclists were most comfortable riding with traffic (entering and circulating) and least comfortable on the sidewalk, while "enthused and confident" cyclists fell in the middle. The most comfortable situations were entering and exiting the roundabout, while the least comfortable situations were riding on the sidewalk or in the crosswalk. Comfort in all of the situations (except for sidewalk riding) was positively associated with overall comfort, although the link was strongest for circulating within the roundabout. It appears that circulating is front-of-mind when cyclists consider overall comfort questions, perhaps because most time is spent in this situation or because this is when the most conflicts (with entering/exiting motor vehicles) occur. These results are in line with situational concerns found in past perceptual research (Chapter 2), and they match findings from crash data and behavioral observations that the most common crashes and most serious conflicts were between circulating cyclists and entering or exiting motor vehicles. In other words, current U.S. cyclists correctly perceive the most significant risks involved with bicycling through roundabouts.

6.2 Recommendations

To improve the safety performance and perceptions of roundabouts for people bicycling, our study's results offer several recommendations for roundabout design, operations, and planning and policy.

- *Design*
    - U.S. roundabout design guidance should continue to recommend against or prohibit in-roadway painted bicycle lanes along the outer edge through roundabouts, since research shows that these in-roadway bike lanes lead to worse safety performance and more crashes for cyclists.
    - Bicycle ramps to sidewalks—a current design option in U.S. guidance (Rodegerdts et al., 2010)—do not seem to be preferred by anyone but infrequent cyclists, and they lead to potential conflicts with pedestrians and at crossings.
    - There is a need to revise U.S. roundabout design recommendations (Rodegerdts et al., 2010) to account for newer bicycle planning, selection, and design guidance (Schultheiss et al., 2019; NACTO, 2019), specifically to allow for "protected roundabouts" with separated bike lanes (MassDOT, 2015). This design was preferred and perceived to be the most comfortable by current U.S. cyclists, especially the "interested but concerned" majority.
    - Separated bicycle facilities (cycle paths) 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 bicycling for people of all ages and abilities (including among potential cyclists).
    - Designs for separated bicycle lanes could allow "strong and fearless" or "enthused and confident" cyclists to take the lane and ride with motor vehicle traffic while also providing the protection sought by "interested but concerned" cyclists.
    - When using protected 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).
    - In areas where right-of-way constraints prohibit the construction of separated bicycle lanes, it may be worth considering shared lane bicycle markings and signs as an alternative, since this treatment was preferred over no markings/signs (although less so than separated bicycle lanes).
    - If the design user is the "interested but concerned" cyclist, 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 FHWA, 2019, p. 23). Otherwise, separated shared-use or cycle paths may be required to provide adequate levels of comfort and safety.

- *Operations*
    - Because cyclist preferences seem to be focused on safety-related elements, doing everything possible to reduce vehicle speeds, volumes, and conflicts would make more preferred roundabouts for the general population.
    - Reducing the speed and volume of motor vehicle traffic at roundabouts seems likely to yield fewer bicycle crashes, based on the literature.
    - We suggest borrowing from Schultheiss et al. (2019, p. 23) and using 20 or 25 mph and 2,000 to 3,000 AADT as the upper limits for roundabouts with no bicycle facilities, considering "interested but concerned" cyclists as the design user.

- *Planning and policy*
    - When roundabouts are first installed in an area, educational efforts focused on both cyclists and drivers are recommended to teach all road users about intended behaviors and ways of safely interacting at roundabouts.
    - In order to encourage more bicycling and more people bicycling of all ages and abilities, intersections and roundabouts need to be perceived as comfortable.
    - 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.
    - Some of these recommendations (those regarding design and operations) may require changes to local/state traffic laws and/or the MUTCD, especially regarding the right-of-way of bicyclists on paths at roundabout crossings.

6.3 Future Work

Given the stated limitations of this study (see Chapters 2, 4, and 5 for details), we offer several suggestions for future research to help further illuminate bicycle safety performance, preferences, and perceptions around roundabouts. Specifically, we organize our suggestions into three categories, those pertaining to the roundabout attributes and situations being considered, the populations being studied, and the use of a variety of research methodologies.

- *Roundabout attributes and situations*
    - Research should continue to explore the role of a variety of roundabout design and operational attributes, characteristics, and situations when investigating bicycle safety performance, perceptions, and preferences. These could include:
        - *Design factors*: central island height, circulating lane widths, pavement markings, crossing types, two-way cycle tracks, landscaping of non-paved areas.
        - *Operational factors*: bicycle and pedestrian volumes, circulating speeds, medium- and heavy-duty truck presence, signalization options for crossings, bicyclist movements (left, thru, right).
        - *Temporal factors*: lighting, light conditions, weather conditions.
        - *Spatial factors*: land uses, build environment conditions, urban context, topography/terrain.

- *Study population*
    - The sample collected in this study (Chapter 3) focused on the current US adult cycling population. It was potentially subject to self-selection bias. Some improvements to the sample and the broader study population could improve knowledge. Specifically:
        - A larger and more representative sample could highlight even more variations in perceptions and preferences across the population.
        - More attention to recruiting and surveying potential but current non-cyclists could help to accommodate the perceptions and preferences of people who are deterred from cycling due to a lack of safety or comfort.
    - In general, most studies in the literature have been done in northern Europe. There is a need to do research on this topic in other countries and cultures.
        - Questions regarding the validity of knowledge transferred from one context to another—especially northern European findings to places like the U.S. with fewer cyclists and roundabouts, or to places in Asia or Africa—calls for the study of such demographic and cross-cultural comparisons.

- *Research methodologies*
    - Our research helped fill a gap in the literature on cyclists' safety perceptions of roundabouts and preferences for different kinds of design and operational features. However, the methods we used could be improved in several ways. Notably:
        - Our choice experiment used only two unlabeled roundabout alternatives; future state choice experiments could add a non-roundabout alternative to understand cyclist preferences as compared with traditional stop-controlled or signalized intersections, which could inform bicycle route choices.
        - Our comfort variables had no neutral option, forcing a choice between somewhat comfortable or uncomfortable. While this may be beneficial in discouraging ambivalent or inattentive responses, it also results in a potential loss of precision compared with a 7- or 10-point comfort scale. Future work should test different scales to find the best balance between precision and respondent burden.
    - There are a variety of topics that have yet to be fully explored in the area of bicycle safety at roundabouts: avoidance of roundabouts, cyclist route choices, awareness and experience with roundabouts, and lane positioning when riding in roundabouts. It would be useful to study these topics to better understand the alignment of bicycle preferences, perceptions, and behaviors related to safety at roundabouts.
    - Through our research and our literature review, we identified some research areas and methodologies that could be studied in more depth to provide greater insights regarding bicycle safety at roundabouts. These include the following:

- Placing respondents in a bicycle simulator or immersing them in a 3D virtual environment (i.e., using virtual or augmented reality) may generate more accurate assessments of roundabout preferences or perceptions of comfort.
- With sufficient resources and facilities, it could be possible to have participants cycle through a real roundabout (in live traffic or in a controlled test-track environment), and supplement questionnaires about comfort with eye tracking software and/or physiological sensor measurements related to stress.
- 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.
- To our knowledge, few naturalistic studies of driver–cyclist interactions, which seem like promising areas of research, have been undertaken. Automated video-based conflict analysis is promising for larger-scale studies, but limitations remain regarding the reliability of the analysis along with the proper positioning of the cameras. Such studies could investigate cyclist behaviors at roundabouts, interactions with pedestrians and heavy vehicles, and driver behaviors such as driver acceleration actions (or passing clearances) when encountering cyclists and the effects of sight distance on drivers looking and yielding.

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