Bicyclists' perceptions of urban roundabout safety

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by

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Preface

In choosing my thesis topic, I was torn between research in active transportation modes or the public transport domain, an area I am more comfortable in, having worked in public transport for 10 years. In the end, I chose to explore bicyclists and their perceptions of safety at roundabouts. Bicycling as a mode of transportation is changing rapidly. Not only is the objective safety of bicyclists important, but their perceptions of safety are too. To reduce or reverse climate change as well as to maintain our health and well-being, more of us must start bicycling again and we must not be afraid of doing so. Most people learn to ride a bicycle as a child so it shouldn't be that hard to get adults back on the saddle. Bicycling has always been a wonderful pastime for me but it wasn't until secondary school that I realized it could also be my primary mode of transportation. I've used a bicycle to visit the temples of Angor Wat, to explore the shimmering megalopolis that is Tokyo, and more recently to move from The Netherlands to Ireland (with some ferry help). Choosing to write my thesis about design aspects that impact bicyclists' perspective of safety and comfort is a step towards helping designers create more bicycle-friendly infrastructure that can benefit all road users. Personally, this has been a tumultuous year. My grandmother died in January, I am becoming an engineer this summer, and I am starting a job in August. On top of all of that, I moved countries while writing this thesis.

This thesis has introduced me to rigorous academic and scientific research. A big thanks goes to my thesis committee: Dr. Haneen Farah, Dr. Amir Afghari, and Dr. Maria Salomons, for guiding me through the thesis process. Haneen's initial input and enthusiasm for bicycle safety was vital in helping me formulate my research objective. Maria's input throughout the survey, conceptual model, and attribute creation phase was instrumental in the creation of a well-designed survey that was not only short and easy to use, but also allowed me to investigate most of the variables I wanted to research. Without Amir's guidance on modeling and surveying, I probably would have embarked on an impossible model setup that would have taken months to assemble and run. All three supervisors provided excellent support throughout my entire research project, from the HREC process to even facilitating a GoPro camera purchase.

I want to thank my friends and family for encouraging me to take breaks and to get outside for some fresh air, but also for reminding me that my thesis project was not my entire life. A special thanks to the members of Dispuut Verkeer (DV) for showing me that a student association is not only about tours and fun activities, but can also provide great career advice. I made Dutch friends as well as many international friends and improved my Dutch language skills. As a member of the DV Board from 2022 to 2023, I gained experience in management and an in-depth perspective on Dutch culture. I want to thank my mother for her eagerness in proofreading my report, down to the last apostrophe. Finally, I want to thank my wife, Lauren, for all her love and support. Watching her research and write her own thesis, gave me inspiration to continue to complete this thesis paper. She encourages me to do better, to challenge myself and to be active in life, whether its in my personal life, my studies or my work.

I.R.J. (Ian) Trout
Dublin, August 2024

Summary

Introduction

While roundabouts, in comparison with intersections, are associated with decreased severity of motor vehicle crashes, recent crash data suggest that this is not the case for bicycle crashes, with 12% of all bicycle crashes occurring at roundabouts. At the same time, the Netherlands is experiencing increasing congestion in bicycle facilities as new types of bicycles (e.g., fat tire bicycles, e-bicycles, cargo bicycles, etc.) are becoming increasingly popular. Due to the increased diversity of bicycle types (e-bicycles, cargo bicycles) and their speeds, increased complexity at roundabouts with smaller sightlines, and more bicycle usage, roundabouts were the location of 12% of all bicycle crashes in the period between 2014 and 2021. This statistic is relevant: with 3450 roundabouts in the Netherlands, this intersection type represents merely 0.6% of all intersection types in the country, yet it accounts for a disproportionate share of bicycle-related crashes. Researchers and professionals are actively working on updating roundabout design guidelines. Several factors were identified from past research that have an influence on objective and subjective bicycle safety at roundabouts. These include among others: bicyclist crash history, yielding priority, buffer width between car lanes and bicycle path, the number of crossing points for bicycles, and bicyclists' behaviours (e.g., long-term level of risk-taking, errors, and positive behaviours such as obeying red traffic lights). Whilst these studies have focused on either perceptions of safety or comfort, no study has looked at both concepts at the same time and the correlations between them. This research will dive into specific roundabout attributes that are often complex and pose challenges to road users, whilst still controlling for differences among the study population, in an effort to provide design recommendations for designers on how to design urban roundabouts for current and future generations of bicyclists.

Research aim

This study aims to explore which design characteristics and socio-demographic factors influence bicyclists' perceptions of safety and comfort at urban Dutch roundabouts. The objective of this study is to assess how typical Dutch bicycle infrastructure design at urban roundabouts influences bicyclists' behaviour, and their subjective safety and comfort (i.e. perception of safety and comfort).

Research method

The research utilized a mixed-method approach, comprising a literature review, field observations, expert interviews, and a stated preference survey. This research is novel as it is the first such study to look at both perception of safety and comfort of bicyclists using a bivariate random effects probit model. The literature review and expert interviews assisted in determining which independent socio-demographic and roundabout infrastructure variables were important to include in the survey. Expert interviews were conducted with designers and government officials participating in the Center for Regulation and Research in Civil, Water and Road Construction and Traffic Technology (CROW) workshops. The goal of the workshops was to create an update to the 2014 roundabout design guidelines, focusing on bicycle design. During the workshops, topics such as yielding priority, bi-directional vs uni-directional bicycle facilities, different types of bicycles and how these affect designs, visibility for the bicyclist and anticipation of turning movements, and the buffer width between bicycles and vehicles were discussed. These workshops and a subsequent expert insight survey were instrumental in determining which roundabout attributes should be included in the final model. These attributes were often identified as either novel or ambiguous.

Field observations at over 50 Dutch urban roundabouts were performed, observing the behaviours of bicyclists, and taking survey photos. These 15 minute field observations were performed during the

weekday rush hour periods (between 16h00 and 18h30) to get the busiest traffic volumes, which may add stress for bicyclists and increase the probability of crashes. Scooters, as well as anything legally using the bicycle facility during the observation period, were counted in the bicycle volumes. The field observations allowed the researchers to classify roundabouts based on bicycle volumes and to observe bicyclist behaviour and compliance with local traffic regulations. A stated choice experiment design was then used to determine the number of locations to use in the survey. Photos of eight real-world roundabouts were modified and used in the survey construction in order to ensure an even variable distribution (e.g. yielding priority for bicycles was at four of the eight locations). In addition to the other mentioned factors in the introduction, this research analysed different bicycle volumes, the presence of art and/or advertisements in the center island, directionality of the bicycle path (uni-directional or bi-directional), and the shape of the bicycle path at the roundabout (e.g. a bent/diamond or circular shape). All the roundabout infrastructure characteristics were reduced to binary variables in order to simplify the survey and reduce the amount of respondents needed to reach statistical significance. Respondents were asked in the survey to rank on a 5-point Likert scale, how comfortable and how safe they would feel if they were to cycle through those locations. Other socio-demographic and bicyclists' behavioural questions were asked as well, including income, age, gender, crash history, self-ascribed bicycling skill level, and 12 questions that indirectly get at how much a respondent portrays risky bicycling behaviour (taken from the cyclist behavioural questionnaire (CBQ) developed by Useche et al. (2021)).

The survey was conducted via random sampling of the Dutch population, through online forums such as Ouders.nl and Fietsersbond, Linkedin, and through flyers distributed in the cities of Amsterdam, Rotterdam, and The Hague. There was a total of 239 complete responses from bicyclists, with some being non-Dutch residents. Following completion of the data collection, a multivariate random effect ordered probit model was used to investigate the heterogeneous interactions amongst respondent groups regarding the relationship between bicyclists' perceptions of comfort and safety with the aforementioned roundabout features. Due to the ordinal nature of most of the independent variables, an ordinal model was used in order to prevent underestimation of the fit indices and the standard errors of the parameter estimates.

Results

Literature Research

Findings from the literature review, expert interviews, and field observations have yielded interesting results. The literature review concluded that the link between perceived comfort and safety and objective safety is ambiguous, with past studies finding that only vehicle speed had a strong correlation between subjective and objective safety. In addition, past research and design workshops found that the heterogeneity of roundabouts can cause confusion in both motorists and bicyclists as they may encounter two roundabouts in the vicinity of each other which vary in design characteristics such as speed limit, bicycle facility, or center island features.

Expert Insights

The expert interviews confirmed that the CROW design guidelines leave some room for designer's choices, in particular with regards to which mode should have yielding priority when the distance between the bicycle crossing and the vehicle entrance/exit of the roundabout is between 5 and 10 meters. Deviation from the CROW design guidelines occurs due to various reasons. The CROW workshop confirmed that certain bicycle design features are more important than others (yielding priority, buffer width, and bi-directional bicycle paths) in terms of providing the safest possible design. Those design features were added into the survey. Notable design features that were not mentioned in the expert interviews or CROW workshops were center island radii, presence of art/advertisement, or bicycle path width. The presence of art/advertisement was added to the survey due to the theory that art/advertisements can cause distractions to motorists which can cause crashes and impact perceptions of comfort. In addition, other key takeaways were the debates on collecting better bicycle crash data due to chronic under-reporting, lowering speeds (all modes) to accommodate all the complex roundabout turning movements, and attaining city-wide consistency of roundabout designs which may increase road user compliance. Yielding priority, bi-directional bicycle paths, diverse bicycle types, and buffer width were variables that were included in the final model and survey. Due the complexity of demonstrating speed or visibility in a survey based on pictures, these variables were not included.

Field Observations

During the field observations, several notable behaviours were observed such as: preference for bicyclists to use one side of a roundabout (even though the bicycle facility was bi-directional on all sides); bicyclists weaving into the vehicle lane as a shortcut when the buffer width was less than one meter; bicyclists riding the wrong-way in the bicycle facility. This non-compliant behaviour was done in order to avoid a complex tram crossing; take the most direct path to residences; and directly access a major grocery store at one corner.

Bivariate random effects ordered probit model

The findings from the survey show that the presence of yielding priority for bicycles is positively correlated with perceptions of safety and comfort. According to the model elasticities, the presence of yielding priority for bicycles increases the probability of a bicyclist feeling comfortable by 20%. In contrast, the lack of yielding priority increases the probability of a bicyclist feeling very uncomfortable by 18%. It was found that a bi-directional bicycle path and large bicycle volumes increase the probability of a bicyclist feeling very uncomfortable by 31% and 39% respectively. If a bicyclist frequently commits violations (according to the cyclist behavioural questionnaire (CBQ) violations questions), that decreases the probability of a bicyclist feeling very unsafe by 32%. This finding means that bicyclists who commit violations and have more risky bicycle behaviour, tend to be less alert and cautious, and thus have a reduced perception of risk. According to the elasticities, the presence of a four-legged roundabout increases the probability of a bicyclist feeling very unsafe by 39%. The model results found that Dutch respondents, would perceive higher safety and comfort levels, when compared with non-Dutch respondents. The Age variable was negative, which is intuitive since older cyclists perceive less comfort and safety and it suggests that older population groups have greater sensitivity to whether a roundabout has yielding priority or not, compared with a younger population. The bicycle crash history variable was negative in sign and very statistically significant, which is intuitive and aligns with past studies that that have shown that if one has been in a recent crash, one will have a lower perception of safety and comfort.

Discussion, Conclusion, Recommendations

Discussion

Notably, in terms of perception of comfort towards roundabouts, one's frequency of use of an e-bicycle or normal bicycle was found to be more important than the design feature of yielding priority. This insight aligns with past studies that concluded that the more people bicycle, the more confidence and perceived control they may have, which leads to higher perceptions of comfort and safety. Another important finding was that roundabouts that have a strong attractor at one corner and high bicycle volumes had a lower perception of safety and comfort. This is intuitive since a strong attractor such as a grocery store or a geographic barrier will cause more turning movements which causes friction amongst bicyclists and between bicyclists and other modes. This would cause lower perceptions of safety and could lead to more actual crashes.

Roundabouts four, five, and six(Planbaan/Kernbaan, Amstelplein, and Gordelweg/Rodenrijsestraat respectively) did not follow CROW design guidelines as they did not provide yielding priority to bicyclists. At these locations there was a noticeable drop in the percentage of respondents who answered favorably (i.e. either neutral to high feeling of safety or comfort). The average neutral-positive ratings for comfort were 65.2% at these roundabouts compared with the average of 80.4% at the other roundabouts. The average neutral-positive ratings for perception of safety were 74% at these roundabouts compared with the average of 86.1% at the other roundabouts. This research found that deviation from the CROW design guidelines does lead to lower perceptions of comfort and safety, and that large bicycle volumes and more vehicular legs entering/exiting a roundabout have negative correlations with perceived comfort and safety.

Conclusion

The results of ordered probit model were that older adults are more sensitive to perceptions of safety, which aligns with the general premise that older adults are more risk-averse. When comparing the non-Dutch respondent results with those of the Dutch respondents, the statistical model shows a strong positive correlation for perceptions of comfort and safety. This indicates that non Dutch people feel less comfortable or safe at roundabouts, when controlling for yielding priority, bi-directional bicycle paths, and the other attributes. This is logical, as there are less roundabouts with dedicated bicycle facilities outside of the Netherlands, so non-Dutch respondents are more cautious when bicycling near conflict points such as an urban roundabout.

Recommendations

The main contribution that this research hopes to provide is bicycle infrastructure design and policy recommendations for government agencies in order to maximize perceived safety and in this way also maximize compliance. The more bicyclists perceive themselves as comfortable and safe, the more likely they will be to obey traffic laws. As such, this report recommends the following design features at roundabouts: provide bicycles with yielding priority at all urban roundabouts and build roundabouts that mitigate current and future bicycle congestion. Too many bicycles lead to less comfort and to lower perceived safety, especially with bicyclists using cargo bicycles and special bicycles. Another policy recommendation would be to follow the CROW guidelines as much as possible since that means that there is uniformity between roundabouts, which is positively correlated to perceptions of safety and comfort. Finally, when designing a roundabout, one should minimize the amount of vehicular legs entering/exiting, to the extent possible, given the adjacent land uses and roadway network.

The non-statistically significant result of this research was that bi-directional bicycle paths at roundabouts decrease perceptions of comfort and safety. However, this report recommends following the CROW design guidelines. While this report recognizes that in some cases a bi-directional bicycle path may provide better accessibility and connectivity, depending on adjacent land uses and the nearby bicycle network, this report wishes to point out that bicyclists' subjective safety should be considered when assessing the use of a bi-directional bicycle path at a roundabout.

Limitations and Future Research

Research Limitations

This research was limited by resources and time, which meant that a large model with many variables would not be suitable. In addition, the objective crash data was not used to compare the survey findings as there was so little reported crash data. Other limitations included the use of a camera that did not have a built-in 180 degree lens, the binary nature of the roundabout variables which meant that more detailed thresholds for bicycle volumes and buffer width could not be explored, and finally lack of data responses for certain transportation mode frequencies (car/motorcycle, scooter, and public transport).

Future Research: Methods

Further research could extend the data collection to more roundabouts or analyse differences of urban and rural roundabouts. In addition, one could work with hospitals to get objective safety records of bicycle crashes at urban roundabouts in order to make more inferences between subjective and objective bicycle safety. Looking into the use of ordinal structural equation model (SEM) models to compare results between the two models and looking at other design features such as width of the bicycle path, visibility, or presence of public transport could provide more roundabout information that could better serve designers and practitioners. Other ideas could be to study the correlations that could exist between individual characteristics and the CBQ factors and to investigate external factors, such as weather or lighting. Performing the field data collection and survey preparation in the middle of April, with thunderstorms and fluctuating weather patterns, made it difficult to control for the weather. The desired effect was that the final survey pictures represented a cloudy and partially wet day but some pictures used in the final survey ended up looking less wet. Pavement wetness could affect bicyclists' perceptions of comfort and safety due to the increased possibility of slipping. More in-depth research could be done on the various types of bicycles and how their speed differences affect bicyclists' perceptions. Further research could determine the thresholds of bicycle volume at which it starts to feel uncomfortable or unsafe for bicyclists. Research into bi-directional bicycle paths at or near roundabouts could include adjacent land uses and the local bicycle network to see if this changes people's subjective safety perceptions. More topics include: isolating different modal sub-groups, such as users of e-bicycle or scooters, to see if there were different beta coefficients and differences in their perception of safety and comfort compared to the entire sample population; performing an ordinal factor analysis on the CBQ variables, allowing for a more detailed interpretation of those independent variables; and collecting respondent data on "intention to comply" in order to have statistical information that could link compliance with subjective safety. Finally, studying the impacts of vehicle speed and bicyclist/motorist eye to eye contact as independent variables could provide more information on the link between relative speed and yielding behaviour. Such a study could lead to changes to roundabout design features in order to reduce speeds.

Moreover, there are several procedures that could be implemented in future research that would save time and effort for the research team whilst producing a more realistic survey that is simple and easy for respondents to understand and complete. For example, the use of a GoPro camera (or similar) for the 180 degree photos would provide less image distortion. As an alternative, videos would provide a more realistic perspective of roundabout attributes such as raised bicycle/pedestrian crossings, which are practically impossible to convey to respondents via a photo-only survey. Additional considerations in the experimental setup could be to locate roundabouts that do not require modifications in order to fit the attribute characteristics. Finally, additional online forums and in-person sampling would provide for a greater sample of the Dutch population and thus increase model stability.

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1 Introduction

1.1. Background

An increasing number of cities around the world have pledged to use the Safe System or Vision Zero approaches with the goal of achieving no road related fatalities or injuries. More protected bicycling facilities, particularly those which separate vulnerable road users from motor vehicles, can help achieve this goal. Furthermore, these projects improve accessibility to bicycling: lowering exposure to injuries and fatalities goes a long way toward getting more people to consider biking for their daily travel (Kelly et al., 2014; de Hartog et al., 2010). In 2021, 63% of all road crashes in the Netherlands that resulted in severe injury did not involve a motor vehicle; bicyclists represented more than 90% of that value (Wegman and Schepers, 2024). The majority of these crashes equate to single-bicycle crashes. More troubling statistics indicate an increase over the past decade in road-user fatalities that involve a bicyclist, with 32% in 2013, 36% in 2021 and 39% in 2022 (Wegman and Schepers, 2024).

This trend needs to be reversed if the Dutch government is going to achieve zero road casualties (fatalities and serious injuries) by 2050 (van Infrastructuur en Waterstaat et al., 2018). Bicyclist injuries and their severity are dependent upon many variables, such as bicyclist characteristics (age, gender), conflicting modes (if there is one), intersection characteristics, environmental conditions, bicyclist's movements and location preceding the crash, and types of crashes (Shen et al., 2020). Recent studies have found that the increase in e-bicycle usage (with higher speeds) and the aging population in the Netherlands are two of the factors contributing to the rise in traffic fatalities involving bicyclists (85% of all bicyclist fatalities involve bicyclists older than 50 and 51% involve bicyclists older than 75 years of age) (Wegman and Schepers, 2024). Moreover, in comparison with bicycle crashes that resulted in severe injury, fatal crashes most often involve a motor vehicle (Wegman and Schepers, 2024). The main reasons for bicyclist crashes are related to infrastructure, notably bollards, sharp curves, parked cars, and the amount of protection (particularly the distance between bicyclists and motor vehicles) at intersections. Sightlines and blind spots for motorists are also key factors in crashes (Schepers and den Brinker, 2011). In addition to infrastructure and physical objects or obstructions, there are behavioural factors that decrease safety, such as distracted or fatigued bicycling, not obeying right-of-way rules, and riding on the wrong side of the road or bicycle path (Wegman and Schepers, 2024). Due to the increased diversity of bicycle types (e-bicycles, cargo bicycles) and their speeds, increased complexity at roundabouts with smaller sightlines, and more bicycle usage, roundabouts were the location of 12% of all bicycle crashes in the period between 2014 and 2021 (News, 2022). This statistic is relevant: with 3450 roundabouts in the Netherlands, this intersection type represents merely 0.6% of all intersection types in the country, yet it accounts for a disproportionate share of bicycle-related crashes.

1.2. Problem definition

Roundabouts have existed for over a century and it is now known that roundabouts offer high levels of safety, in particular with regards to motor vehicle traffic (Distefano et al., 2019). When compared to signalized intersections, roundabouts offer additional benefits, such as improvements in traffic flows and a reduction in CO_2, HC, and NO_x emissions (Bahmankhah et al., 2019). Many countries have installed roundabouts for their proven reduction in vehicle crashes, but studies have noted that careful attention must be paid to bicyclists and pedestrians as the major safety benefits for motorists may not necessarily translate to more vulnerable modes (Werner and Birgit, 1990). Data gathered between 2001-2011 in New Zealand showed that injury crashes involving bicyclists were 20% to 23% higher than at priority or signalized intersections, respectively (Tan et al., 2019). A similar result was found by using Surrogate Safety Assessment Methodology (SSAM) in a Portuguese study (Bahmankhah et al., 2019). In general, the bicycle infrastructure in the Netherlands is well designed and safe due to the separation of traffic modes, in particular high-speed motor vehicle traffic (Schepers et al., 2017). However, architects and engineers still have work to do with regards to updating bicycling infrastructure to accommodate not only the diversity of bicycles being used, but also the diversity of people living in and visiting the Netherlands. Roundabouts should be a particular focus as their characteristics are often complex and pose challenges to both local and non-local residents which lead to more maneuvering errors (de Waard et al., 2020). Roundabouts with bi-directional bicycle facilities and varying yielding priority (e.g. whether bicycles have to yield to vehicles or vice-versa), can be particularly challenging. Recently, some Dutch municipalities have even converted bi-directional roundabouts to uni-directional ones, in order to have more predictable interactions between bicyclists and other traffic modes, but these conversions required a behavioural campaign in order to be successful (CROW, 2023). In order to strike a balance between bicycle accessibility, movement predictability, bicyclists' behavioural preferences, and bicycle safety, more research is needed.

1.3. Perceived safety versus objective safety

The interrelationship between actual safety and perceptions of safety is important and this research will focus on perceived safety/risk and attempt to relate it to actual safety. One's intention to ride a bicycle relates to one's comfort levels, perception of safety, and history and behaviour as a bicyclist (Fernández-Heredia et al., 2014). A recent focus of research on understanding a bicyclist's risky behaviour (Useche et al., 2018; Useche et al., 2021), led to the development of the bicyclist behavioural questionnaire (CBQ) which has been applied in Belgium, the United States of America (USA), and Spain. The CBQ makes the link between bicyclists' behaviours and their socio-demographic background, allowing for roadway design changes that better match bicyclists' real-world actions (Useche et al., 2018). Studies have shown that if bicyclist's underestimate the risks of bicycling, they are more likely to be involved in a crash and to suffer more severe injuries as a result (Han, 2023). If bicyclists take on too much perceived risk, they may become mentally fatigued, which leads to mistakes and potentially to crashes (Chaurand and Delhomme, 2013). This becomes a self balancing feedback loop: the occurrence of bicycle crashes raises a bicyclist's subjective risk perception; this leads to decreased risky behaviour, and potentially less crashes (Useche et al., 2019). The interrelationship between perception of safety and actual safety is also often politicized. When residents perceive a roundabout as unsafe, they demand that the local government make design changes, even when that location has a good objective safety record (Duivenvoorden, 2021).

1.4. Research contribution

The practical contribution of this research is to provide recommendations to local and national governments regarding bicycle safety at urban roundabouts and propose design alterations and new designs that would maximize compliance and perception of safety. This will be done from the point of view of the bicyclist only, thus designers and governments should include the findings of this research with other modal considerations, such as designing roundabouts for proper turning radii for buses. The scientific contribution of this research is the novel use of a bivariate random effects ordered probit model to investigate bicyclists' perceptions of comfort and safety simultaneously, against the independent variables of roundabout attribute and socio-demographics.

1.5. Research aim

The research aim is to determine the extent to which factors such as infrastructure design and human behaviour influence bicyclists' perceptions of safety and comfort at urban roundabouts. This paper will also attempt to establish a link between these perceptions of safety and objective safety at urban roundabouts in the Netherlands. In order to reach these aims, a complete understanding of the current Center for Regulation and research in civil, water and Road Construction and traffic technology (CROW) design guidelines and an overview of why certain urban roundabout locations may not follow this will be undertaken. Then, an investigation of bicyclists' perceptions on safety and comfort level will be conducted through the use of a respondent survey based on various roundabout design configurations. The survey will be analysed using a quantitative model. Lastly, a comparison between the survey results and aggregated historical crash data will be performed, so that the links between subjective safety and actual safety may be made.

2

Literature review

As part of the qualitative analysis, a literature review was conducted to gain a better understanding of the latest research related to bicycles at roundabouts, the various design characteristics of urban roundabouts within the Dutch context, bicyclists' perceptions of safety, and human behavioural factors. The following sections address those related topics: Section 2.1 presents general roundabout characteristics and the impacts of those design details. Next, Section 2.2 explores in detail the various guidelines and design standards originating from CROW. Section 2.3 presents safety challenges that roundabouts pose for bicyclists. Finally, Section 2.4 elaborates on various behavioural models that look at bicyclists' perceptions of safety in various situations. More details on the safety studies used in this Chapter, such as aim, research method, variables, findings, and research gaps, can be found in Appendix C.

2.1. Roundabout characteristics and impacts of those designs

Roundabouts come in many different shapes and sizes. In the Netherlands, there are four main types of roundabouts: turbo-roundabouts, roundabouts with a bicycle lane, roundabouts with a separate bicycle facility (oftentimes mimicking the shape of the vehicular roundabout), and roundabouts with no bicycle facility (CROW–Kennisbank, 2014b). This report will focus on roundabouts that have a separate bicycle facility. As turbo-roundabouts are not found in urban areas and there are no roundabouts with a bicycle lane (e.g. Cornelius Joosstraat/Hendrik Berlagestraat in Breda) in the Randstad, these two were excluded from this study. Figures 2.1 and 2.2 depict examples of typical roundabouts considered in this study. One can note that no two roundabouts are alike, with details such as curb radii, central island diameter, outer diameter (inscribed circle diameter), lane width, number of legs or roads feeding into and out of the roundabout, and others that heavily influence how fast motor vehicles travel through the roundabout and whether they yield or not to bicyclists (Poudel and Singleton, 2021). Distefano et al. (2019) found that deflection angle, number of lanes within the roundabout, entry radius, lane width of the approaches, width of the roadway in the roundabout, and width of the center island are the main factors when it comes to motorists' behavioural responses. Designers take into account design speeds, anticipated traffic volumes, and sight distance (often referred to as visibility) when designing and constructing a roundabout. Low deflection designs (e.g. designs with a small center island diameter but a large inscribed circle diameter) lead to higher vehicle speeds within the roundabout and lower yielding rates at bicycle and pedestrian crossings (Lawton et al., 2003; Zhang and Ma, 2015). These important design factors impact how motorists and bicyclists yield to one another. Silvano et al. (2014) tested a multi-hierarchical probabilistic model on a single Swedish suburban roundabout with the aim of accurately predicting yielding behaviour. Their main findings align with CROW design guidance (CROW–Kennisbank, 2014b) that speeds are negatively correlated with yielding behaviour of motorists. This can have significant safety consequences, depending on whether bicycles are in the vehicular lane or in a dedicated bicycle facility, and studies have concluded that a dedicated bicycle facility is recommended when vehicular speeds are above 30km/h (L. B. Meuleners et al., 2019).

Figure 2.1: Satellite view of Meerzichtlaan, Zoetermeer, where the two-way bicycle facility is clearly present from the pavement markings. Note how the bicycle facilities have a bent shape that provides more buffer width between the bicycle facility and the vehicular lanes. The grey pavement on the left side of the roundabout is a driveway and not a road. Image courtesy of Google Earth

A bicycle facility within a roundabout is an important design characteristic that can significantly reduce the number of bicycle-motorist interactions and conflicts (Macioszek et al., 2010). Many studies have looked at various bicycle treatments within roundabouts, ranging from no facility, bicycle sharrows, a bicycle lane in the middle of the vehicular lane, a bicycle lane on the outer perimeter of the roundabout, and a separate bicycle facility (see Figure 2.1) (S. U. Jensen, 2017; Sakshaug et al., 2010; Møller and Hels, 2008; Poudel and Singleton, 2022; Cantisani et al., 2021). L. Meuleners et al. (2023) performed a bicycle simulator study of one roundabout with and without bicycle sharrows in an attempt to see if bicyclists would situate themselves in the middle of the roundabout or remain on the edges, but the study was inconclusive. As bicycle volumes increase above 270 bicycles per hour, the presence of a separated bicycle facility results in a significant decrease in severe conflicts (Bahmankhah et al., 2019), highlighting the importance of this design feature at roundabouts.

Roundabouts with a dedicated bicycle facility incorporate various design characteristics as well, such as bi-directional cycle paths, bicycle crossings at only some of the vehicle streets, bent or circular shaped bicycle paths, various bicycle path widths, and bicycles having to yield to motorists (relevant

CROW guidance will be discussed in detail in Section 2.2). Some of these designs allow bicycles to have a more direct path of travel, with one study in Sweden finding that 38% of bicyclists travel in a clockwise direction, against the vehicular circulating direction (Sakshaug et al., 2010). In Sweden, both bicyclists and motorists must yield even when shark teeth yield markings are present. That same study noted that when there are no clear traffic rules pertaining to yielding priority, confusion and conflicts can occur. Another study used a Multi Criteria Analysis (MCA) to study three different intersection types and also concluded that ”something which clearly showed with the roundabout, is the influence of bicyclists driving against the regular driving direction. Car drivers did not always notice these bicyclists, which led to a conflict. The fact that this showed most at the roundabout, was because the bicyclist had priority here” (van der Leeden, 2012).

Figure 2.2: Satellite view of Kralingseweg and Plaszoom intersection, Rotterdam. The notable features of this roundabout are that there is no bicycle crossing on the south side or a bicycle path on the south side of the Kralingseweg approaching the roundabout on either side (the two-way bicycle path on the north side serves both directions. Attention is due at the shape of the bicycle facility around this roundabout, as one can see the bent path shape clearly in the NW corner whilst the three other corners resemble the circular shape (closely following the shape of the vehicular lane). Another thing to note is that two-way bicycle facility connection on the NE corner which is the main bicycle path crossing Kralingse Bos. Image courtesy of Google Earth

Clarity and consistency in roundabout characteristics is important. A SWOV (Foundation for Scientific Research on Road Safety) study found that certain design features, such as a circular versus a bent bicycle path (see Figure 2.2), may not be give clear indication of which mode (i.e. motor vehicle or bicycle) has yielding priority (CROW–Kennisbank, 2014b). It is important to note that different countries have different design and cultural preferences (Poudel and Singleton, 2021).

In 2012, a new innovative roundabout, called the bicycle roundabout, was created in the city of Zwolle. Its novelty was being the first roundabout in the Netherlands to allow bicyclists to turn in every direction while restricting car movements (Bruno, 2022). It has since been repeated in at least 7 other cities. A study in 2022 determined that the following geometric factors are critical to its success as an intersection treatment: speed of vehicles and bicyclists, clear consistent network markings such as shark teeth and bicycle yielding priority, and bicyclist visibility (ARUP, 2022). An interesting recommendation is to slow down the speed of bicyclists through a slight uphill grade and small entrance curve radii at the approaches to the roundabout. There are two main types of the bicycle roundabout, which are shown in Figure 2.3.

(a) Vondelkade/Wipstrikkerallee, Zwolle. Image courtesy of Google Earth.

(b) Herenstraat/Koninginnelaan, Lieden. Image courtesy of CROW.

Figure 2.3: Aerial photos of both types of bicycle roundabouts, that restrict automobile movements but allow for bicycle accessibility. Note that they both have a circular shape to the bicycle facility but the buffer width is very different.

2.1.1. Conclusion and identified gaps

This review underscores the critical influence of roundabout design on the safety and interaction of bicyclists and vehicles. There are many different design characteristics to consider when building a roundabout and engineers and designers may choose based on their expertise and local knowledge of the traffic network. However, encountering two roundabouts quickly in time but that vary greatly in design characteristics such as speed limit, yielding priority, bicycle facility, etc can cause confusion to motorists and bicyclists. The variance in findings across different studies emphasizes the need for a more in-depth analysis of the various design factors that affect interactions between bicyclists and motorists which impact safety. There have been many studies in Denmark and the USA but they have unique regulatory aspects and there are fewer roundabouts with dedicated bicycle facilities. Many studies that analysed different roundabout characteristics, did so in one city or region and often did not differentiate between urban and rural areas. Therefore there is a research gap of Dutch studies analyzing urban roundabout design characteristics found commonly in the Netherlands but rarely in other countries.

2.2. CROW roundabout guidelines

CROW is an organization that develops guidelines, training, and practical tools for infrastructure, public urban spaces, traffic, public transport, and bicycle infrastructure in the Netherlands (CROW–Kennisbank, 2020). Over the years, various publications have been made pertaining to different design guidance for intersections, with a particular focus on roundabouts.

The bicycle publications pertaining to roundabouts exist in multiple sources (CROW–Kennisbank, 2014a; CROW–Kennisbank, 2014b; CROW–Kennisbank, 2014c). Most of them are in the ”rotonde” or roundabout section of the Kennisbank. Within that chapter, sections 3.6, 4.1, and all of 6 contain design guidance for general safety as well as indications for yielding priority, design speed and curb radii calculations, object visibility along the edges and in the center of the roundabout, traffic delay based on traffic volumes and bicycle crossing speeds, capacity calculations, and more (CROW–Kennisbank, 2014c).

Certain design guidelines leave no room for ambiguity, such as Section 6.3.1 that dictates what signage and markings should be placed at a roundabout depending on where the roundabout is located (urban vs rural) and who has yielding priority (bicyclists vs motorists). An image of a roundabout is shown in Figure 2.4 with the required signage for a portion of a bi-directional bicycle path. The CROW design guidelines also dictate certain road markings, such as the following quote: ”At a roundabout with a separate bicycle path with no bicycle yielding priority (and the distance between the traffic lane of the roundabout and the cycle crossing is 10.00 m), channelization stripes must be applied to the roadway at the crossing.” (CROW–Kennisbank, 2014c).

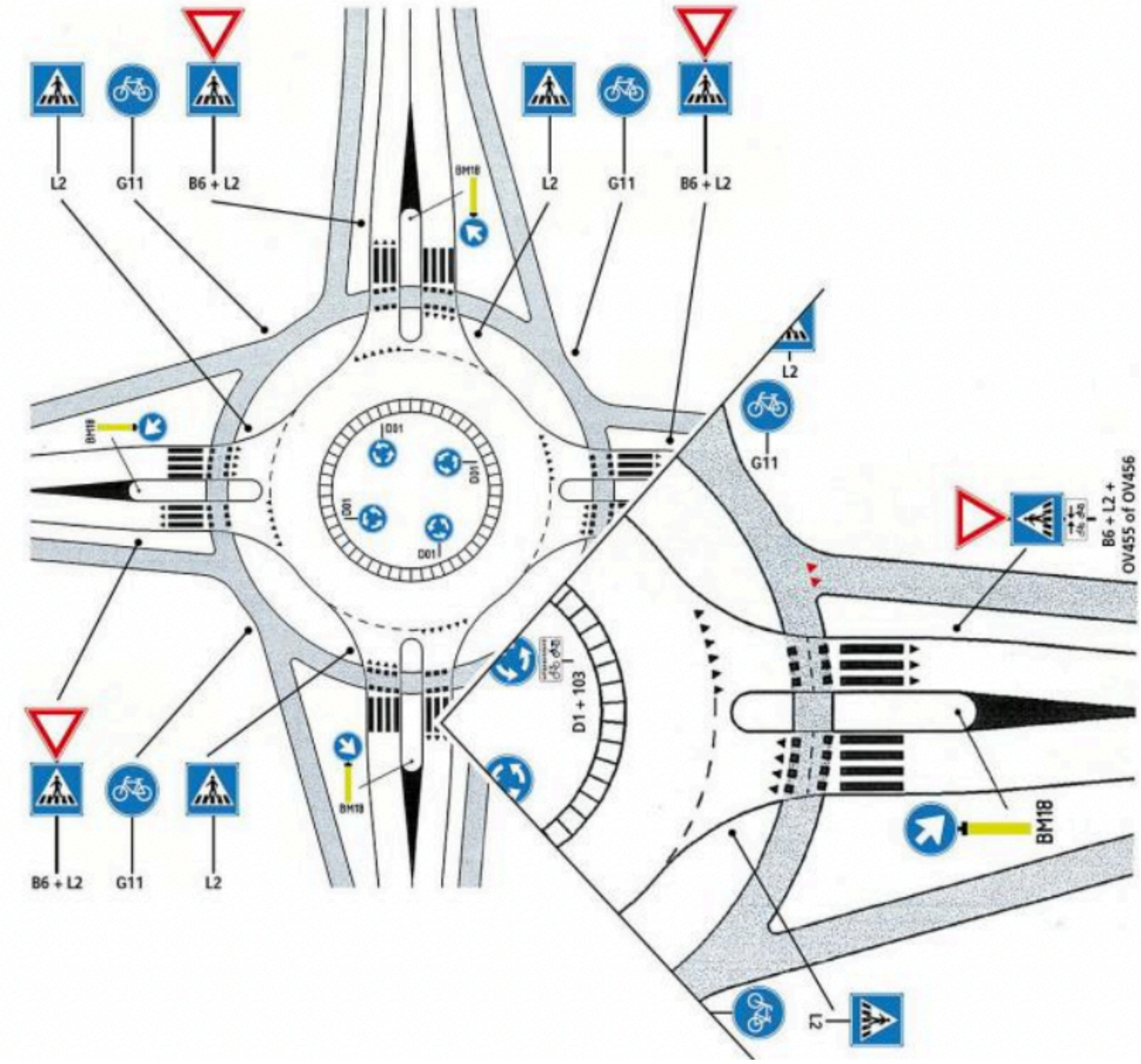


Figure 2.4: Signage diagram for roundabout with yield priority for bicycles. Image courtesy of CROW

However, the design guidance makes an exception later in this same section, when it states that if there is a pedestrian crossing on the same road, it is recommended that bicyclists have yielding priority, even when the distance between the traffic lane of the roundabout and the cycle crossing is more than 10 meters. In terms of analysing who has right-of-way, a study performed by TNO Technical Human Engineering in 2014 found that traffic signs and the shark teeth paint markings are the only major design factors that dictate yielding (CROW–Kennisbank, 2014b). However, this study only looked at the color of the bicycle facility, whether the roundabout location was rural or urban, and the design of the shoulder. It is unknown also how many respondents they got and how many different case studies they chose to examine. In the urban area of Tilburg, 32 roundabouts are in the process of being converted give yielding priority to bicyclists after the municipal government performed research on crash patterns, traffic congestion, and psychological factors. Despite the research findings that roundabouts giving priority to bicycles are four times as likely to have bicycle crashes than those that give priority to cars, a political decision was made to proceed with the priority conversion anyway (CROW, 2021).

Other sections, such as Section 6.3.2 (Decoration), leave more room for designer freedom, only dictating that there be a high opacity on the objects placed in the center island and that the island is at least 1.10m tall (CROW–Kennisbank, 2014c). Section 6.1 on safety recommends that separate bicycle facilities be provided at roundabouts with over 6000 vehicles per day and that roundabouts with a bicycle lane should be discouraged. Another example is that only a minimum width is indicated for a median island between vehicle lanes at a pedestrian/bicycle crossing, which allows designers and traffic engineers the flexibility to adjust their roundabout design as needed for geographical and site condition reasons. Lastly, in Section 6.4.2, Dimensioning bicycle facilities, there is simply an acknowledgement that bi-directional bicycle facilities at roundabouts require additional consideration and ”extra attention from the designer” (CROW–Kennisbank, 2014c).

More recently, there has been renewed interest in an update to the CROW design guidelines for bicycles within roundabouts, particularly due to changing bicycle types, the introduction of the bicycle roundabout, and the ongoing discussion about bicycle yielding priority (CROW, 2024c). This has led to the current workshops that are being held at CROW regarding a new guideline called: ”everything about roundabouts”, which will consolidate all the other guidelines that mention roundabouts and also include new, updated information. More information about these workshops can be found in Chapter 5 and Appendix B.1. A study performed for CROW in 2019, analysed the risk factors for bicyclists at roundabouts. The study by CROW (2019b) performed a multivariate regression analysis using bicycle crossing points and 31 other design features. They found that out of the 2448 urban roundabouts with a separate bicycle facility, 54% of them have bi-directional bicycle paths on all or a portion of the roundabout and that those had a lower accident rate than roundabouts with only one-way direction. The study also performed a small in-depth analysis of 93 roundabouts and found that the inscribed radius was a significant design characteristic that lowered bicycle crashes whilst the width (buffer space) between the motorist and the bicycle facility (CROW guideline is 5 to 6 meters maximum) was a significant design characteristic that increased bicycle crashes. This study has led to the release of a design guideline in January 2024 for the bicycle roundabout (CROW, 2024b) and a recent article on visibility issues within the buffer space that may contribute to crashes (CROW, 2024a). This article mentions how the local government has tried to solve visibility issues at Hugo de Grootplein roundabout in Amsterdam by using different colored pavers and banning bicycle parking.

2.2.1. Conclusion and identified gaps

As this section explained, the CROW design guidelines change as new regulations are adopted, travel behaviours evolve, and research is performed. Many roundabouts predate the 2014 update of the CROW design guidelines and thus contradict the recommended 5 meter distance between the bicycle crossing and the vehicle entrance/exit of the roundabout. In addition, there is ambiguity regarding which mode (bicycle or motor vehicle) should have yielding priority in between the 5 meter and 10 meter values. The only recent yielding priority study performed by DTV consultants for CROW did not look at the subjective safety from the point of view of bicyclists. The CROW design guidelines are written in such a way that designers, local and provincial government staff, and engineers can interpret a lot of the design guidance to suit their particular project needs. Also, there is always a possibility to deviate from the guidelines so long as there is a strong justification. There is no evidence in the CROW design guidelines that safety perceptions of bicyclists need to be taken into consideration when justifying a deviation. This leads to the same conclusion as Section 2.1: there is a lot of variability, in particular with regards to bi-directional bicycle facilities and yield priority, at Dutch urban roundabouts which are discussed in an ambiguous fashion within the CROW design guidelines.

2.3. Safety issues and crashes at roundabouts

Whilst there are a lot of studies that report that converting a regular signalized intersection to a roundabout lowers motor vehicle crashes, there are many studies that have found that bicyclist crashes do not decline and may even increase by as much as 65% (S. Jensen, 2013; Zhang and Ma, 2015; Thomas et al., 2016; Daniels et al., 2008; Pulvirenti et al., 2021; Poudel and Singleton, 2021; Cantisani et al., 2021). A study from western Australia looked at 400 sites and found that roundabouts and signalized intersections significantly increase the risk of bicycle crashes compared with priority intersections (L. B. Meuleners et al., 2019); however the study also found that half of the crashes at roundabouts did not involve a motor vehicle. This leads one to believe that signage, slope, and other site conditions contributed to crashes. As for painted bicycle lanes, their data found that there was not a significant difference between control sites and crash sites. This section will go into more detail on various aspects of roundabouts and their impacts on safety.

Design and driver behaviour

An Italian study performed a stated choice survey and used a correspondence analysis to look at driver behaviour and geometric characteristics of roundabouts (Distefano et al., 2019). Unsurprisingly, the more aggressive a driver, the more they preferred a roundabout design that has less vehicle deflection, thus allowing for higher speeds in both approaching and driving through the roundabout. If roundabouts have a small diameter, then vehicles don't have a strong deflection angle, which can lead to higher speeds. That means longer stopping sight distances are needed in order for vehicles to properly yield to bicyclists or pedestrians at their crossing point (Zhang and Ma, 2015). This highlights the need for design considerations that inherently slow down vehicles and make aggressive driving less appealing or feasible. A study from the USA (Thomas et al., 2016), interviewed and compiled treatments, designs, and policies from 11 different countries and concluded that the safest design, assuming bicyclists do not have their own facility, was a lower-speed multi-lane roundabout, with approaches that maximized vehicular deflection. However, a detailed safety analysis was not performed as that paper only did qualitative research. Another study, performed a year later on single-lane roundabouts, concluded that roundabouts with central island diameters between 20 and 40 meters which are elevated by at least 2 meters are safer for bicyclists (S. U. Jensen, 2017) as they provide enough deflection angle to force drivers to slow down and focus on the vulnerable road users in their immediate vicinity.

Visibility and speed control

Even if speed is reduced to 30km/h, visibility remains an issue at roundabouts, particularly ones that have bi-directional bicycle facilities since motorists are more accustomed to looking to the left when entering a roundabout and have to look for bicyclists, pedestrians, and motor vehicles before successfully entering the roundabout (Pulvirenti et al., 2021). The study by Pulvirenti et al. (2021) revealed that there are frequent interactions between vehicles and bicycles in large and small diameter roundabouts, with many interactions occurring as the bicyclist enters the roundabout. The study used surrogate safety indicators based on past research but used limited data (only 32 hours of video for each of the four roundabouts). A research report done as part of a NCHRP report in the USA, concluded from behavioural observation that exit approaches and their associated sightlines and vehicle speeds were a source of conflict for bicyclists (Harkey and Carter, 2006). However, this study was done at a limited number of roundabouts. The study by González-Gómez and Castro (2020) on approach visibility reinforces the critical balance between visibility and speed control for enhancing yielding behaviours and reducing Safe Stopping Distance (SSD) at roundabouts. This finding is echoed in the work of Cantisani et al. (2021), which demonstrated the importance of dedicated separated bicycle infrastructure within roundabouts in reducing crash risk. These studies highlight the necessity of careful infrastructure design to manage vehicle speeds and enhance visibility for all roundabout users.

Infrastructure and crash risk

An Italian study used a Poisson's law probabilistic model on a roundabout in order to test various traffic volume and design configurations in order to lower the risk of conflicts. Cantisani et al. (2021) found that having dedicated separated bicycle infrastructure within the roundabout itself reduces the risk of bicycle-vehicle crashes. The limitations of this study are that it only considered a uni-directional (counter-clockwise) motion of bicyclists, typical roundabouts with only 4 legs, and it only performed small modifications of bicycle volumes (10% and 30% more than the initial option). However, this Italian research performed an investigation into the physical distance between the bicycle path portion and the vehicle portion of the roundabout, finding that too little a distance of separation (a 4 meter reduction, compared with the base roundabout layout) increases the probability of bicyclist crashes. The opposite was found to be true in a recent Dutch study, with a determination that too great distance of separation (more than 6 meters) increases chances of bicyclist crashes (CROW, 2019a). These insights stress the importance of tailoring infrastructure design to specific urban contexts in order to optimize safety. A more recent study performed in the city of Haarlem found ”unexpected high bicycle crash risk for roundabouts” (van Bentem, 2022). This study followed a safety performance functions analysis approach, as opposed to a more qualitative approach, in line with Sustainability Safety principles and the Strategic Road Safety Plan adopted in the Netherlands (van Bentem, 2022). Another shortcoming of this research was that there were few roundabouts with crash data reported in Haarlem. A similar study in Canada also found an increase in bicycle crashes at the entrance/exit points of a roundabout after the conversion of the intersection from a signalized one (Dabbour and Easa, 2008). Their model used a signalized bicycle path crossing and looked at various bicycle path configurations around the vehicular roundabout.

Priority rules and yielding behaviour

The entrances and exits of roundabouts have been found to be areas with high conflict potential due to motorists and bicyclists yielding and making directional decisions (Pulvirenti et al., 2021). The analysis by CROW (2019a) regarding priority rules at roundabouts reveals a significant influence on crash rates. This theory is supported by a Danish study, which found an increase in bicycle crashes following the conversion of intersections into roundabouts, particularly when bicycle priority was not clearly defined (S. Jensen, 2013). These studies underscore the critical role of clear priority rules in minimizing conflicts and enhancing safety for bicyclists at roundabouts. A Dutch analysis compared roundabouts, pleintjes (bow-legged intersections), and priority intersections. The study used a MCA based on 6 criterion to and determine the 'safest' type of intersection but was hindered due to lack of observation points (only two examples per intersection type) (van der Leeden, 2012). A key observation was that when bicyclists rode in the wrong direction with regards to the motor vehicle traffic (i.e. clockwise), conflicts would arise. Yielding priority is key in any future research topic related to the safety of bicyclists at roundabouts. A study performed by Rijkswaterstaat found that roundabouts where bicyclists did not have priority had significantly lower crashes (0.18 vs 0.73 crashes per roundabout) between 2015 and 2018 (CROW, 2019a). This was also the conclusion of another study in Denmark that had 180 participants (S. Jensen, 2013). However, there are many Dutch roundabouts that give yielding priority to bicyclists and CROW guidance recommends this for urban areas (CROW–Kennisbank, 2014c). A Swedish study used video detection coupled with quantitative and qualitative methods in order to analyse vehicle-bicycle conflicts in one roundabout with and one without dedicated bicycle paths (Sakshaug et al., 2010). Despite a small sample size (only two roundabouts in the town of Lund, Sweden), they concluded that a roundabout with dedicated bicycle paths had less conflicts but that it caused ambiguous yielding behaviours, both for bicyclists and motorists. Their research acknowledged that a more detailed study on the exiting behaviour of motorists and bicyclists or the clockwise movement of bicycle traffic could be done.

2.3.1. Conclusion and identified gaps

Past studies have concluded that both motor vehicle and bicycle speed contribute to bicycle related injuries and crashes at roundabouts. The design of a roundabout, particularly characteristics such as center island diameter, shrubs and bushes that block visibility, buffer space between bicycles and cars, and inscribed radius, all have varying degrees of influence on the number and severity of roundabout crashes. Other factors, such as weather and motor vehicle volumes, also have an effect but they are less significant. Studies could not find conclusive results regarding bi-directional versus uni-directional bicycle paths and reports contradicted each other about which transport mode should have yielding priority.

2.4. Perceptions of bicyclists

Safety, convenience, and the existence of proper facilities are key to improving people's perceptions on biking (Fernández-Heredia et al., 2014). That study used a Structural Equation Model (SEM) to analyse survey results from Madrid residents to explore factors promoting bicycle use, including safety perceptions. Actual traffic safety issues, such as a high incidence of left hook crashes, are not necessarily how bicyclists perceive safety issues (Kummeneje et al., 2019). The study by Richard Mantona et al. (2016) used mental mapping with a Generalised Linear Mixed Model (GLMM) statistical analysis and found similarities between perceived and real traffic risks for bicyclists at roundabouts. Significant variables included: segregated bicycle infrastructure, road width, vehicle volumes, past bicycling experience, and gender. Visibility is another important factor that affects safety perceptions of bicyclists. Dozza and Werneke (2014) analysed factors that influence bicyclists' safety and found that bicycling near an intersection represented a risk 4 times higher than normal, whilst bicycling at a partially obstructed intersection (due to hedges or buildings) represented a 12 fold risk increase. Visibility can be closely linked to yielding behaviour as was found in Sections 2.1 and 2.3 above. A risk analysis undertaken in Denmark concluded that there is a general lack of knowledge regarding yielding behaviour, which can lower the operational performance (e.g. amount of vehicles and bicyclists that go through per hour) of the roundabout and also lead to crashes (Møller and Hels, 2008).

A bicyclist's history and related experiences impact their view of perceptions of risk and safety. Sanders (2015) performed a dis-aggregated risk behavioural study for potential and current bicyclists to better understand what prevents more people from bicycling. They found that bicycling frequency and witnessing ”near misses” caused a heightened awareness of traffic risk. Another study interviewed Italian bicyclists regarding their perception of risk and control during ”near misses” and concluded via a path analysis using Bayesian estimation that confidence and perceived control had a positive indirect effect on bicycle use (Marín Puchades et al., 2018).

Unlike the Netherlands, unfamiliarity with roundabouts and how to navigate them in the United Kingdom, Germany, and the United States of America has led to perceptions of higher risk from bicyclists and potential bicyclists (Friel et al., 2023). Studies that compared roundabouts with other intersection types, concluded that many potential bicyclists prefer a signalized intersection with separate bicycle facilities (Friel et al., 2023), or even being directed to the sidewalk (Poudel and Singleton, 2023). As bicyclists in the Netherlands continue to get older, they are bicycling longer distances, which can lead to situations where they become mentally fatigued (Schepers et al., 2017). A recent study used Virtual Reality (VR) to test how young bicyclists performed under complex traffic situations, particularly when they were mentally fatigued; they fared worse and had slower reaction times when mentally fatigued and confronted with complex traffic situations (Zeuwts et al., 2021). It thus can be reasoned that older populations may also suffer from lapses in judgement due to mental fatigue and will need changes in bicycle infrastructure to make bicycling less risky (Schepers et al., 2017). Certain roundabout features have been studied using stated preference (SP) surveys (S. Jensen, 2012; Poudel and Singleton, 2023; Distefano et al., 2019). The results found that bicyclists prefer single lane, lower traffic volume roundabouts that have large central islands (thus more deflection and lower traffic speeds) rather than roundabouts with separate bicycle facilities (Poudel and Singleton, 2023). This study also found that there is a preference for protected bicycle facilities as traffic volumes increase, but that bicycle crossings posed perceived risks (which ranked as ”least comfortable” by the study). Another recent study by the same researchers performed a SP survey on US bicyclists regarding their perceptions of roundabout safety. The panel mixed Multinomial Logit (ML) model produced results that showed that separated, continuous bicycle facilities, lower traffic speeds, fewer travel lanes, and lower traffic volumes are preferred, however, they did not specifically analyse crash data, crash risk, and behavioural effects when there are higher bicycle/pedestrian volumes, specific turning movements through the roundabout, adjacent land uses, and weather conditions (Poudel and Singleton, 2022).

When performing a subjective safety study, bias can lead to underestimation of actual risk. As mentioned in Chapter 1, even though the majority of bicycle crashes do not involve motor vehicles, safety perceptions of bicyclists are that crashes occur due to the presence of a motor vehicle (Han, 2023). In order to reduce survey respondent interpretation bias, clear definitions must be made as is the case for comfort level. S. Jensen (2012) used the Highway Capacity Manual level of service (LOS) designations of A through F and aligned them with a 6 point Likert scale by defining LOS A if 50% or more of responses were 'very satisfied', LOS B if 50% or more were 'very or moderately satisfied' but less than 50% were 'very satisfied', and so forth. Another study found that comfort for bicyclists was related to surface quality, alignment changes that caused them to deviate away from their intended direction of travel, and complexity of turning maneuvers but it was noted that more research on these design features was needed (Friel et al., 2023). Poudel and Singleton (2022) stated that respondents' preferences between two different roundabouts (with varying characteristics) are motivated by their perceptions of comfort and safety. Further research done by the same authors in the USA, assert the assumption that comfort levels reflect safety concerns experienced by bicyclists (Poudel & Singleton, 2023). The study further defined bicycling comfort by asking respondents their overall comfort level and situational comfort levels in 5 situations (entering, circulating within the roundabout, exiting, on the sidewalk, and in the crosswalk) using a 4 point Likert scale.

Various models have been used to study bicyclists' perceptions of safety, including a perceived bicycling intersection safety model (PBIS) that looks at a range of intersection features and their effect on safety perceptions whilst controlling for socio-demographics and bicycling experience level (Wang and Akar, 2018). Most other models used either a SEM type model (Distefano et al., 2019; Fernández-Heredia et al., 2014; Kummeneje et al., 2019; Poudel and Singleton, 2023), or a form of regression analysis (S. Jensen, 2012; Aldreda and Goodman, 2018; Møller and Hels, 2008; Richard Mantona et al., 2016; Wang and Akar, 2018; Zeuwts et al., 2021; Fernández-Heredia et al., 2014; Aldreda and Goodman, 2018; Sanders, 2015) to see if there are significant correlations between variables and certain categories of variables. Amongst the studies that used regression analysis, Fernández-Heredia et al. (2014) and Møller and Hels (2008) performed a multiple hierarchical linear regression, allowing them to look at multiple dependent variables whilst eliminating non-significant variables. Aldreda and Goodman (2018) assumed a Poisson distribution in their linear regression analysis of bicyclists' interpretations of "near misses" by means of a travel diary. Sanders (2015) used the Univariate Analysis of Variance (ANOVA) form of linear regression to analyse perceived traffic risk but did not include predictor variables such as bicycle volumes. Amongst the studies that used regression analysis, three studies used a form of logit or probit regression (ordered probit regression (Poudel and Singleton, 2023), cumulative logit (S. Jensen, 2012), and non-linear least squares (John Parkin et al., 2007)). Only a few studies performed a multinomial logit model (MNL) or a Latent class cluster model (LCCM) (Poudel and Singleton, 2022; Vos et al., 2021; Wang and Akar, 2018; John Parkin et al., 2007), which allows for simultaneous comparisons by considering a heterogeneous respondent group and alternative decision rules. No study was found to have performed a multivariate ordered probit regression on bicyclists' subjective safety and comfort levels.

2.4.1. Conclusion and identified gaps

This section provides a comprehensive understanding of the factors that influence safety perceptions and causes problems and crashes at roundabouts. It highlights the impact of design on perceived safety among bicyclists and whether it correlates with actual safety outcomes. Some studies found that high speed situations have a higher perception of danger, which correlates with a higher crash risk and risk of severe or fatal injury. Further research on bicyclists' perceptions of safety from a Dutch perspective is needed (given their exposure to roundabouts) and it should include some of the similar attributes that have been studied in other countries in the past, in particular crash history, bicycling experience, bicycling frequency, turning movements within roundabouts, and visibility issues.

2.5. Conclusions from literature and research gaps

This literature review serves to acquaint oneself with the present design guidelines and characteristics of roundabouts, and how the present-day mix of roundabout configurations in the Netherlands and abroad poses challenges to subjective and objective safety for bicyclists. This study should expand upon the analysis performed by the Rijkswaterstraat and CROW (CROW, 2019b) and should target the research gaps identified. This can be done by looking at the subjective safety of certain roundabout features, such as the buffer width distance between vehicles and bicyclists, the uni-directional vs bi-directional aspect of the bicycle path, or the yielding priority for bicycles. In order to look at subjective safety of these specific roundabout parameters, behavioural data will be collected via observations and an advanced logit model will be used, asking members of the general public about their stated preferences regarding what their perceived comfort and safety levels are at multiple roundabouts. The link between perceived safety and objective safety is ambiguous, with many studies only focusing on just one form or the other (Poudel and Singleton, 2023; S. Jensen, 2012; Sanders, 2015). In addition, LOS is an outdated form of measuring congestion, delay, or satisfaction and is no longer being used in many transport studies.

Overall, there have only been approximately 50 prior scientific research reports on roundabouts and many of them compare roundabouts with other intersection types. These studies use various methods, depending on whether they are focused on subjective or objective safety. Subjective safety studies using advanced discrete choice theory have only been used in the past 10 years and not many of them have been dedicated to researching roundabout characteristics. The underlying issue in many of the studies mentioned above is that the data available or collected only pertains to that location or country; there can not be a transfer of information as the crash data and design standards vary from country to country. In addition, there were other research gaps of note:

- No study has looked at bicyclists' perceptions of safety and comfort in the same model.
- Whilst several studies did SP models (logit models), few focused on the clockwise direction of bicyclists (i.e. bicyclists travelling in the opposite direction through the roundabout compared to motor vehicle traffic) and turning movements.
- No study looked at turning movements at roundabouts (signalized intersections have been evaluated with regards to how bicyclists make turning movements [i.e. via pedestrian crosswalk, in vehicle lane, etc]).
- Some studies concluded that visual obstructions increase safety risk for bicyclists but others concluded that visual obstructions generate lower speeds and increased alertness for vehicle drivers.
- No studies have done a discrete choice model looking at bicyclists' comfort levels at Dutch roundabouts.
- The 2019 CROW study on roundabouts only compared geometric features and crash reports, not perceptions of safety.
- Studies that have included Dutch roundabouts have focused on all intersections and not solely on roundabouts.
- Bent-shaped roundabouts where bicyclists can travel in a clockwise direction have not been studied very often.
- There is little homogeneity in roundabout designs, which can cause confusion and conflicts.
- There is a lot of ambiguity regarding yielding priority within the 5 to 10 meter distance space between the bicycle crossing and the vehicle entrance/exit of the roundabout.
- Little temporal differentiation (rush hour vs non-peak) was done. This is most likely due to the limited crash data available which meant that a large time period was required in order to correctly perform a crash/risk analysis and subsequent models.

For these reasons, it was decided to use an ordered probit model to evaluate Dutch bicyclists' perceptions of safety and comfort at urban roundabouts with various bicycle facility features, such as buffer width, bicycle path shape, and yielding priority. This paper can recommend design factors most appreciated by bicyclists to aid Dutch governments and CROW in providing updated design guidance.

3 Conceptual model

This chapter expands upon the literature review by developing the main research question, sub-questions, and subsequent hypotheses, which can then be answered by creating study variables and placing them into a conceptual framework. This chapter explains how the variables are refined, with some being removed and others being combined in order to properly address the goals of this research.

3.1. Research question and sub-questions

Based on prior Chapters, this report will address the research objectives and goals by answering the following main research question:

What factors contribute to bicyclists' perceptions of safety at roundabouts?

The main research question is jointly answered by the following sub-questions:

1. What bicycle infrastructure design and behavioural factors at urban roundabouts in the Netherlands affect bicyclists' perceptions of safety and comfort?
2. What bicycle infrastructure design and behavioural factors affect bicyclists' compliance with traffic laws?
3. How do different bicyclist groups perceive the safety of roundabouts?
4. Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?
5. What type of correlation is there between a bicyclist's perceived risk level versus actual crashes at roundabouts?

Perceptions of safety are based on various factors, including physical infrastructure, traffic volumes, and a person's stress levels, comfort, and past experiences. Many studies found that a bicyclist who has experienced a conflict or crash, has a more heightened perception of risk and safety (Bösehans and Massola, 2018; Poudel and Singleton, 2022; van der Leeden, 2012; Poudel and Singleton, 2023). This study aims to gain insights into how roundabout design features influence bicyclists' perceptions of safety and comfort. Thus two dimensions were considered: design effects/features of roundabouts and individual safety/risk perceptions. It is expected that there are various latent people groups that are internally homogeneous but that may have different opinions. For example, there may be 'avid lovers' of bi-directional bicycle paths at roundabouts who only see benefits with that design, whilst 'interested but concerned' bicyclists may see several safety issues with that design. Identifying these groups and their socio-demographic profiles, is relevant when designing roundabouts for all potential and current bicyclists. Given that CROW design guidelines leave room for implementation interpretation, such as with the buffer width between motorists and bicyclists, this research will make recommendations for updating the guidelines to fit the preferences of bicyclists, many of whom are aging (Wegman and

Schepers, 2024). This research defines the measurement of a bicyclist's comfort level as overall level of ease as one cycles around a roundabout and perception of safety as one's sense of risk whilst bicycling around a roundabout.

3.2. Research hypotheses

Building on the literature review discussed in Chapter 2, main research question, and sub-questions mentioned above, several hypotheses can be put forward pertaining to bicyclists' perceived safety that can subsequently be placed into a conceptual model and be used to generate attributes and their respective levels:

1. Bicyclists who have recently experienced a crash or "near miss", will perceive a higher risk at a roundabout, regardless of the design features.
2. Higher traffic volumes lead to higher perceived risk by bicyclists.
3. Less experienced bicyclists have a higher perceived risk at roundabouts.
4. Yielding priority for cars does not increase bicyclists' perceived risk.
5. A buffer distance of four to five meters decreases perceived risk at roundabouts.
6. Bi-directional bicycle paths do not increase bicyclists' perceived risk.
7. Females and elderly bicyclists will have a higher perception of risk.
8. A bicyclist's perceptions of safety and comfort are highly correlated.

3.3. Conceptual model and attribute table

Taking the hypotheses mentioned above, this report developed a conceptual framework. Figure 3.1 illustrates this conceptual framework, describing the relationship between urban roundabout infrastructure design features, bicycle types, individual factors, bicyclists' comfort using a roundabout, and bicyclists' perceived safety at roundabouts. Note that this Figure shows only the factors that were studied in the stated choice survey and analysed in the model results.

What is unique about this conceptual framework is the use of a group of "Cyclist behaviours" variables, measured from 12 independent variables modified from the Useche et al. (2018) study that used 29 independent variables, called the cyclist behavioural questionnaire (CBQ). These "bicyclist behaviours" variables are hypothesised to have a direct effect on the comfort and safety perception latent variables: if a bicyclist takes more risks under various typical situations encountered whilst bicycling, they are likely to have a higher tolerance for what is considered an unsafe situation. More information about how the 12 variables were selected and the CBQ in general is located in Section 4.4 and Appendix D.2. Note that as there have yet to be any studies looking at the correlation between comfort and perceptions of safety of bicyclists, this research is setting a precedent by looking at both latent variables within one dataset.

By controlling certain factors and eliminating variables that are too difficult to measure, this report will only look at certain factors, as shown in Figure 3.1 and elaborated more in Appendix D.2. There are several key factors that were excluded from this research:

- The removal of a mental fatigue independent variable due to the complexity in properly measuring it without performing a more in-depth simulator or eye-monitoring study (Zeuwts et al., 2021; Richard Mantona et al., 2016; Wegman and Schepers, 2024).
- The removal of all external factor variables such as time of day, weather, construction, adjacent land use, and knowledge of traffic regulations.
- Lane markings and signage were removed since the roundabouts all have consistent markings to delineate yielding priority as required by the CROW design guidelines.

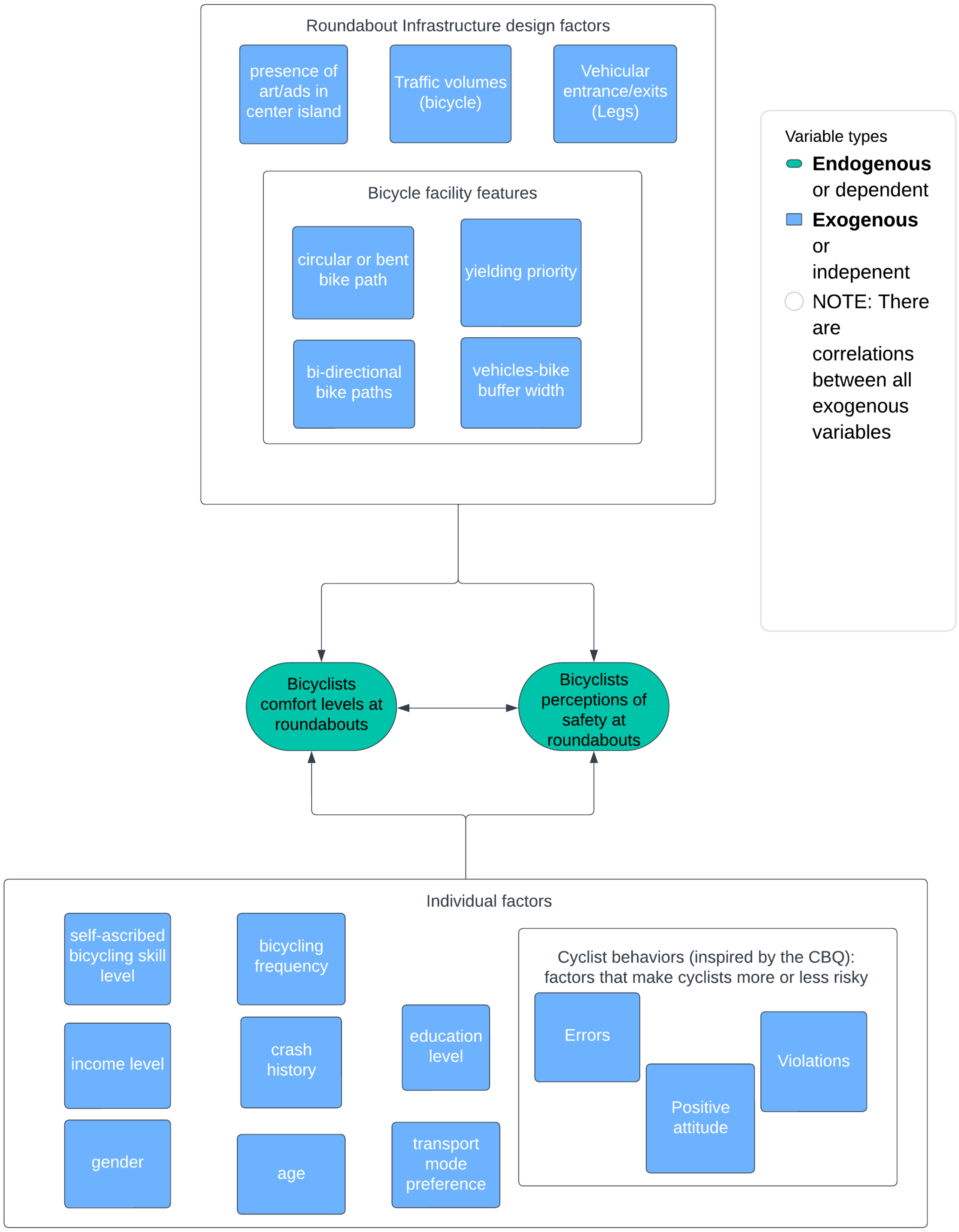


Figure 3.1: Final conceptual model showing the two dependent variables in green and measured independent variables in blue. Model created via Lucid.

- Due to the limited existence of urban Dutch roundabouts that have no bicycle facility at all, this research decided to focus solely on roundabouts with bicycle facilities.
- The vehicle speed variable was removed since it would be hard to convey that information to participants via an online survey and because the prevailing speed at single lane urban roundabouts is below 30km/h. In addition, past research has confirmed that the center island size increases

the deflection angle, which decreases vehicle speeds, and thus decreases perception of risk (van der Leeden, 2012; Richard Mantona et al., 2016; Poudel and Singleton, 2023).

- The roundabout visibility independent variable was removed as it is subjective to each respondent as to how bush height or tree canopy coverage can affect visibility. In addition, the eye levels of bicyclists and motorists vary, depending upon motor vehicle type and individual physical height.
- The public transport presence independent variable was removed as it adds complexity to the roundabout. This is because public transport normally has priority over all other modes.

Based on the conceptual model, the attributes and their respective levels can be described in more detail, following the use of an orthogonal fractional factorial design for a stated choice experiment (for more information, refer to Section 4.4 or Appendices B and D).

Table 3.1: Model attributes and levels/categories of the indicators

Label	Variable	Definition	Categories
Buffer	Buffer width between vehicles and bicycles	This space is critical for clear separation of modes and allows for reaction time for yielding behaviour	0-5.07, 5.07-11.92 meters
Yield	Yielding priority for bicycles	Roundabouts with yielding priority for bicycles are more common in urban areas and where the separation between cars and bicycles is ≤ 10 meters	No, Yes
Art	Presence of art in the center island	The center island features can help focus drivers on the immediate approach in front of them but also could add distractions	No, Yes
Direction	Is the bicycle path uni-directional?	Roundabouts can have bicycle paths that are partially bi-directional on certain legs or all around the circle. This adds complexity but allows for better accessibility and route choice for the bicyclists	No/hybrid, Yes
Flow	Bicycle volumes	This criteria relates to roundabouts that have bicycle volumes above or below 480 bicycles per hour (PM peak hour)	Below 480, Above 480
Shape	Bicycle path shape	Separated bicycle facilities come in two different shapes: circular (mimicking the vehicular lane) and bent (resembling more of a polygon shape)	Circular/hybrid, Bent

As shown in Table 3.1, the roundabout design variables have only two levels. Note that the Shape and Direction variables include a hybrid version where part of the roundabout was bi-directional and/or in a bent or circular shape. This decision was made in order to facilitate the choice of real-world roundabouts and to minimize the amount of photo editing required. More information on the survey creation process can be found in Sections 4.3.4, 4.4 and Appendices B and D.3. The socio-demographic questions are shown in Table 3.2 and are built in such a way as to keep respondents' responses anonymous but also to provide sufficient detail to perform descriptive statistics, to look at the heterogeneity of respondents, and to identify groups with similar safety and comfort perceptions.

Table 3.2: Model attributes and levels/categories of the indicators–(Continued)

Label	Variable	Definition	Categories
Legs	Vehicular entrance points	This criteria is whether or not the roundabout has 4 entrance/exit points for vehicles which can reduce or add complexity to the roundabout	No, Yes
		Socio-demographic questions	
Mode	Most common mode of transportation	What is your primary transport mode to commute to your work/studyplace?	Bicycle, E-bicycle, Scooter(Brommer), Bus/Metro/Tram, Train, Auto/Motorcycle, Walking, Cargo bicycle, Special bicycle
TR_DAYS	Travel frequency	In the past year, how often have you used the modes mentioned in the previous question?	Never, Less than once a month, 1-3 days per month, 1-3 days per week, 4-6 days per week, Always
Crash	Crash history	Have you had any crashes or "near misses" in the past 3 months?	Yes, No, Prefer not to say
Education	Highest education level attained	What is the highest degree or level of school you have completed?	Primary, Secondary, University (Bachelor, Graduate or professional)
Gender	Gender of the respondent	What is your gender?	Female, Non-binary, Male, Prefer not to say
Age	Age of the respondent	What is your age?	18 - 24, 25 - 34, 35 - 44, 45 - 54, 55 - 64, 65 - 74, $\geq$ 75, prefer not to say
Income	Income range	What is your monthly income?	<1,000, 1,001 - 4,000, $\geq$ 4,000, prefer not to say
Skill	Self-ascribed cycling skill	What would you qualify your level of expertise in bicycling?	inexperienced, competent, highly skilled, prefer not to say
Risky	Risky behaviour as a bicyclist	This gets at how risky someone is when they are bicycling since the assumption is that influences their perceptions of safety and comfort	see Table 4.4

3.4. Conclusion

This chapter described in detail the refinement of the model, going from a set of hypotheses to a final conceptual model that fits the research objective whilst optimizing for survey fatigue, model complexity, and computational time requirements. The following chapter explains the various methodologies used in this research, in particular the survey creation process and the discrete choice statistical model used.

4 Research methodology

This section explains the methodologies used to answer the main research question and sub-questions. The choice for each of the methods was based on 10 years worth of work experience as a designer and transportation engineer in the state of California, the courses taken in the Transportation, Infrastructure, Logistics (TIL) program, and the fact that this research is for a Masters thesis at a technical university in the Netherlands. An overview of the sub-questions and the corresponding methods used is provided in Table 4.1. The methods are further explained in the subsections. Section 4.4 describes how the survey was generated and distributed to participants.

Table 4.1: Research sub-questions and corresponding method used

What factors contribute to bicyclists' perceptions of safety at roundabouts?	
Sub-question	**Method**
1. What bicycle infrastructure design and behavioural factors at urban roundabouts in the Netherlands affect bicyclists' perceptions of safety and comfort?	Literature research and stated preference survey and ordered probit model
2. What bicycle infrastructure design and behavioural factors affect bicyclists' compliance with traffic laws?	Literature Research and field observations
3. How do different bicyclist groups perceive the safety of roundabouts?	Literature Research and stated preference survey
4. Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?	Expert Insights and stated preference survey and ordered probit model
5. What type of correlation is there between a bicyclist's perceived risk level versus actual crashes at roundabouts?	Crash Analysis and stated preference survey and ordered probit model

The first part of this research is a qualitative analysis, focusing on literature research, expert insights, field observations, and open feedback from survey respondents regarding traffic safety at roundabouts. The literature review was conducted to define the research problem and to demonstrate the presence of research gaps. The expert insights were performed to better understand the nuances associated with following or not following CROW design guidelines and what designers and government officials are currently concerned about regarding roundabout design. The field observations allowed the researchers to classify roundabouts based on bicycle volumes and to observe bicyclist behaviour regarding compliance with local traffic regulations. The final question in the stated preference survey allowed participants to freely express their thoughts and concerns regarding traffic safety at roundabouts. This allows for roundabout attributes that were not in the survey to be discussed, should there be concerns about those. In addition, the qualitative analysis is used to formulate and verify the conceptual model, complete with model variables and roundabout study locations that will be measured in the second part of the research.

The second part of this research represents the quantitative analysis, which analyses data provided via a survey with photos of actual roundabouts, using two methods: a descriptive analysis of the survey results and a bivariate random effects ordered probit model. The subsequent interpretation of the model results will be presented. Additionally, crash data from each location will be processed in order to compare the perceived safety of a roundabout with the actual crash data. Aggregation of the crash data may be needed due to the lack of available data.

4.1. Literature research

The methodology for the selection of papers is described in this section. For the collection of papers, six sources were used: SWOV publication database, the CROW Kennisbank, the database Scopus, the Transportation Research Board (TRB) Research Information Database (TRID), Google Scholar, and the TU Delft repository (TUD). The overall search strategy is summarized below in Table 4.2. Word combination searches were performed in order to cast a wide net for research papers. For example, using two keywords from Table 4.2, over 3000 hits were retrieved. After further review, the number of papers ultimately used for this report was reduced to 37. They are listed in the bibliography section and Appendix C.

Table 4.2: Search framework for literature review

Concept groups	intersections; mode; preferences; risks/safety	
Keywords	Intersection: roundabouts, roundabout, intersection Preferences: Stated preference, revealed preference, stated choice, logit model Mode: bicycles, vulnerable road users, bicyclists, bikers Risks/Safety: crashes, conflicts, close calls, near crashes, deaths, injuries, perceived safety	
Truncation	(Intersection) AND (Preferences) OR	73 hits(TRID), 633 hits(Scopus)
	(Mode) AND (Preferences) OR	14 hits(TUD), 1300 hits*(TRID), 2063 hits(Scopus)
	(Safety) AND (Intersection) OR	29 hits(TUD), 4109 hits*(TRID), 6247 hits(Scopus)
	(Mode AND Intersection) OR	11 hits(TUD), 297*hits (TRID), 2315 hits(Scopus)
	(Safety AND Mode) OR	102 hits(TUD), 4604 hits*(TRID), 24228 hits(Scopus)
	(Mode) AND (Preferences) AND (Intersection) OR	9 hits (TRID), 24 hits(Scopus)
	(Mode) AND (Safety) AND (Intersection) OR	5 hits(TUD), 134 hits*(TRID), 298 hits(Scopus)
	(Mode) AND (Preferences) AND (Safety) OR	4 hit(TUD), 194 hits*(TRID), 241 hits(Scopus)
	(Mode) AND (Preferences) AND (Intersection) AND (Safety)	3 hits (TRID), 11 hits(Scopus)
Note that for Scopus, the search was filtered for fully published English journals under the subjects of engineering, econometrics, and multidisciplinary.		

* indicates that a date range was chosen (only papers published after October 2011).

Note is that there were four overlapping papers between the Scopus and TRID databases.

Some additional papers were found via a method called ”snowballing”, where one makes use of papers that have been cited by other papers. Upon conclusion of this process, a final literature list, encompassing 77 sources, was created. This can be found in the Bibliography. The findings of these sources are described in more detail in Chapter 2 and in Appendix C. An overview of each research study is presented, along with its sample size, model used, location, aim of the research, and the main findings of the study. Note that additional sources were used for the purposes of the introduction Chapter and the Sections referring to the CROW guidelines which are also located in the Bibliography section.

4.2. Expert insights

Researchers participated in two workshops led by CROW staff targeted towards the creation of a new design guideline called: ”Everything about roundabouts.” (”Alles over rotondes”, in Dutch.) In addition to learning about current challenges and topics that government officials and designers are concerned about, the workshops allowed this research to ask six questions regarding the existing CROW design guidelines and the current thought processes when designing roundabouts (or redesigning existing ones). Workshop participants represented engineering consulting firms; local, provincial, and national government agencies; the national motorcyclist association; and research institutes such as CROW, SWOV, and TU Delft. The questions were related to the CROW publications regarding bicycle or roundabout designs and were the following:

1. In section 4.1 Background (Achtergronden in Dutch), it states that “within built-up areas, spatial limitations are often the cause of the diversity in roundabouts.” Is this the only consideration that changes roundabout design? What are other factors that may force a city or consulting firm to propose something different (such as not following the recommended five meter distance between bicyclists and road users)?
2. How does the option to deviate from the CROW guidelines work and what constitutes a strong motivation? What considerations are taken into account (e.g. directness for bicyclists, complex transit operations)?
    - Haarlemmermeerstation in Amsterdam [rebuilt in 2019 with the priority for cars (uitvoorang in Dutch) established] is a good example of a location which doesn’t follow Article 18 of the RVV 1990 [artikel 18 van het RVV 1990], which states that bicyclists should have priority at exit points if there is less than a 10 meter separation (or if the cycle path is considered part of the roadway).
    - CROW-publication 230 ‘Ontwerpwijzer fietsverkeer’ (Bicycle traffic design guide in English)– recommends to not do bi-directional roundabouts but there are many examples where they exist (even new ones such as Stieltjesweg/ Schoemakerstraat in Delft constructed in early 2022).
3. To what extent do the CROW guidelines grant safety (e.g. designing for lower vehicle speeds)? Are there guidelines (regarding safety) that should be reconsidered?
4. Are the CROW guidelines (such as Section 6.4.1) clear enough?— a visual connection between the roadway and the bikeway for the comfort of the bicyclist as well as safety— “This can easily be achieved by providing the intermediate verge of the cycle path and roundabout with a hard surface (clinkers or tiles).”
5. Why isn’t it mandatory to have physical separation at roundabouts that have more than 6000 movements per day (vehicle, bicycle, truck)–Section 6.4.1?
6. Recent research has found that wider bicycle paths are good for preventing bicycle crashes due to the increasing variety of types of bicycles and bicycle congestion in general. Roundabouts however, tend to be points of conflict, so have you considered narrowing the bicycle paths in roundabouts (narrower than 2 meters), to force bicyclists to travel in single file?
7. Do you have anything else you would like to mention about the CROW guidelines?

The questions this research posed to the experts encouraged them to question and support their own design processes and preferences, to explain why CROW guidelines are not always followed and to consider when guidelines merit being updated. The workshop meeting notes and question responses are further elaborated in section B.1 in Appendix B. A summary of the question responses and a discussion of the main points raised at the two in-person CROW workshop sessions are presented in detail in Section 5.1.

4.3. Quantitative and qualitative Analysis

A large portion of this report focuses on quantitatively measuring respondents' perceptions of safety and comfort for several roundabout design attributes by asking behavioural as well as indicator questions and then analyzing them using a ordered probit model. As described in Chapter 2, these models allow researchers to determine underlying choice preferences at an individual level, allowing for heterogeneity in the population in the final results and providing parsimoniousness (Zheng et al., 2014). Participants will be shown roundabouts with various characteristics and movement scenarios. The characteristics and scenarios are chosen based on characteristics that past research identified as needing more study and on typical traffic movements through the roundabouts. This is done in such a way that the photo collection process doesn't imperil the person collecting the data (i.e. no illegal or erratic movements that could cause a crash).

4.3.1. Data collection

Before modeling could be performed, data had to be collected and processed. The data processing procedure is described in section 4.3.4. The data was collected from different sources as described in the following subsections.

Photo data

Photo observations were collected via a camera, that is aimed at key areas of the bicycle path approaching and within a roundabout. The observations were performed during the weekday rush hour periods (between 16h00 and 18h30) to get the busiest traffic volumes, which may add stress for bicyclists. More traffic, including pedestrians who are crossing the bicycle path and bicyclists who are entering or exiting the roundabout, makes for more stressful decision making, which can increase the probability of crashes (Møller & Hels, 2008). External factors such as construction and weather were controlled to the extent possible so that the images used in the survey do not vary. On average, approximately 10 photos were taken at each roundabout location, using the 180°camera feature in order to mimic a bicyclist's field of vision. Only three or four photos of each location were placed into the final survey. An example of one photo is shown in Figure 4.2.

Field observations

Field observations allow researchers to note how a roundabout functions and how users of the roundabout behave as they interact with the physical infrastructure and other modes whilst not in a controlled setting. These observations were made at the same time as the photo data collection in order to maintain consistency regarding the levels of traffic intensity. Primarily, these field observations looked for compliance behaviour from bicyclists and motorists as they interacted with each other. Some of the roundabout locations are too large to observe the entire roundabout from one viewpoint, thus the observer moved around the roundabout during the 15 minute observational period. Scooters were counted in the bicycle volumes, as well as anything legally using the bicycle facility during the observation period. More details on these observations are located in Section 5.2.

4.3.2. Locations

There are significant differences between urban and rural roundabouts such as daily traffic volumes, crash rates, complexity, and dimensions (S. U. Jensen, 2017; Shen et al., 2020). For those reasons, this report will only focus on urban roundabouts. This report focuses on the Randstad area as that is where the majority of the Dutch population live. If one were to consider cities with a population over 300 thousand, then only Utrecht, Den Haag, Rotterdam, and Amsterdam would be included. Since there are roundabouts found in urban, dense environments that have small population sizes, such as Delft, Pijnacker, and Zoetermeer, those cities were also included. During the preliminary survey, only a few urban roundabouts were found that had no bicycle facility (e.g. Slaghekstraat/Beijerlandselaan in Rotterdam, and two in Den Haag at Prins Hendrikplein and Plein 1813). In order to be able to collect more data on specific infrastructure design factors, it was decided to focus solely on urban roundabouts with bicycle facilities. Utrecht has only five urban single lane roundabouts with bicycle facilities, all located on the northern edge of the urban area, so this city was not included in the study due to logistical reasons. The real-world location characteristics used in the survey are shown in Table 4.3. In order to select site locations for this research, the following characteristics were evaluated as shown in Table 4.3 and further explained in Appendix B.2:

- Buffer or Separation from vehicle lane–Average width of the buffer between the bicycle path and the vehicular lane
- Yield–Yielding priority for bicycles
- Art–Presence of art/advertisement signs within the center island of the roundabout
- Uni-directional or Bi-directional–Whether the bicycle path in the roundabout is one-way or has at least some two-way sections
- Flow or Bicycle volumes–High rush hour bicycle volumes (> 480 bicycles per hour)
- Shape or Facility style –Bicycle path's geometric shape (bent, circular, or a hybrid of both)
- Legs or 4-legged–If the roundabout is 4-legged or not (4 entrance/exit points for motor vehicles)

Table 4.3: Location characteristics table

Label	Location	City	art/ ads in cen- ter	bicycle yiel -ding prio- rity[1]	uni- direct -ional	4- leg- ged[2]	separat -ion from vehicle lane	bicycle volumes[3]	facility style
1	Dierenselaan/ Apeldoornselaan	Den Haag	✗	✓	✓	✗	3.79m	80	Circular
2	Neherkade/ Slachthuisstraat	Den Haag	✗	✓	✓[4]	✓	5.13m[5]	90	Circular
3	Putsebocht tram stop	Rotterdam	✗	✗	✓	✗	11.39m	83	Bent
4	Planbaan/ Kernbaan	Zoetermeer	✗	✓	✓[6]	✓	4.45m	13	Bent
5	Amstelplein	Amsterdam	✗	✓	✓[7]/[8]	✗	5.76m	559	Circular
6	Gordelweg/ Rodenrijsestraat	Rotterdam	✓	✓	✓[9]	✓	5.00m	193	Circular
7	Meerzichtlaan/ Berglaan	Zoetermeer	✓	✓	✗	✗	4.81m	39	Bent
8	Delftlandplien	Delft	✓	✓	✓	✓	9.55m	341	Bent

During the stage of survey construction, the roundabouts in Pijnacker were not chosen as they did not closely match the desired characteristic combinations. The cutoff point for high bicycle volumes was determined during the field observation phase of work when bicycle volume counts were performed. The average of all 50+ initial site locations was 122 bicycles in 15 minutes. Thus this was used as the threshold for a high bicycle volume location.

The roundabouts found in Table 4.3 were the ones that closely represented the various roundabout attributes that were created during construction of the stated choice survey. Note that seven of the eight roundabout locations required roundabout attribute editing in order to match the stated preference survey. This is explained in more detail in Sections 4.3.4, 4.4, and Figure D.10. More details about this process can also be found in Appendices B and D.

[1]do bicycles have priority
[2]for cars
[3]15 minute counts
[4]No crossing possible on the north side
[5]This includes the truck aprons
[6]southside of intersection is bi-directional
[7]except the west side
[8]No crossing possible on the east side
[9]the northern side is bi-directional

4.3.3. Crash and traffic analysis

For comparison reasons and to build the conceptual model and subsequent survey, this report used manual field collection bicycle traffic count data and publicly accessible crash data, called BRON and NWB. The BRON and NWB data was filtered to include only roundabouts within urban areas and was analysed to determine the date and location of crashes. The traffic counts were performed in order to have another data point for characterizing roundabouts with similar characteristics. Numerous studies found that traffic volumes affect objective and subjective safety values (John Parkin et al., 2007; Møller and Hels, 2008) but little research has looked into how bicycle congestion may change the notions of objective and subjective safety. Both crash and traffic count data are used in Chapter 6 and any resulting correlations are discussed in Chapter 7.

4.3.4. Data processing

Image data needed to be processed to remove all personal information to avoid violating GDPR regulations and to keep the control variables the same (i.e weather, vehicle traffic patterns, construction). Image data was then placed into a Qualtrics survey form that showed respondents four to five images per roundabout (including an aerial or isometric image). The aerial image gave respondents a general overview of the roundabout, including its orientation. Images were followed by a short prompt and then the Likert scale questions (see example in Section 4.4) for the indicators of perception of comfort and safety. Unfortunately, during the comparison process, it was found that only one of the 50+ real-world locations matched exactly one of the roundabouts created by the experimental design process. Thus, the roundabouts listed in Table 4.3 were used as a base and subsequently modified to match the experimental design requirements for each studied roundabout. More information regarding this process is explained in Section 4.4 and Appendices B and D.3.

The field observations are summarized to highlight important findings, such as illegal behaviours, turning movements that led to near-misses, and high directional flows (i.e north to south).

4.4. Survey creation

The project team decided to go with the BASIC 1 plan (experimental design) as that allows this research to examine many binary attributes whilst remaining attribute balanced, and thus reducing multicollinearity which could cause a poor model fit. This BASIC plan also has the advantage of keeping the number of choice situations low. The alternatives are unlabelled, allowing the main researcher to proceed with a sequential choice set construction. The design of the choice sets used Ngene software in order to preserve orthogonality but have a fractional factorial design (Choice-Metrics, 2024). Thus there was a total of 8 different roundabout locations in the survey, so that each respondent would see the same number of roundabout attribute types. The order in which each participant would see a roundabout location was randomized (e.g. Person A may see roundabout one first but Person B may see roundabout eight first).

Once the survey was created, an initial pilot survey was performed with four individuals in order to test the length and complexity of the survey. The findings of the pilot survey were that the survey language was too technical and that the survey took approximately 15 minutes to complete. In addition, the Dutch language version of the pilot survey used antiquated words that confused the testers. For the final survey, the project team shortened the attribute number to seven in order to reduce the required sample size for a statistically significant result. Furthermore, all the attributes were reduced to binary levels for the same reason. This meant that the linearity of the roundabout characteristic variables could not be checked and the precision of these variables was reduced. The visibility and transit presence attributes were removed. These would have captured user preferences related to different visibility levels between motorists and bicyclists and to roundabouts with special transit lanes/movements.

At the beginning of each survey, participants were asked to provide demographic data, including: age, gender, income range, highest education level obtained, and how often they use various modes of transport. Table 3.2 shows all the socio-demographic attribute questions and the categories that respondents had to choose from for each attribute. In addition, each participant was asked to rank themselves on their bicycling behaviour regarding 12 different agnostic questions, based on the proven CBQ developed by (Useche et al., 2018). The questions are shown in Table 4.4.

Table 4.4: Cyclist behavioural questionnaire (CBQ), showing questions and scales/levels/categories of the indicators

Label	Question Formulation	Scale
	Violations latent variable group	
2	Cycling under the influence of alcohol and / or other drugs or hallucinogens.	1=Never - 5= Always
3	Going against the direction of traffic (wrong way).	1=Never - 5= Always
10	Crossing what appears to be a clear crossing, even if the traffic light is red.	1=Never - 5= Always
	Errors latent variable group	
17	Unintentionally, crossing the street without looking properly, making another vehicle brake to avoid a crash.	1=Never - 5= Always
18	Colliding (or being close to it) with a pedestrian or another bicyclist while cycling distractedly.	1=Never - 5= Always
20	Brake suddenly and be close to causing an accident.	1=Never - 5= Always
22	Not braking on a "Stop" or "Yield" sign/marking and being close to colliding with another vehicle or pedestrian.	1=Never - 5= Always
30	Failing to be aware of the road conditions and therefore falling over a bump or hole.	1=Never - 5= Always
31	Mistaking one traffic signal for another, and maneuvering according to the latter.	1=Never - 5= Always
	Positive Attitude latent variable group	
36	I try to move at a prudent speed to avoid sudden mishaps or braking.	1=Never - 5= Always
38	I keep a safe distance from other bicyclists or vehicles.	1=Never - 5= Always
39	When I use the bicycle path (or bicycle-lane), I use the indicated lane.	1=Never - 5= Always

The questions above were selected from the groundbreaking study by Useche et al. (2018) and the original 42 dependent variables that were asked (only 29 variables were significant). The study by Useche et al. (2021) found that three variables were not significant with the Belgian population, but since a similar study has yet to be conducted in the Netherlands, this research chose not to copy the Belgian study. Some questions would not apply as many Dutch bicyclists perform actions such as allowing riders on their bicycle racks or carrying large cumbersome objects such as beer crates, plywood, and more. Since this research is focused on design elements and bicyclists' perceptions, the questions presented in Table 4.4 reflect only the questions that had the strongest correlations to the latent variables found in the CBQ studies (Useche et al., 2018; Useche et al., 2021). During the model run stage, an ordinal factorial analysis of these 12 questions was discarded, as the CBQ is secondary to this study. Instead, an averaging of each respondent's responses for each category (Violations, Errors, Positive Attitude) was performed. This simplified the overall model and run times, whilst maintaining detailed information about these three aspects of the CBQ. In addition to the CBQ factors, socio-demographic factors such as age, gender, and income were also analysed. More information about the CBQ and how it fits within the conceptual framework of this report is explained in Chapter 3 and Appendix D.

Finally, each participant was shown several roundabouts prompted by a few images, followed by questions that look similar to the following:

Figure 4.1: Bicyclist using bi-directional portion of roundabout

You are biking at this location, shown in Figure 4.1 (Location: Plaszoom/Kralingseweg, Rotterdam); Please answer the following questions:

Table 4.5: Perception of safety and comfort questions and scales/levels/categories of the indicators

Label	Question Formulation	Scale
Overall comfort	Overall, how comfortable would you feel bicycling through this roundabout?	1=very uncomfortable - 5= very comfortable
Safety perception	How safe do you feel biking through this roundabout?	1=very unsafe - 5= very safe

The decision to use a 5-point Likert scale was based on the fact that this survey asks for respondents' opinion regarding their perceived safety and comfort when biking through the choice situation roundabouts. As an even-numbered Likert scale leads to a "forced choice" situation, this research chose a 5-point scale, thus allowing respondents to express a neutral opinion on a roundabout and its specific characteristics (services, 2023).

After the survey was generated, the main researcher placed it in Qualtrics for online distribution to respondents and storage of the results. The survey was created in English and Dutch and was made available via a QR code link which allowed for greater distribution to TU Delft students, bicyclists who used the selected roundabouts, and the general public via social media channels. A combination of non-physical and physical survey collection was used to increase the number of responses. By directly asking random bicyclists, a more even distribution of rider population was achieved, which reduced bias in the results. An image of a part of the Qualtrics survey can be found in Figure 4.2.

This roundabout **has 4** entrance/exit points for cars, **no art or advertisements** in the center island, a **large** buffer between the vehicle lane and the bicycle path, and a **partially bi-directional circular shaped** bike path with a **low** amount of bicycles and **yielding priority** for bicycles.

Overall, how safe do you feel this roundabout is as a bicyclist?

- ◯ Super unsafe
- ◯ Unsafe
- ◯ Neutral
- ◯ Safe
- ◯ Super safe

Figure 4.2: Image of the final survey, showing one of the roundabouts and the associated indicator question about perception of safety.

Based on the survey creation and setup, a dataset comprising responses by individuals with their socio-demographic categorical data, their indicator safety and comfort categorical responses for each of the 8 roundabouts, and their responses to the 12 CBQ questions were placed into a discrete choice statistical model for analysis.

4.5. Model choice

4.5.1. Regression models

Regression models have been used since the 1950s for transportation studies as they provide an easy way to observe and determine any trends and relationships between dependent and independent variables.

Table 4.6: Regression methods

Label	Summary of type of regression	Recent uses in transportation
Generalized Ordered logit	OLR that can handle some model assumption violations	(Shen et al., 2020) & a random effects version by Zheng et al. (2014)
Partial Proportional odds model (ordered logit)	Same as above model with constant odds ratios	(Shen et al., 2020)
Ordinal Logistic Regression (OLR)	It assumes a specific order of the categories but not the equal distance between categories. Estimation method is maximum likelihood	A cumulative logit model by S. Jensen (2012)
Multivariate Ordinal Logistic Regression	This is an extension of OLR that can handle multiple ordinal outcomes. Estimation method is maximum likelihood	Random effects by Zheng et al. (2014)
Bivariate probit or logit models	Allow for correlation in the error terms of the equations for each dependent variable. Estimation method is maximum likelihood	Hierarchical logit models (LCCM) (Wang and Akar, 2018; Silvano et al., 2014) & random-effects model by Xiao et al. (2021)
Bayesian multivariate probit	A powerful model that allows for beta priors for faster calculation times. Estimation method is maximum likelihood	Study on automotive sales by Kim and Ratchford (2013)
Generalized Linear Mixed Models (GLMM)	You can fit a random intercepts model that allows intercepts to vary across individuals, capturing the correlation between the two outcomes. It does capture it external random effects. Model estimation is done through methods like restricted maximum likelihood (REML) or penalized quasi-likelihood (PQL). Maximum likelihood may be possible too.	(Zeuwts et al., 2021 & Richard Mantona et al., 2016)
Random effects generalized ordered probit	Model that can interpret a panel data set and allows for certain assumption violations	(Jafari Anarkooli et al., 2017; Lee et al., 2018)
Correlated Random parameters ordered probit	Model that allows for stochasticity within each variable term	(Chen et al., 2019; Se et al., 2021)
Random effect ordered probit	regression model for ordered variables with a panel data set	(Lee et al., 2018)
Random effect multivariate ordered probit	Handles panel data set with multiple latent variables	(Chen et al., 2019; Kim and Ratchford, 2013)

Regression models have frequently been used in objective traffic safety studies, comparing crash rates with variables such as road design, traffic volumes, time of day, and other factors (S. U. Jensen, 2017; Shen et al., 2020; Chen et al., 2019; Xiao et al., 2021; Lee et al., 2018; Schepers et al., 2017; Silvano et al., 2014). With more advanced computing power, extensions of generalized linear models have been made in order to account for random effects and multiple variables (a bivariate or multivariate type model). Table 4.6 summarizes the various types of regression methods that have been used for transportation research.

With an ordinal regression analysis, an ordinal dependent variable is predicted with the aid of one or more independent variables (Statistics, 2018). In more recent years Generalized Linear Models (GLM) and Machine Learning have been developed. These have the power to look at non-linear relationships and dependent variables that are binary or count data. The benefit of these models is their simplicity. This is compared with an ordinal Structural Equation Model (SEM) model that can get complex quickly due to the need to assume distributions for every error term and the fact that each correlation (double headed arrow) represents a variance-covariance matrix that must be properly defined.

For the purposes of this research, a random effect ordered probit model will be used. This model is best matched to handle a cross sectional study with panel data sets via the incorporation of an additional error term that only changes between respondents, thus preventing overfitting of the model (Sungjun et al., 2022; Jafari Anarkooli et al., 2017). The ordered probit model for this research will mimic the conceptual model shown in Figure 3.1. The following section goes into more detail on the formula specification.

4.5.2. Random effects ordered probit model

The generic formula for this model is:

$$Y_i^* = X_{ij}\beta + \lambda_{0ij} + \epsilon_i \tag{4.1}$$

$$\lambda_{0ij} \sim N(0, \sigma_\lambda^2) \tag{4.2}$$

$$\epsilon_i \sim N(0, \sigma_\epsilon^2) \tag{4.3}$$

where the Y_i^* is a continuous latent variable that is assumed to underlie the observed ordinal data. Y_i is the t th observation value at the i th individual, X_i is a $(1xj)$ vector of observed independent variables; and β is a $(jx1)$ vector of coefficients for the independent variables(Lee et al., 2018). λ_{0ij} is the effect term of the individual at the j th roundabout location, and ϵ is the error term (person level random effects). This error term links the two latent variables. Equations 4.2 and 4.3 both have a mean of 0 and variance of either σ_λ^2 or σ_ϵ^2 respectively. A normal discrete distribution is assumed, and the estimated value of the variance refers to the volatility between clusters (local variables)(Sungjun et al., 2022).

Due to the normalization of the error terms, the two error terms are assumed to be normally distributed (Xiao et al., 2021). Equation 4.1 shows the latent variable whereas what is gathered in the survey are observed ordinal data, Y. The observed values (1,2,3,4,5) presented via indicator variables, but these latent variables have cutoff points that will be estimated (Lee et al., 2018) via the following format:

$$Y_f = s \qquad \text{if} \quad \mu_{s-1} < Y_f^* \leq \mu_s \tag{4.4}$$

where μ_s are thresholds or cut-off values of the continuous scale of Y^*, used to determine the comfort levels and perceptions of safety of bicyclists(Chen et al., 2019). f symbolizes either the comfort or safety variable whilst s is the category that the Y is observed in when the latent variable falls in the μ_s interval. In other words, Y_f is observed to be in category 1 when the latent variable falls in the interval between μ_0 and μ_1 (Zheng et al., 2014).

4.5.3. Data distribution

There can be different distributions for categorical data but given that the data is discrete, either an ordinal, logistic, ordered probit, or ordered logit distribution should be used. It is worthy to note that ordinal data that has very few levels (mostly binary), means that this research can't make any assumptions on what kind of distribution the data will have that maximizes the goodness of fit (Xing et al., 2019). See Section 6.2 for the data distribution for the two indicator question responses.

4.5.4. Model performance

For the test of the goodness of fit, the Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC) will be used as both of these correctly penalize every additional independent variable that is added to the model (Washington et al., 2020). This section reviews the AIC and BIC methods and includes other tests that are performed to measure model run convergence and statistical significance of the variables and their intercepts. The generic formulation for AIC and BIC is:

$$\text{AIC} = 2p - 2\ln(L) \tag{4.5}$$

$$\text{BIC} = p\ln(n) - 2\ln(L) \tag{4.6}$$

where p is the number of estimated parameters, n is the number of observations, and L is the maximum value of the likelihood function.

In addition to the BIC and AIC estimations, a Z-test will be applied to test for significance of the independent variables. In order to do this, the Z-value will be calculated. It is equal to the number of standard deviations from the mean. $(P > lZl)$ then shows the probability that the the null hypothesis is true. Here, the null hypothesis is that the variable is not correlated to a bicyclist's perception of safety or comfort at roundabouts. Variables with $(P > lZl)$ lower than 0.05 signify that they are statistically significant. The null hypothesis then could be rejected, meaning that the variable significantly correlates to a bicyclist's perception of safety or comfort with a confidence level of 95%.

Elasticities

Due to the non-linear nature of Equation 4.1, the β coefficient values can't be directly interpreted as increases or decreases in the latent variables (Jafari Anarkooli et al., 2017). As such, the marginal effects or elasticities will be calculated to show the percentage of contribution that each independent variable has on each dependent variable (Hirk et al., 2020). However, marginal effects are more often used for continuous variables and as such, this research will use elasticities which are better suited for discrete data (with binary and categorical variables). Equation 4.7 represents the elasticity calculation where i is the individual at the j th roundabout location and where β_p represents the explanatory variable p:

$$\text{Elasticity}_{sp|X_{jp}} = \frac{X_{jp}}{P(Y_{ij} = s|X_{ij})} \cdot \left[f(\mu_{s-1} - X'_{ij}\beta) - f(\mu_s - X'_{ij}\beta)\right] \cdot \beta_p \tag{4.7}$$

s represents the index for the ordinal categories of the dependent variables and p is the index for the independent variables.

4.5.5. Other models considered

Tables 3.1 and 3.2 show the final set of roundabout design features and individual behavioural factors that are employed in the quantitative analysis. An ordinal SEM or a non-linear regression model, specifically a ordinal probit model, matches the type of variables used and the conceptual model. More information about the ordinal SEM model family and the attempt to run such a model by this research team is located in Appendix D.6. Ultimately this research did not want to have respondents choose between one roundabout and another, so Taboo aversion, and latent class discrete models were removed from consideration. Furthermore, this research aims to make recommendations to designers and CROW regarding which roundabout characteristics are strongly correlated or uncorrelated to a bicyclist's perception of safety and comfort. Thus a latent class cluster model was not the right model as it only finds underlying heterogeneity within the survey respondent population.

4.6. Conclusion

Overall, this Chapter provided the detailed methodology for the various qualitative and quantitative methods used in this report to answer the conceptual model and therefore the research question and sub-questions. A bivariate random effects ordered probit model was used for the quantitative regression method, with the qualitative analysis in Chapter 5 and the probit model results in Chapter 6.

5 Qualitative analysis

Based on research gaps found in the literature review, it was found that studying the detailed roundabout design features and how they affect bicyclists' behaviours is critical to fully understanding bicyclists' subjective safety and comfort and analyzing both latent concepts. In addition, it was shown that bicyclists' behaviours are linked to their demographic data. This was proven by the results of previous CBQ studies (Useche et al., 2021; Useche et al., 2018) and by studies using discrete choice modeling (Poudel and Singleton, 2022). This qualitative analysis compliments Chapters 3 and 4 by providing valuable insights from experts and field observations, which helped inform the final survey questions and variable selection for the final model. This Chapter starts with a summary of the expert insights regarding designing roundabouts and the CROW design manual. This Chapter will also summarize the field observations performed at each of the roundabouts listed in Table B.1, with subsections devoted to the main behavioural characteristics observed. Finally, this Chapter will provide a synopsis of the optional open response question that was asked to the survey respondents. This Chapter will partially answer sub-questions two: *What bicycle infrastructure design and behavioural factors affect bicyclists' compliance with traffic laws?* and four: *Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?*.

5.1. Expert insights and CROW survey results

This section summarizes the various conversations amongst designers and government officials regarding roundabouts between February and May 2024. Via a survey form and two in-person workshops, the following roundabout design factors and road policies were discussed and debated amongst the attendees:

- Yielding priority
- Bi-directional vs uni-directional bicycle paths
- Different types of bicycles and how they affects roundabout designs
- Lowering speeds (all modes) to accommodate all the complex turning movements
- Visibility for the bicyclist and anticipation of turning movements
- Underreporting of crashes
- Consistency of designs (at city level) for increased road user comprehension and compliance.
- Buffer width between bicycles and vehicles
- Whether good analysis, using micro-simulations, leads to good designs that provide an appropriate balance for each mode.
- GOW30 (the enactment of policy to reduce main arterials within cities down to 30km/h) and its intended and unintended consequences.

Through the expert insight survey, the experts confided that deviation from CROW design guidelines occurs due to politics, geometrical constraints, private land boundaries, trees, water management or, in rare cases, funding challenges. There is a general design framework that must be followed for all roadway projects, which details how CROW deviations should be clearly documented (Rijkswaterstaat, 2024). There is no official review by a committee or review board since the CROW publications are not standards, only design guidelines to assist designers in their project development and design process. Many times, common sense (e.g. tram lane cutting through the center of the roundabout means yielding priority is given to the tram) and unique local characteristics (such as the entire city having bi-directional bicycle paths) are valid reasons to deviate from the CROW design guidelines.

Most survey respondents agreed that it is time to update the CROW guidelines as there is increasing diversity of bicycle traffic, making current bicycle paths congested and causing more ”near misses”. One response noted that the CROW design guidelines influence only the infrastructure side of the three-prong equation of traffic safety (Education, Enforcement, and Engineering/Infrastructure). The experts also noted that people going at lower speeds (scooters, bicycles, pedestrians) are harder to control via infrastructure changes. Education (which encompasses compliance) and enforcement are not addressed by the CROW design guidelines. These two sides of the equation shouldn't be ignored. New types of bicycles with their various speeds influence not only bicyclists' subjective safety but that of users of other modes aswell (news, 2019; News, 2022).

Most survey respondents think that the CROW design guidelines are well written, with enough clarity and detail to allow them to perform their job functions but also allow them to deviate if justified. One topic that elicited debate was whether the width of the bicycle path at roundabouts should be purposely narrowed to force bicyclists to travel in single file, thus allowing motorists to better predict bicyclists' turning movements. Some agreed with this idea but others pointed out that this would mean longer wait times for motorists, who then may get impatient and attempt to cross, potentially causing a crash. The detailed survey question responses and workshop meeting notes are located in Appendix B.1.

This section discussed how deviations from the CROW design guidelines occur but did not completely answer sub-question four as it did not clearly address how guideline deviations relate to how bicyclists perceive safety at roundabouts. By performing the stated preference survey and incorporating roundabouts that do not follow the CROW guidelines (Roundabouts four, five, six), this report will be able to conclude if the design details impact bicyclists' perception of safety. Please refer to Chapter 6 for the survey results and to Chapter 7 for the full discussion pertaining to sub-question four.

5.2. Field observations

To get a better understanding of how bicyclists in the Randstad use roundabouts, 15 minute field observations were performed during the weekday rush hour periods (between 16h00 and 18h30) between March 15th and April 20th. This enabled researchers to also observe vehicular congestion, noting any close calls/”near misses”, and to verify bicycle volume data. The observations were done under similar weather conditions to avoid any data bias. Certain themes emerged from these observations. These themes and the correlating observations are explained below. More photos and explanations can be found in Appendix B.3. Scooters and broomers were counted in the bicycle volumes, as well as anything legally using the bicycle facility during the observation period. These field observations were used to select the eight roundabouts for the final survey and also to identify roundabout attributes and their associated levels to use in the survey.

On average, the number of bicycles going through the roundabouts was 122, with the highest roundabout occurring at Haarlemmermeerstation in Amsterdam (Figure 5.6), where a total of 747 bicyclists rode through the roundabout. The roundabout with the lowest volume was Planbaan/Ruimtebaan in Zoetermeer (Figure B.1b), with only eight bicyclists observed. These values show that there is a great variety in the amount of bicyclists that may use an urban roundabout, depending upon the city and the roundabout's location within the city. The following location characteristics may act as traffic generators: public transport hubs, commercial streets, grocery stores, or dense residential areas. More details on those specifics and other observations are mentioned below.

5.2.1. Presence of grocery stores

Whenever there is a large grocery store located at one corner of the roundabout, there were notably more turning movements to and from that corner. In Rotterdam, this occurred at Jacques Dutilhweg/-Nancy Zeelenbergsingel (Figure B.2b), whilst in Pijnacker, this occurred at Oostlaan/Emmastraat (Figure B.2a). At the Rotterdam location, this resulted in a lot of left turning movements to get from the SE corner to the NW corner and vice-versa. At the Pijnacker location, this meant a lot of left turning movements and southbound through movements to get from the N or NE to the SW corner.

(a) Image of roundabout in Amsterdam with shops around the entire roundabout

(b) Image of roundabout in The Hague with AH located at the SE corner and other stores on the south side

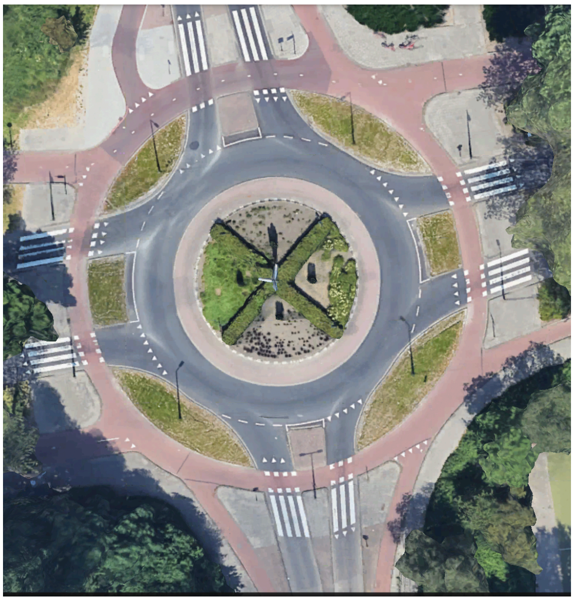
Figure 5.1: Two urban roundabouts that have many stores around or nearby. Images courtesy of Google Earth.

However, locations where there were stores along the entire street (Dierenselaan/Apeldoornselaan, Den Haag or Hugo de Grootplein, Amsterdam (Figures 5.1b and 5.1a)) in busier retail/public transport locations didn't show a visible relationship between the location of the grocery store and bicycle movements.

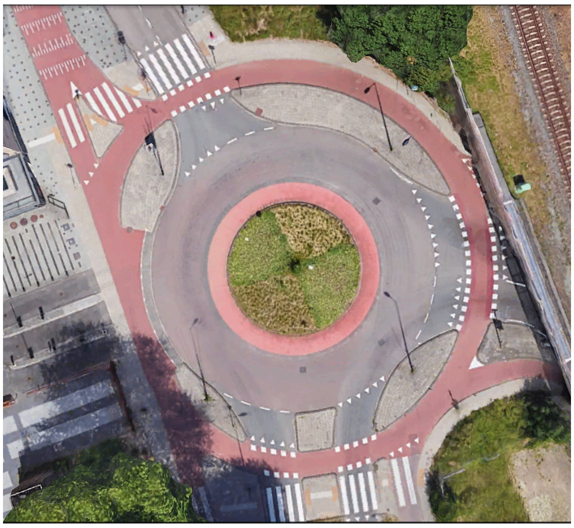
5.2.2. Strong directionality

At some roundabouts there were a lot of turning movements due to the presence of intersecting local/regional bicycle routes, such as Karlingseweg/Plaszoom, Rotterdam (Figure B.3b), where there is a bi-directional bicycle facility that crosses Kralingsebos, leading bicyclists to make a southbound to westbound movement. Other reasons for high turning movements could be due to the presence of shopping (as mentioned in 5.2.1), or due to a main commuter route to residences from a public transport station (such as the large amount of westbound right turns at Prinsenlaan/Michelangelostraat, Rotterdam(Figure B.3a)).

Another reason could be natural and man-made barriers such as at Gordelweg/Rodenrijsestraat, Rotterdam (Figure 5.2a) where the presence of the A20 and Noorderkanaal force all bicyclists wanting to head to Rotterdam Noord to use one of only six crossings, thus leading to many bicycle movements going from the SW corner to the NE corner of the roundabout. Another location where this occurred was at Amstelplein, Amsterdam (Figure 5.2b), where a canal to the south and NS tracks to the east meant a lot of north to east and south to east movements were observed. Planbaan/Lijnbaan (Figure 5.3a) had a bi-directional bicycle path leading away from the roundabout on the south side only as it is the main path to/from downtown Zoetermeer.



(a) Aerial view of roundabout on Gordelweg, where a canal and highway to the north are the reason for many north/south bicycle movements



(b) Aerial view of roundabout in Amstelplein, Amsterdam, where NS train tracks and a canal pose barriers

Figure 5.2: Roundabouts that have strong directionality due to geographic barriers. Images courtesy of Google Earth.

(a) Aerial view of PLanbaan, where the west side of roundabout has a bi-directional bicycle path only on the south side, leading towards downtown Zoetermeer

(b) Aerial view of Putsebocht tram stop in Rotterdam, where north of this intersection is the main bicycle route to downtown

Figure 5.3: Roundabouts that have strong observed bicycle volume directionality. Images courtesy of Google Earth.

In Rotterdam, a slight majority of bicyclists were going from south to north at Putsebocht tram stop (Figure 5.3b) whilst at Groene Tuin/Reyerdijk(Figure B.4a) many bicyclists were going east to west or west to east to access the commercial shopping center.

At Zuiderparkweg/Hijkerveld(Figure B.4b), most bicyclists were going northbound or southbound and making no turns. In Zoetermeer at Zwaardslootseweg/Aidaschouw (Figure B.4c), there were a lot of movements from the southwest corner to the northeast corner of the roundabout due to that being the primary route to De Leyens neighborhood from the commercial city center.

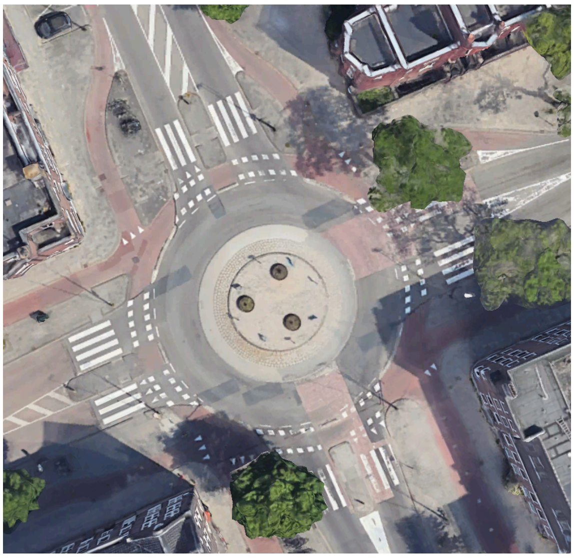
5.2.3. Wrong way bicycle riding

A lot of of wrong-way bicycle riding was observed at the following Rotterdam roundabouts: Boezemlaan/Karmelweg, Putsebocht tram stop, and Prinsenlaan/Jacob van Campenweg (Figures B.5a, 5.3b, and B.5b). This non-compliant behaviour could be due to the desire to reach the bi-directional bicycle facility on the south side of Boezemlaan leading to the Crooswijk neighborhood, the desire to avoid multiple tram tracks on the southern and eastern crossings at Putsebocht, or the presence of apartments on the north side of Prinsenlaan.

Some wrong way bicycle riding going northbound on the west side of the roundabout was observed at the Slinge/Langenhorst in Rotterdam (Figure 5.4a). Warande/Vondelweg (Figure 5.4b) and Neherkade/Slachthuisstraat (Figure 5.4c) roundabouts had some minor illegal movements heading either north or south for Warande in Rotterdam or along the northeast crossing heading southeast for the roundabout in The Hague. In Delft, at Stieltjesweg/Schoemakerstraat (Figure 5.4d), there were some bicyclists that went the wrong way on the north crossing, heading eastbound. They may have been coming from TU Delft library or other buildings on campus and were headed to their residence located in a fairly isolated neighborhood boxed in between the A13 and Schoemakerstraat.

5.2.4. Other notable behaviours

At Pieter de Hoochweg/Willem Buytewechstraat in Rotterdam (Figure 5.5b), bicyclists were observed weaving into the vehicle lane due to the narrow width of the buffer between the vehicle lane and the bicycle facility. If a bicyclist did that, they were observed reentering the bicycle facility at the roundabout exit, thus using the vehicle lane as a shortcut. Also in Rotterdam, at Olympiaweg/Buitendijk (Figure 5.5a), bicyclists could access a bicycle path through a park on the north side of the roundabout, which used to be a vehicular lane prior to 2019.



(a) Aerial view of a roundabout on Pieter de Hoochweg in Rotterdam, where one can see the small buffer width which allows bicycles to enter the vehicle lane.

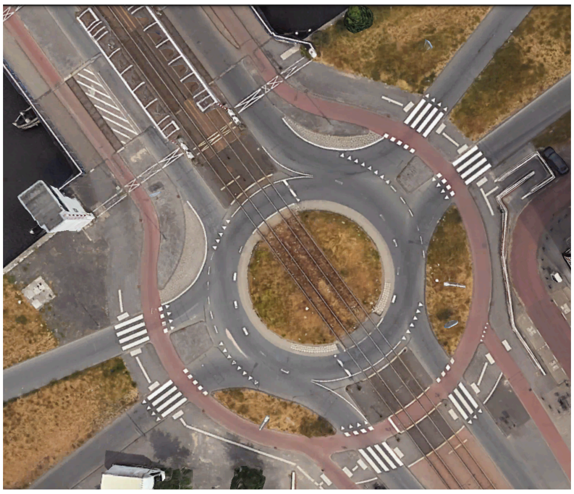
(b) Aerial view of a roundabout on Olympiaweg in Rotterdam, showing the bicycle path north through the park.

Figure 5.5: Roundabouts with non-compliant behaviour and strong directionality. Images courtesy of Google Earth.

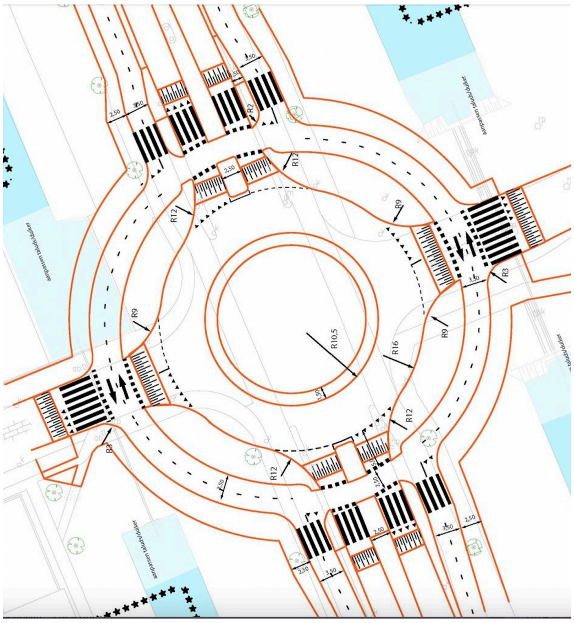
Haarlemmermeerstation (Figure 5.6) in Amsterdam was notable for the complexity of the road layout, with a public transport lane, a vehicle lane, and multiple public transport boarding platforms located on the southside (Figure 5.6c), as well as the inconsistency of the yielding priority (Figure 5.6b) (the east, west, and southeasterly legs give priority to bicycles, but the north and south legs do not). This caused noticeable confusion, with many observed ”near misses” and vehicles yielding to bicyclists when they were not legally required to do so. When this roundabout was reconstructed in late 2018, the yielding priority changed for the north and south legs, presumably due to the many lanes and possible bicycle-vehicle or bicycle-public transport conflicts. Many citizens have complained and a traffic psychologist has agreed that the inconsistency of regulations at this roundabout makes it particularly challenging (news, 2019).

(a) Aerial image of Slinge roundabout, with shops located at the NW corner.

(b) Aerial image of Warande roundabout, with a bicycle only connection on the west side.



(c) Aerial image of Neherkade roundabout in The Hague. Note there is no north crossing due to a draw bridge and tram tracks.



(d) Engineering drawing of the new Schoemakerstraat roundabout in Delft. The roundabout was completed in Spring 2022. Drawing courtesy of Dickvanveen.

Figure 5.4: Roundabouts with non-compliant bicyclist behaviour (continued). Images courtesy of Google Earth.

5.2.5. Observation conclusions

Overall, the behaviours at the observed roundabouts varied depending on location factors. This research focused on the elements cited in Tables B.1 and 4.3 and, as best as possible, it controlled for other factors such as number of lanes, type of bicycle facility, and vehicle volumes. This section answered part of sub-question two as urban roundabouts with a strong attractor at one corner were found to lead to more non-compliant bicyclist behaviour. This was further accentuated when there were bi-directional bicycle facilities leading away from the roundabout (e.g. Boezemlaan/Karmelweg). In addition, compliance was lower at complex roundabouts such as Haarlemmermeerstation, or at ones with a narrow one meter buffer width between vehicles and bicycles.

(a) Aerial image of Haarlemmermeerstationplein in Amsterdam with 747 bicyclists per 15 min

(b) Haarlemmermeerstationplein, from the perspective of the motor vehicle, looking east to exit. Note that this vehicular crossing, bicycles have yielding priority and that the tram/bus lane turns as well.

(c) Haarlemmermeerstationplein, from the perspective of the motor vehicle, looking south to exit with the two southbound bus stops in the center of the image. Note that this vehicular crossing, vehicles have yielding priority (bicycles have to yield to cars).

Figure 5.6: Haarlemmermeerstationplein images, courtesy of Google Maps and Streetview, showing the complexity of this roundabout.

5.3. Respondent qualitative survey results

This research was able to gather additional user perspectives by distributing the survey via online methods (Linkedin and Ouders.nl) and asking the following final question to participants in an open style format:

Is there anything else you would like to mention regarding safety at roundabouts?

The full transcript of all the responses can be found in Appendix B.4. The following paragraphs describe the common themes that respondents raised.

5.3.1. Bicyclist and motorist behaviours

Many respondents said that Dutch drivers tend to always yield to bicyclists, especially at roundabouts where there is little buffer width between the vehicle lane and the bicycle path. Most respondents agreed that bicycles should always have yield priority at roundabouts, with a few noting that it's much more difficult for a bicyclist to stop and start again compared to a motor vehicle. Uniformity of roundabout designs and familiarity was mentioned, as this affects how vigilant a bicyclist or motorist may be in a difficult traffic situation. Some respondents noted that bicyclists must remain vigilant and not assume that cars will stop, regardless of who has priority.

5.3.2. Confusion and yielding priority

Confused bicyclists and drivers were mentioned often in regards to "near misses" or who yields to whom. This could have been due to the many different roundabout designs encountered, not only in the survey, but also from the respondents' experiences. This inconsistency creates a dangerous environment as bicyclists and motorists are unsure about who has the right-of-way, leading to hesitation and potential crashes. However, some respondents actually like this since it means that all road users are more alert. Uniformity in priority rules was frequently mentioned as a way to reduce confusion and improve safety.

5.3.3. Traffic volumes, two-way bicycle paths, and multi-lane roundabouts

Many respondents noted that increased car volumes make them feel less safe. One respondent mentioned that a good balance between car and bicycle volumes is crucial so that everyone respects fellow road users and obeys all the traffic signs. Survey respondent answers noted that increased bicycle congestion makes it uncomfortable to ride, especially when turning. Multi-lane roundabouts and bi-directional bicycle paths were frequently mentioned as problematic. Respondents said that these increase the complexity of navigating roundabouts, leading to higher crash risks. Many suggested that single-lane roundabouts would enhance safety by reducing confusion and ensuring smoother traffic flow. This last comment pertains to all kinds of roundabouts and all traffic types, from truck traffic to pedestrians.

5.3.4. Visibility, and other infrastructure changes

Survey respondents frequently mentioned vegetation, tall objects, and lighting as key factors that they use to determine their comfort level at a roundabout. This is partially consistent with past research that found that clear signage, and unobstructed views are crucial for safe roundabout navigation (Friel et al., 2023; Poudel and Singleton, 2021). Proper lighting was found to slightly increase bicycle crash risk in one study (van Bentem, 2022) and was found to be statistically insignificant in another (Akgün et al., 2018). These findings are counter-intuitive. In addition, respondents recommended infrastructure improvements, such as the installation of speed humps and the better placement of the bicycle paths within a roundabout, to enhance safety. Respondents also suggested that roundabouts should be designed to slow vehicles as they enter and exit, ensuring that drivers have ample time to notice and yield to bicyclists and pedestrians.

5.4. Discussion and conclusion

Bicyclists' compliance with traffic laws at roundabouts was seen to be strongly associated with the physical infrastructure present at the roundabout and adjacent geographical features. For example, bicyclists would go the wrong way when a grocery store was at the SE corner and they were entering the roundabout at the SW corner. This indicates that routing directness is important (bicyclists don't want to cross three vehicular legs when they could simply illegally cross one vehicular leg). Another observation related to compliance was when the buffer width of the roundabout was so narrow that it allowed bicyclists to weave into the vehicle lane. This was again bicyclists' efforts to minimize circuitous routing. Finally, roundabouts that consisted of 1/2 to 3/4 bi-directional bicycle paths were treated as if the entire roundabout was bi-directional by bicyclists. This aligns with the illegal movements observed at Stieltjesweg/Schoemakerstraat (Figure 5.4d) and the confusion by many bicyclists due to the non-uniform yielding priority rules observed at Haarlemmermeerstationplein.

This chapter described the roundabout observations done in the field, expert insights regarding the CROW design guidelines for roundabouts, and finally the comments given by survey respondents. Through a summary of the observations at the 50+ roundabouts, this chapter partially answered sub-question two: *What bicycle infrastructure design and behavioural factors affect bicyclists' compliance with traffic laws?* The observations of the roundabouts provided invaluable information regarding how Dutch bicyclists use roundabouts and obey or disobey traffic regulations. Revealed preference data is acquired through observation since survey respondents may not be inclined to admit that they disobey the law, when directly asked. The qualitative observations showed that if there is a strong attractor at one corner of a roundabout, then bicyclists' behaviours are to go via the most direct route to that corner, even if that means it would not be in compliance with traffic regulations.

Through a review of the expert insights, this chapter also partially answered sub-question four: *Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?* The anonymous survey responses from the CROW design workshops shed light on why the CROW design guidelines are not followed under certain, justifiable circumstances and what these designers think is most important regarding bicycle safety. An interesting note were the debates regarding bi-directional cycle paths, having a consistent design approach city-wide, and using roundabout design to lower speeds of e-bicycles. In both the expert insights and the qualitative survey results there was a lot of discussion on yielding priority, bi-directional bicycle paths, and roundabout visibility design components. Design uniformity was also mentioned in both response groups. Deviation from the CROW design guidelines contradicts a uniform design, which may be justified under certain conditions but it does lead to more confusion from a bicyclist's viewpoint.

Overall, this Chapter provided additional information that was used to further refine the survey and the ordered probit model described in the following Chapters and partially answered sub-questions two and four.

6
Quantitative analysis

This Chapter provides an overview of the dataset collected, the selection of the independent variables based on the conceptual framework from Chapter 3, and the detailed results from the final model run. Section 6.1, presents a summary of the respondent characteristics and provides additional descriptive statistical details. Sections 6.2 and 6.3 analyse the distribution curves for the indicators of the latent variables and check the correlation between all the variables (dependent as well as independent). Section 6.4 describes the variable selection process that was used to build the model and shows the results of the random effects ordered probit model. Finally, Section 6.5 discusses the objective safety record of each roundabout used in this research.

6.1. Descriptive analysis

In total, 260 respondents completed the survey. Out of those, 239 rode a bicycle (or e-bicycle or cargo bicycle). Each respondent had to rate their perceptions of safety and comfort for bicycling through all eight roundabouts. In total, 1912 perception ratings were collected (239 respondents x 8 locations). The distribution, mean, median, and standard deviation for both rated perceptions at each roundabout location are given in Table 6.1. Most (78.1%) answers for the indicator questions (comfort and safety) are in the range from 3 (neutral) till 5 (very comfortable or very safe). The following Tables and Figures show the various socio-demographic data of the respondents.

Table 6.2 presents the results from the socio-demographic questions. There were slightly more male respondents than female respondents which is representative of other bicyclist surveys. The average survey respondent age was 40, whilst the largest age group that completed the survey was people between 25 and 34 years old. Most respondents (85%) replied that they did not have a bicycle crash within the last three months. Every survey respondent answered that they have at least graduated secondary school, with over 80% holding a Bachelors degree or higher. The income question had a normal distribution. An interesting note was the strong majority of respondents saying that they believe their bicycle skills are very good, which is inline with other studies that show that people overestimate their skill level when asked to judge themselves (Wang and Akar, 2018; Richard Mantona et al., 2016 Sanders, 2015).

Table 6.1: Response distribution for comfort and safety. Refer to Table 4.3 for more information about each roundabout.

Rating	Roundabout 1	Roundabout 2	Roundabout 3	Roundabout 4	Roundabout 5	Roundabout 6	Roundabout 7	Roundabout 8
Comfort								
1 (Very uncomfortable)	1.1%	0.6%	1.7%	6.2%	3.9%	5.1%	1.1%	1.7%
2 (Somewhat uncomfortable)	14.7%	12.4%	28.8%	30.5%	25.9%	32.8%	13.0%	22.6%
3 (Neutral)	16.9%	17.5%	25.9%	23.7%	32.2%	24.9%	15.8%	22.0%
4 (Somewhat comfortable)	36.7%	36.7%	29.9%	28.2%	29.4%	26.6%	40.7%	33.3%
5 (Very comfortable)	30.5%	32.8%	13.6%	11.3%	8.5%	10.7%	29.4%	20.3%
Mean	3.80	3.88	3.25	3.09	3.13	3.06	3.83	3.46
Median	4	4	3	3	3	3	4	4
Mode	4	4	4	4	3	4	4	4
Std. Dev.	1.06	1.01	1.07	1.13	1.02	1.10	1.03	1.10
Safety								
1 (Very unsafe)	1.7%	2.2%	1.7%	2.8%	2.8%	5.1%	0.0%	1.7%
2 (Unsafe)	9.0%	6.8%	19.2%	19.8%	22.6%	24.9%	10.7%	16.4%
3 (Neutral)	24.3%	19.8%	29.9%	36.2%	40.1%	32.8%	18.6%	27.1%
4 (Safe)	52.5%	57.1%	41.8%	35.0%	31.6%	31.6%	50.3%	45.2%
5 (Very safe)	12.4%	14.1%	7.3%	6.2%	2.8%	5.6%	20.3%	9.6%
Mean	3.64	3.73	3.34	3.23	3.09	3.08	3.79	3.43
Median	4	4	3	3	3	3	4	4
Mode	4	4	4	4	4	2	4	4
Std. Dev.	0.88	0.87	0.93	0.92	0.87	0.99	0.89	0.95

Table 6.2: Distribution of respondents age, gender, education, income, skill level, transport mode of preference, and crash history

Variable		Respondents
Dutch respondent	(1) No*	29%
	(2) Yes	71%
Crash history	(1) Yes	14.7%
	(2) No*	84.7%
	(3) Prefer not to say	0.6%
Education	(1) Primary	0.0%
	(2) Secondary	10.2%
	(3) Bachelors-University*	38.9%
	(4) Masters/Phd-University	48.6%
	(5) Prefer not to say	2.3%
Gender	(2) Female*	45.8%
	(1) Male	52.5%
	(3) Non-binary	0.6%
	(4) Other	0.0%
	(5) Prefer not to say	1.1%
Age	18 - 24	10.7%
	25 - 34	34.5%
	35 - 44	15.3%
	45 - 54	19.8%
	55 - 64	11.8%
	65 - 74	4.5%
	≥75	1.1%
	prefer not to say	2.3%
Income	(1) <1,000	17.5%
	(2) 1,001 - 4,000*	35.6%
	(3) ≥4,000	33.3%
	(4) prefer not to say	13.6%
Skill Level	(1) inexperienced	0.0%
	(2) competent*	25.4%
	(3) highly skilled	74.0%
	(4) prefer not to say	0.6%

* Reference case for categorical variables. The age variable was reduced to a binary variable in the model with under 40 and over 40 year old as the two categories.

Table 6.3: Transportation mode usage

Mode of transportation	Walk	Normal bicycle	E-bicycle	cargo bicycle	special bicycle	scooter	motorcycle/ car	public transport
Everyday (5)	39.5%	29.9%	5.1%	1.1%	1.7%	3.9%	2.8%	5.3%
4-6 days per week (4)	20.3%	25.9%	4.5%	1.7%	0.6%	6.8%	12.9%	12.3%
1-3 days per week (3)	29.4%	21.5%	11.3%	1.7%	2.8%	17.5%	35.6%	34.6%
1-3 days per month(2)*	5.6%	9.0%	5.1%	5.6%	4.5%	27.1%	38.9%	36.1%
Never/I don’t own one(1)	5.1%	13.6%	74.0%	89.8%	90.4%	44.6%	9.6%	11.5%

* Reference case for categorical variables.

Tables 6.3, 6.4, 6.5, and 6.6 show additional information regarding survey responses, with the first one describing how respondents move around and how often and the second table presenting the bicyclist behavioural question responses respectively. The results of the mode choice for the bicycle type is consistent with other bicyclist surveys, showing that the prevailing bicycle type is still a normal bicycle, with e-bicycle being second. In Tables 6.4, 6.5, and 6.6 the questions are broken down by the latent variable groups of the CBQ. It is interesting to note that in the violations group, almost half of the respondents admitted to disobeying a red traffic light, if there is no sign of any vehicles. In the positive attitude group, the prudent speed question had a fairly balanced response, with 31% of respondents saying that they do not go at a prudent bicycling speed to avoid sudden braking. Overall, only one or two respondents said that they always do all the risky behaviours (the errors and violations groups). The next section will discuss the distribution of the indicator variable responses for the safety and comfort variables.

Table 6.4: Cyclist behavioural questionnaire (CBQ) respondent distribution. For information on the label column, please refer to Appendix D.2.5.

Label	**Question Formulation**	**Never (1)***	**Sometimes (2)**	**1/2 time (3)**	**Most of the time (4)**	**Always (5)**
	Violations latent variable group					
2	Cycling under the influence of alcohol and / or other drugs or hallucinogens.	38.4%	42.9%	15.3%	2.8%	0.6%
3	Going against the direction of traffic (wrong way).	29.9%	49.7%	18.1%	1.7%	0.6%
10	Crossing what appears to be a clear crossing, even if the traffic light is red.	17.5%	41.8%	22.6%	13.6%	4.5%
	Errors latent variable group					
17	Unintentionally, crossing the street without looking properly, making another vehicle brake to avoid a crash.	77.9%	20.3%	1.1%	0.0%	0.6%

* Reference case for categorical variables.

Table 6.5: CBQ respondent distribution (continued). For information on the label column, please refer to Appendix D.2.5.

Label	Question Formulation	Never (1)*	Sometimes (2)	1/2 time (3)	Most of the time (4)	Always (5)
	Errors latent variable group					
18	Colliding (or being close to it) with a pedestrian or another bicyclist while cycling distractedly.	72.3%	25.9%	1.1%	0.0%	0.6%
20	Brake suddenly and be close to causing an accident.	70.1%	28.2%	1.1%	0.0%	0.6%
22	Not braking on a “Stop” or “Yield” sign/marking and being close to colliding with another vehicle or pedestrian.	77.4%	20.9%	1.1%	0.0%	0.6%
30	Failing to be aware of the road conditions and therefore falling over a bump or hole.	58.8%	31.6%	9.0%	0.0%	0.6%
31	Mistaking one traffic signal for another, and maneuvering according to the latter.	61.6%	32.2%	5.6%	0.0%	0.6%
	Positive Attitude latent variable group					
36	I try to move at a prudent speed to avoid sudden mishaps or braking.	19.8%	11.3%	16.9%	34.5%	17.5%
38	I keep a safe distance from other bicyclists or vehicles.	2.3%	5.1%	9.6%	62.7%	20.3%

* Reference case for categorical variables.

Table 6.6: CBQ respondent distribution (continued). For information on the label column, please refer to Appendix D.2.5.

Label	Question Formulation	Never (1)*	Sometimes (2)	1/2 time (3)	Most of the time (4)	Always (5)
	Positive Attitude latent variable group					
39	When I use the bicycle path (or bicycle-lane), I use the indicated lane.	0.0%	1.1%	2.3%	50.3%	46.3%

* Reference case for categorical variables.

6.2. Distribution

Latent variables can not be directly observed, however the indicator for those variables can be shown. The following Figures show the distributions for each of the indicators that show the manifestation of each latent variable. Figure 6.1 shows the distribution of responses for the comfort indicator whilst Figure 6.2 shows the distribution of responses for the perception of safety indicator.

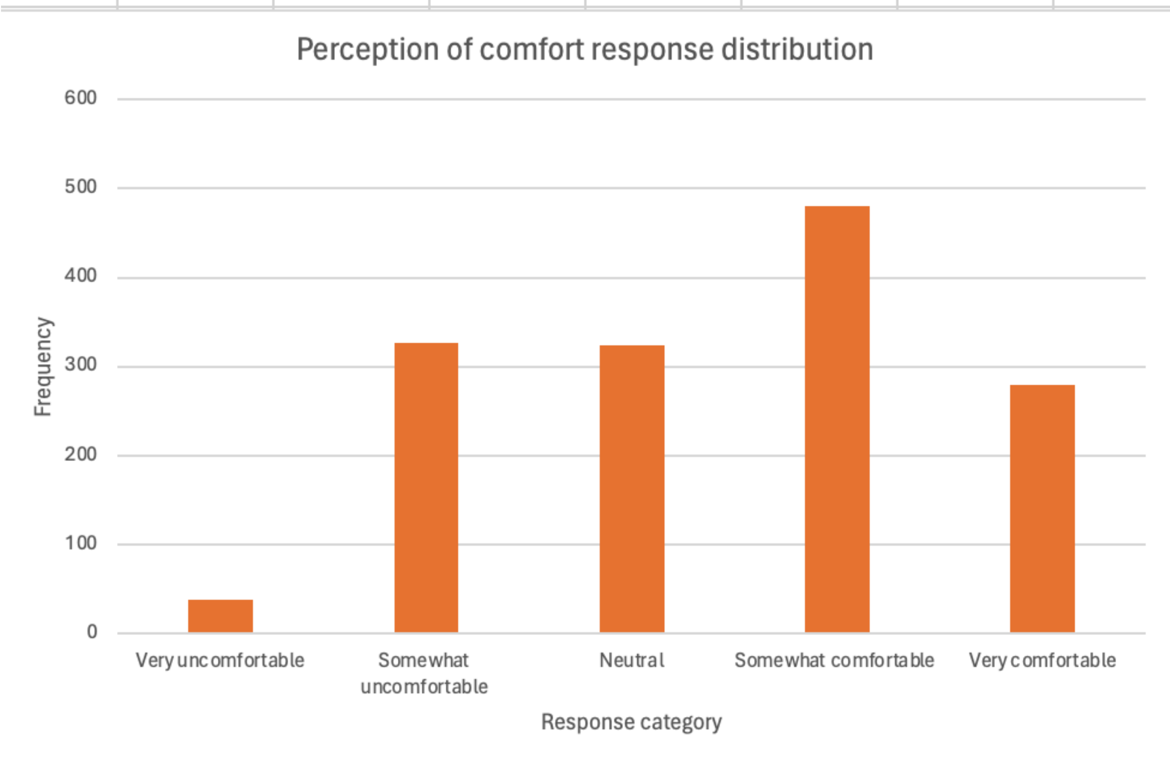


Figure 6.1: Comfort distribution histogram distribution from the respondents of the indicators of the latent variables

Both distributions have a skewness coefficient of above 0.5 which denotes a positive skewness (both histograms are skewed to the right side or comfortable/safe side). The comfort response distribution is nearly symmetric but with a flat top compared with a pronounced peak that is seen for the safety latent variable. Using kernel density estimation (KDE), the histograms in Figures 6.1 and 6.2 are transformed into a continuous probability density function in order to determine what distribution is the best fit for the datasets.

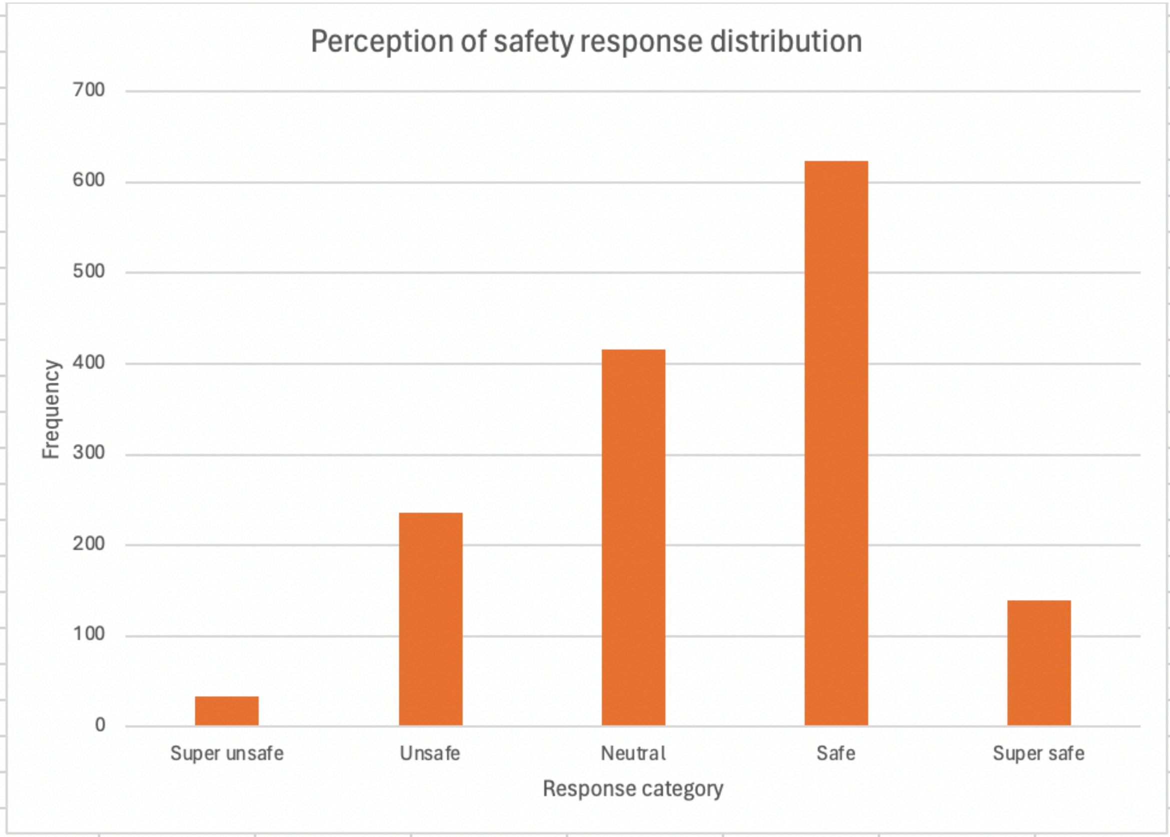


Figure 6.2: Perception of safety distribution histogram distribution from the respondents of the indicators of the latent variables

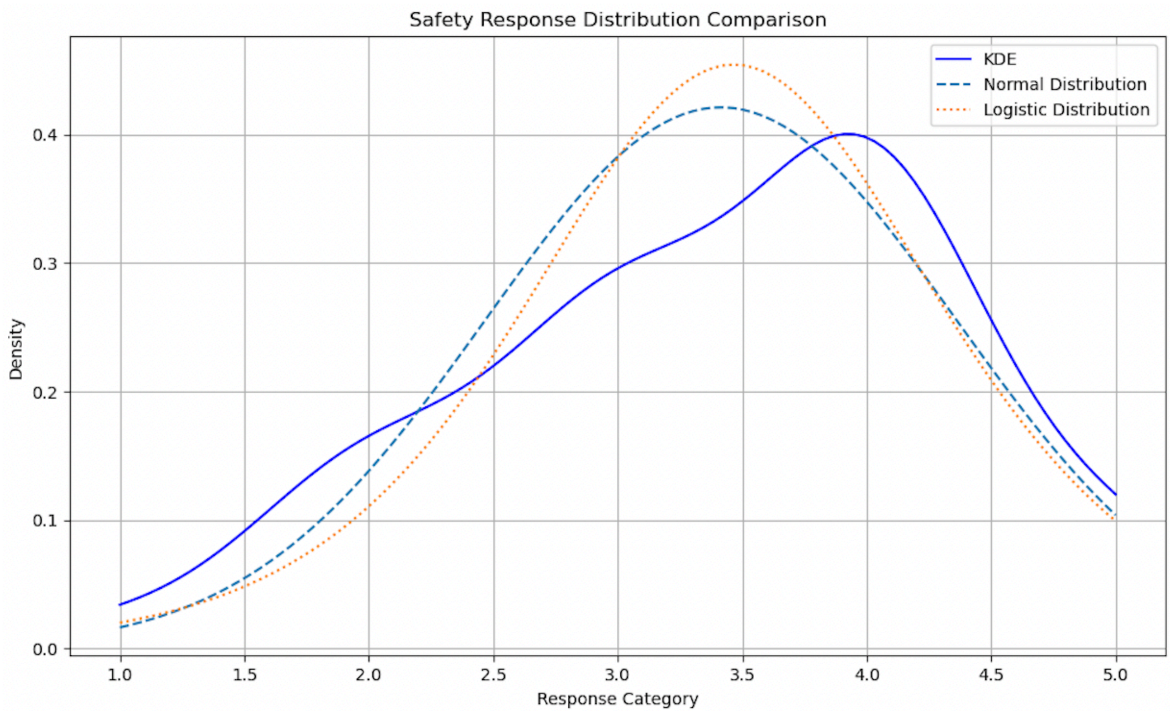


Figure 6.3: Comfort indicator response distribution curve and normal and logistic distribution curves.

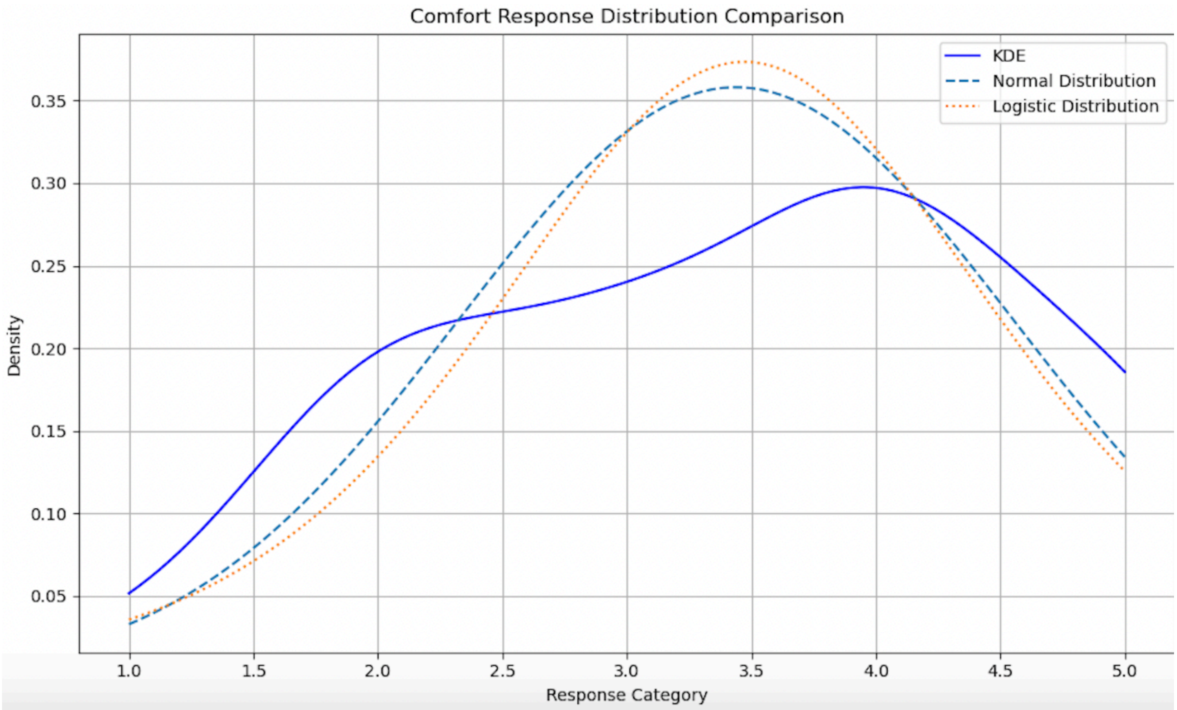


Figure 6.4: Safety indicator response distribution curve and normal and logistic distribution curves.

Figures 6.3 and 6.4 show the comparison of the KDE with normal and logistic distribution curves for both of the indicators. One can note that the distributions of the two indicators fit neither a logistic distribution nor a normal distribution curve. This is due to the fact that the data is categorical with a small sample size. This report will proceed with the use of a discrete normal distribution which is the assumption for the use of a ordered probit model.

6.3. Multicollinearity review

Before the variables are placed into the multivariate ordered probit model, a multicollinearity check was performed. This was done to determine in advance if certain variables would cause instability in the model runs and also to help the research team make appropriate variable selections. In addition, a check on the roundabout attribute variables should be done to ensure that the experimental design was done correctly, which would mean insignificant correlations amongst those variables. As shown in Figures 6.5 and 6.6, the roundabout attributes are not correlated with any other variable (right hand side of the charts).

Figure 6.5 shows all 12 of the CBQ questions numbered as Q1_X and one may note that many of the CBQ variables had a high correlation to the gender variable. In addition, the positive attitude variables (Q1_10, Q1_11, Q1_12) are all negatively correlated with the other CBQ variables, which is in line with results and theories of past studies. By combining the CBQ variables into only three groups (violations, errors, and positive behaviour) as shown in Figure 6.6, this research was able to reduce the multicollinearity amongst those variables (in particular between Q1_2 and Q1_12) to improve the model stability. The bicycle crash history variable was found to be highly correlated with the bicycle skill level variable. In addition, both the comfort and safety variables are highly correlated. This is in line with the hypothesis of this research.

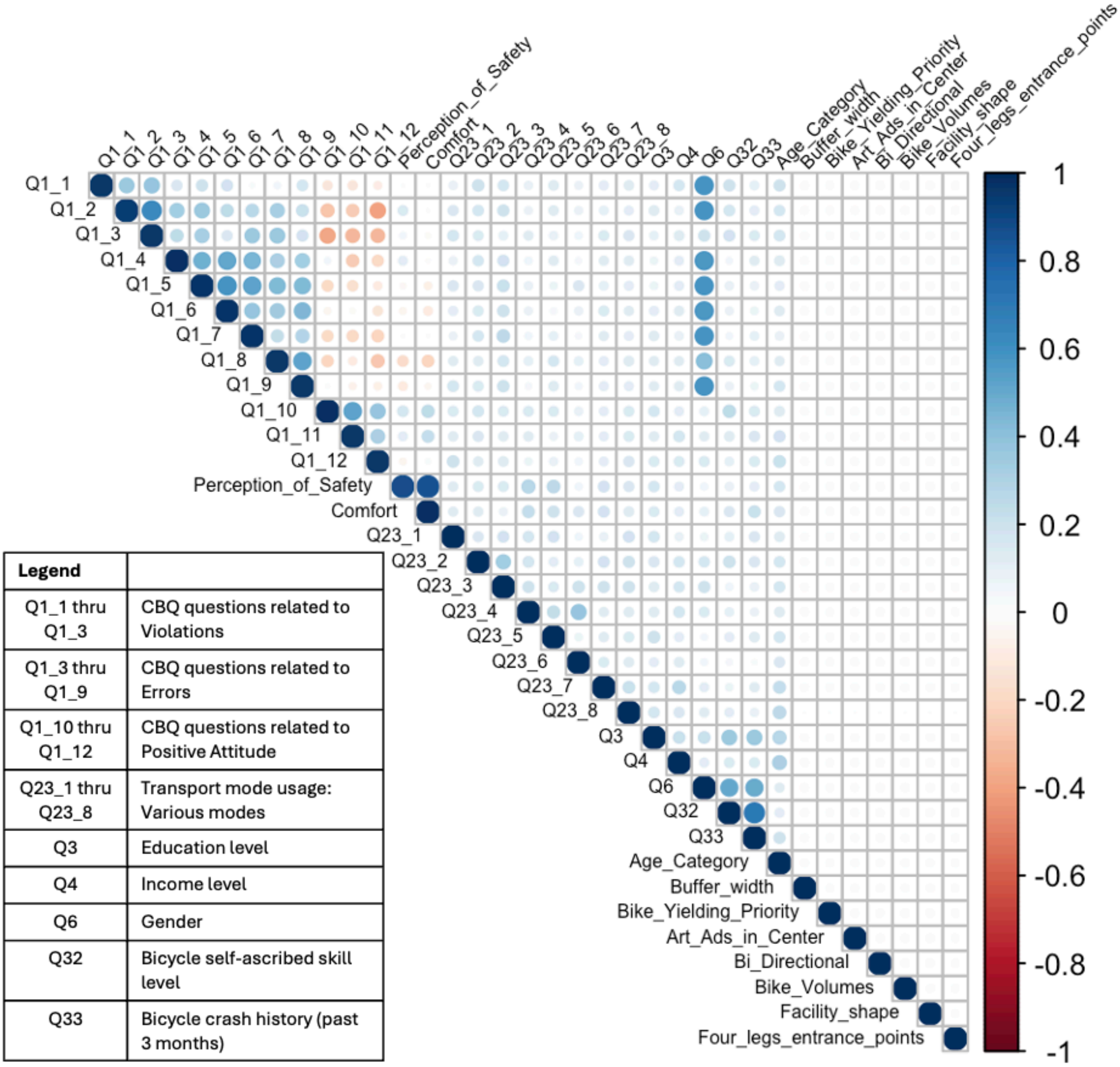


Figure 6.5: Multicollinearity graph, with 0 representing pure non-collinear variables whilst -1 or 1 symbolize 100% collinearity between the two variables. Q1_X variables are the CBQ questions used in the final survey. Q23_X variables represent the following transport modes in order: walking, normal bicycle, e-bicycle, cargo bicycle, special bicycle, scooter, car/motorcycle, and public transport.

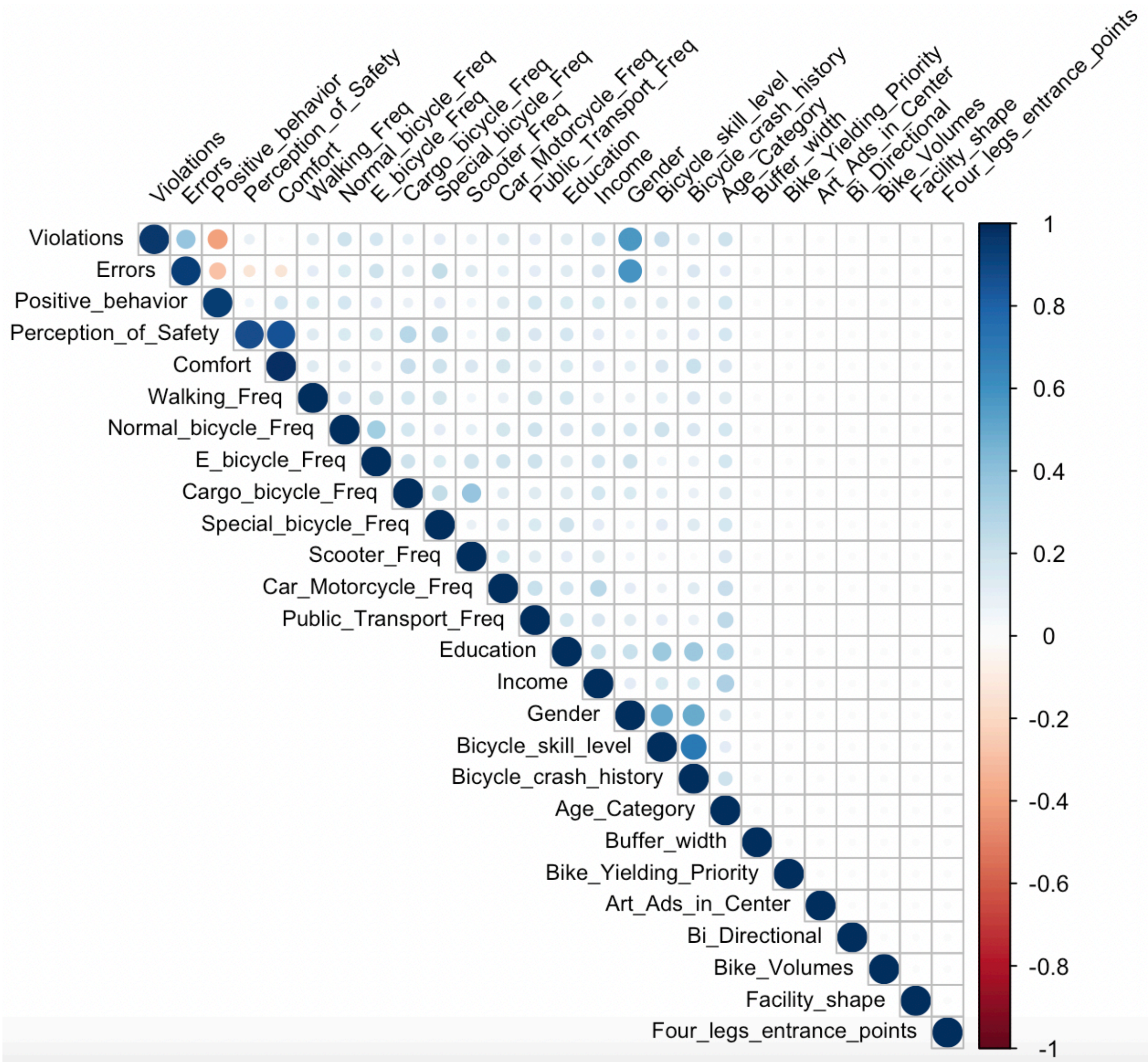


Figure 6.6: A revised multicollinearty graph, showing the combined three CBQ categorical variables, with 0 representing pure non-collinear variables whilst -1 or 1 symbolize 100% collinearity between the two variables.

6.4. Random effects ordered probit

This section describes the variable selection process and the results of the random effects ordered probit model. This research used the program R Studio and the programming language R in order to run the random effects ordered probit model. For more information regarding the pseudo code and programming, please refer to Appendix E. In order to address the research goals and objectives, it was decided to proceed with variable selection in the following order:

1. Analyse all seven of the roundabout attributes, starting with the ones outlined in the hypotheses in Chapter 3.

2. Keep only the roundabout attribute variables that are statistically significant or that help lower the BIC and fit within the conceptual framework (i.e. the presence of art and advertisements would logically improve a bicyclist's perception of comfort).

3. Use the hypotheses from Chapter 3 to add in socio-demographic independent variables one at a time, adjusting them so that the reference category would be logical (see Tables 6.2, 6.3, 6.5, 6.4). This addition also answers research sub-question three, which investigates the differences between respondent groups. Note that not all socio-demographic variables were included in the final model (e.g. income and education) due to the following reasons:

- They were not statistically significant for either latent variable.
- They were not the main focus of the research.
- They were not included in the hypotheses developed.

4. Keep Age and Gender variables in the final model, despite being non statistically significant in one or both latent variables.

5. Add in the consolidated CBQ independent variables. Keep the ones that were statistically significant and helped provide a better model fit. The consolidation of the CBQ questions was previously discussed in Sections 3.3, 4.4, and 6.3.

6. Add in the mode frequency variables one at a time in order to see if differences in a person's most often used transport mode have an impact on a their perceptions of safety and comfort. The cargo bicycle frequency variable was the only variable that was kept at two categories in the final model (sometimes and everyday) due to the change of sign which will be described further in this Section. Only the normal bicycle, e-bicycle, and cargo bicycle were retained in the final model, due to the low model fit improvement when adding in other modes.

More detailed information about the model setup and run processes can be found in Appendices D.4 and D.5. Important assumptions regarding socio-demographic and CBQ variables are mentioned in the next paragraph as they impact the final model results and subsequent model interpretations.

Socio-demographic and CBQ variables
Age was initially included as a continuous variable in the regression model run, which is in line with past studies (Poudel and Singleton, 2023; Pieters, 2019) and was found to be significant for both perception of safety and comfort variables. However, it was decided to make the age variable binary in order to match the other socio-demographic variables. This change also solved errors that occurred when calculating the elasticities. When the age variable was marked as binary, it was not statistically significant in the comfort variable as shown in Table 6.7 below. It was decided to leave it in the final model run due to it's importance for sub-question three and for the conceptual framework. More information on this is presented in Section 6.4.1. The following remaining variables were marked as categorical:

- Dutch respondents (binary)
- gender
- crash history
- frequency of normal bicycle use
- frequency of e-bicycle use
- frequency of cargo bicycle use

The variable selection process also involved deciding on what category level to use for comparison with the reference category in order to provide a meaningful model. It was chosen to compare the "sometimes" response with the "most of the time" response level for the CBQ independent variables. For the transportation mode frequency variables, it was chosen to compare an infrequent usage (1 to 3 days per month) with a very frequent usage (everyday). The study analysed an additional frequency for cargo bicycles (3 to 4 days per week). The following paragraph describes how the model results are formatted and what each column signifies.

General results and result output format
The parameters in this model output consist of four thresholds denoted by the five categories in the Likert scale. Due to the calculation of an intercept for each latent variable, the first threshold is zero and is only a reference. All the other threshold estimates were statistically significant at the 99% confidence level, which symbolizes a good model fit for the categorical data. In addition, the intercepts for both latent variables and the correlation estimates of the random terms for the two latent variables are also statistically significant at the 99% confidence level. The results table presents the beta estimates,

standard errors, Z values, the P value associated with the Z value, and the upper and lower confidence intervals. When the P value is small, that indicates that the null hypothesis can be rejected and that particular variable is significant in the model. Finally, at the end of the table, there are various goodness of fit measurements, such as the Akaike information criterion (AIC) and the Bayesian information criterion (BIC). Log-likelihood is also shown but, by itself, it has no penalization for the number of variables in the model thus only a log-likelihood ratio test or a Chi-square calculation can provide a measure of model fit. All of these indicators look at model complexity, degrees of freedom, and how well the model can predict future data. Values closer to zero demonstrate a better goodness of fit for the model.

6.4.1. Effect of the roundabout characteristics and other factors on perceptions of safety and comfort

The coefficients of the roundabout characteristics on the safety and comfort perception ratings, according to the random effect ordered probit model equation (4.1), can be found in Table 6.7 below. In line with the hypothesis presented in Chapter 3, the correlation between the two latent variables is of positive sign and strongly statistically significant. The AIC and BIC values are equal to 8710.4 and 8931.6, respectively. During the variable selection process, adding more variables would have only caused the BIC to increase. Thus, the decision was made to no longer proceed with variable addition. If one were to perform a model run with only the roundabout attributes, the BIC and AIC values would be higher. This is consistent with past research, where more statistically significant explanatory variables help form a better model fit.

Table 6.7 shows the beta estimates, standard deviations, Z and P values, and the confidence intervals for the independent variables aswell as the for the threshold of the latent variables. A coefficient with a positive sign indicates that the corresponding parameter is directly associated with higher perceptions of safety or comfort, whereas a negative sign implies a reverse impact. Table 6.7 shows that three of the seven roundabout attribute variables were statistically significant at the 0.1 level and of plausible sign. The art, facility shape, bi-directional bicycle path, and buffer width variables were not statistically significant. The yielding priority independent variable was of positive sign and significant at a 99% confidence level. This means that if there is yielding priority for bicycles, then it increases respondents' perceptions of safety and comfort. On the contrary, higher bicycle volumes showed a negative sign, indicating that respondents' perceptions of safety and comfort decreased when roundabouts with that feature were presented. An interesting note is the roundabout legs attribute as that was of negative sign and was significant at a 90% confidence level. This was an unexpected result since there were roundabouts in the survey that had 3, 4, and 5 legs. More details can be found in the discussion chapter, Chapter 7.

In terms of the CBQ and socio-demographic variables, the Violations variable is marginally significant for comfort but it is more statistically significant for safety. This is intuitive as violations would affect the perception of safety latent variable more. The gender variable was found to not be statistically significant but it remained in the final model since it addresses one of the hypotheses. The model results found that Dutch respondents perceived higher safety and comfort levels, when compared with respondents who do not live in the Netherlands. The age variable was negative, which is intuitive: older cyclists perceive less comfort and safety; this suggests that an older population has greater sensitivity to a roundabout whilst controlling for certain design features such as yielding priority, compared with a younger population (Poudel and Singleton, 2023; Wegman and Schepers, 2024; Shen et al., 2020; Kazemzadeh et al., 2024). The bicycle crash history variable was negative in sign and very statistically significant. This is also intuitive and aligns with past studies that have shown that if one has been in a recent crash, one will have a lower perception of safety and comfort (Møller and Hels, 2008).

The final group of independent variables were the mode frequency variables. The normal bicycle and e-bicycle mode variables (comparing a frequency of 1 to 3 days per month to everyday) were statistically significant and positive of sign. This is intuitive: as people bicycle more, they have higher perceptions of comfort and safety. There was an interesting finding between the safety latent variable and the cargo bicycle frequency variable. The difference in sign between the different frequency levels shows that subjective safety is subject to how often one rides a cargo bicycle. For example, a person who rides a cargo bicycle only 4 to 6 days per week will have negative perceptions of safety compared with

Table 6.7: Random effects ordered probit model results, showing confidence intervals and estimated beta coefficients.

Thresholds	Estimate	Std. Error	z value	Pr(>|z|)	CI Upper	CI Lower
Comfort: Very uncomfortable -uncomfortable	0.0000	0.0000	NA	NA	NA	NA
Comfort: Uncomfortable-neutral	1.2395***	0.0560	22.134	0.0000	1.3493	1.1297
Comfort: neutral-comfortable	1.8956***	0.0608	31.158	0.0000	2.0148	1.7764
Comfort: comfortable -very comfortable	2.9098***	0.0688	42.317	0.0000	3.0446	2.7750
Safety: Very unsafe-unsafe	0.0000	0.0000	NA	NA	NA	NA
Safety: unsafe-neutral	1.0791***	0.0617	17.495	0.0000	1.2000	0.9582
Safety: neutral-safe	1.9703***	0.0690	28.541	0.0000	2.1055	1.8351
Safety: safe-very safe	3.4187***	0.0814	41.991	0.0000	3.5782	3.2592
Coefficients:						
(Intercept) (Comfort)	1.7921***	0.0918	19.517	0.0000	1.6121	1.9721
(Intercept) (Safety)	1.9548***	0.0979	19.961	0.0000	1.7628	2.1467
Bike_Volumes (Comfort): Yes	-0.1221*	0.0496	-2.464	0.0137	-0.2192	-0.0250
Bike_Volumes (Safety): Yes	-0.1427**	0.0501	-2.852	0.0044	-0.2408	-0.0446
Bike_Yielding_Priority (Comfort): Yes	0.5601***	0.0502	11.167	0.0000	0.4618	0.6584
Bike_Yielding_Priority (Safety): Yes	0.5291***	0.0509	10.386	0.0000	0.4292	0.6289
Bi_Directional (Comfort): Yes	-0.0347	0.0347	-1.000	0.3174	-0.1027	0.0333
Buffer_width (Comfort): Large 1	0.0084	0.0498	0.168	0.8663	-0.0892	0.1059
Buffer_width (Safety): Large	-0.0362	0.0498	-0.727	0.4671	-0.1338	0.0614
Art_Ads_in_Center (Comfort): Yes	-0.0437	0.0348	-1.256	0.2093	-0.1119	0.0245
Four_legs_entrance_points (Comfort): Yes	-0.1456**	0.0496	-2.933	0.0034	-0.2428	-0.0483
Four_legs_entrance_points (Safety): Yes	-0.1222*	0.0501	-2.439	0.0147	-0.2204	-0.0240
Respondent residence (Comfort): Netherlands	0.4155***	0.0595	6.981	0.0000	0.2989	0.5322
Respondent residence (Safety): Netherlands	0.4864***	0.0604	8.049	0.0000	0.3680	0.6049
Age_Category (Comfort): 40+	-0.0175	0.0513	-0.341	0.7328	-0.1182	0.0831
Age_Category (Safety): 40+	-0.1813***	0.0527	-3.439	0.0006	-0.2847	-0.0780
Gender (Comfort): Male	0.0167	0.0519	0.322	0.7474	-0.0850	0.1184
Gender (Safety): Male	-0.0259	0.0526	-0.492	0.6229	-0.1290	0.0773
Bicycle_crash_history (Comfort): Recent	-0.3817***	0.0846	-4.514	0.0000	-0.5475	-0.2160
Bicycle_crash_history (Safety): Recent	-0.3108***	0.0845	-3.681	0.0002	-0.4764	-0.1453
Violations (Comfort): Most of the time 1	0.2683*	0.1118	2.401	0.0163	0.0493	0.4874
Violations (Safety): Most of the time	0.3352**	0.1090	3.074	0.0021	0.1215	0.5490
Errors (Comfort): Most of the time	-0.5355*	0.2591	-2.067	0.0387	-1.0433	-0.0277
Positive_behaviour (Comfort): Most of the time	0.0786*	0.0361	2.180	0.0293	0.0079	0.1493
Normal_bicycle_Freq (Comfort): Everyday	0.2926***	0.0645	4.539	0.0000	0.1662	0.4189
Normal_bicycle_Freq (Safety): Everyday	0.1383*	0.0639	2.163	0.0306	0.0130	0.2636
E_bicycle_Freq (Comfort): Everyday	0.3494**	0.1157	3.021	0.0025	0.1227	0.5761
E_bicycle_Freq (Safety): Everyday	0.3388**	0.1133	2.991	0.0028	0.1168	0.5607
Cargo_bicycle_Freq (Comfort): Sometimes	-0.0948	0.1675	-0.566	0.5716	-0.4232	0.2336
Cargo_bicycle_Freq (Safety): Sometimes	-0.6931***	0.2081	-3.330	0.0009	-1.1010	-0.2852
Cargo_bicycle_Freq (Comfort): Everyday	0.9700	0.8478	1.144	0.2526	-0.6917	2.6318
Cargo_bicycle_Freq (Safety): Everyday	1.2085**	0.3895	3.102	0.0019	0.4450	1.9720
Error Structure:						
corr Comfort Safety	0.8089***	0.0094	86.013	0.0000	0.8273	0.7905
Measure	**Value**					
Log-likelihood	-4315.395					
Akaike information criterion (AIC)	8710.415					
Bayesian information criterion (BIC)	8931.607					
Number of observations	239					

*, **, *** indicate significant at 90%, 95%, 99% confidence level, respectively.

a person who rides an e-bicycle everyday.

As can be seen from the results of the model, some independent variables were found to be only significant in one of the latent variables (perception of safety or comfort), but not both. This was the case for the cargo bicycle frequency variable, errors and positive behaviour CBQ variables, and the age variable. The age and cargo bicycle frequency variables had statistically significant beta estimates for the safety latent variable whilst the errors and positive behaviour CBQ variables had low p values for the comfort latent variable. This demonstrates the latent differences between the comfort versus perception of safety variables, which is also shown in Table 6.1 in the descriptive statistics, where respondents rated each of the eight roundabout locations. The results of the model follow the conceptual model shown in Figure 3.1 with exception of certain independent variables that were dropped due to low explanatory value (self-ascribed bicycling skill level, income, and education). The following hypotheses stated in Section 3.2 were shown to be at least partially true:

- Bicyclists who have recently experienced a crash or ”near miss”, will perceive a higher risk at a roundabout, regardless of the design features.
- Higher traffic volumes leads to higher perceived risk by bicyclists.
- Females and elderly bicyclists will have a higher perception of risk.
- A bicyclist’s perception of safety and comfort are highly correlated.

The hypothesis that yielding priority for cars does not increase a bicyclist’s perceived risk turned out to be false. The other hypotheses can not be rejected as the model did not find the variables in question to be statistically significant. More interpretation of these results can be found in Chapter 7.

6.4.2. Elasticities

Due to the non-linear nature of random effect ordered probit equations (equation 4.1), one can not directly read the beta coefficients (estimate values).

Table 6.8: Elasticities table - Comfort latent variable

	Comfort variable				
Variable	Very uncomfortable	uncomfortable	neutral	comfortable	very comfortable
Bike_Volumes: High	0.390	0.250	0.010	-0.020	-0.304
Bike_Yielding_Priority: Yes	-0.180	-0.160	0.010	0.204	0.098
Bi_Directional: Yes	0.310	0.210	-0.010	-0.250	-0.270
Buffer_width	-0.350	-0.240	0.010	0.270	0.380
Art_Ads_in_Center	0.320	0.220	-0.010	-0.322	-0.250
Four_legs_entrance_points	0.390	0.240	0.010	-0.420	-0.108
Respondent_residence: Netherlands	-0.470	-0.300	-0.010	0.523	0.312
Age_Category: 40+	0.390	0.280	-0.020	-0.404	-0.324
Gender: Male	-0.490	-0.330	-0.020	0.548	0.297
Bicycle_crash_history: Recent	0.120	0.080	-0.020	-0.094	-0.158
Violations: Most of the time	-0.190	-0.387	-0.240	0.497	0.253
Errors: Most of the time	0.338	0.194	-0.248	-0.258	-0.018
Positive behaviour: Most of the time	-0.410	-0.097	-0.305	0.328	0.411
Normal_bicycle_freq: Everyday	-0.286	-0.119	0.038	0.204	0.308
E_bicycle_freq: Everyday	-0.119	-0.284	-0.096	0.429	0.198
Cargo_bicycle_freq: Sometimes	0.237	0.169	0.056	-0.295	-0.167
Cargo_bicycle_freq: Everyday	-0.036	-0.429	-0.033	0.444	0.299

bold indicates a independent variable that is statistically significant at least at the 90% confidence level.

As such, elasticities are calculated for every level of each latent variable. Presenting the elasticities of the estimated parameters helps to interpret the practical effect of each variable on the likelihood of a comfort level or perceived safety ranking. The parameter estimates of the ordered probit model alone are not sufficient to explore the impacts of each factor on the likelihood of different comfort level or perceived safety categories (Jafari Anarkooli et al., 2017). In essence, it is how many percentages you obtain when you change 1% of the independent variable. The greater the elasticity, the more important that independent variable is for the latent variables. Tables 6.8 and 6.9 show the elasticities from the model presented in Section 6.4.1 for each category of each latent variable.

According to the elasticities, the presence of yielding priority for bicycles increases the probability of a bicyclist feeling comfortable by 20%, whereas the lack of yielding priority increases the probability of a bicyclist feeling very uncomfortable by 18%. It was found that high bicycle volumes at roundabouts increase the probability of a bicyclist feeling very uncomfortable by 39%. If a bicyclist often commits violations (according to the CBQ violations questions), that increases the probability of a bicyclist feeling comfortable by 50%. Behavioural variables such as crash history and bicycling frequency were found to have similar or higher elasticities than roundabout attribute variables for the comfort latent variable.

Table 6.9: Elasticities table - Perception of safety latent variable

	Perception of Safety variable				
Variable	very unsafe	unsafe	neutral	safe	very safe
Bike_Volumes: High	0.390	0.250	-0.040	-0.259	-0.348
Bike_Yielding_Priority: Yes	-0.180	-0.140	-0.020	0.158	0.129
Bi_Directional: Yes	NC	NC	NC	NC	NC
Buffer_width	0.350	0.230	-0.040	-0.422	-0.298
Art_Ads_in_Center	NC	NC	NC	NC	NC
Four_legs_entrance_points	0.390	0.260	-0.040	-0.189	-0.287
Respondent_residence: Netherlands	-0.470	-0.280	-0.040	0.479	0.349
Age_Category: 40+	0.390	0.230	-0.030	-0.277	-0.314
Gender: Male	0.490	0.250	-0.020	-0.399	-0.467
Bicycle_crash_history: Recent	0.120	0.170	0.040	-0.245	-0.097
Violations: Most of the time	-0.248	-0.316	-0.094	0.469	0.149
Errors: Most of the time	NC	NC	NC	NC	NC
Positive behaviour: Most of the time	NC	NC	NC	NC	NC
Normal_bicycle_freq: Everyday	-0.359	-0.186	-0.249	0.456	0.228
E_bicycle_freq: Everyday	-0.306	-0.149	0.068	0.265	0.487
Cargo_bicycle_freq: Sometimes	0.117	0.059	-0.368	-0.088	-0.159
Cargo_bicycle_freq: Everyday	-0.358	-0.296	-0.049	0.198	0.269

bold indicates a independent variable that is statistically significant at least at the 90% confidence level.

Table 6.9 displays some rows as NC, meaning that those variables were not calculated for the safety latent variable by the model. According to the elasticities, the presence of a four-legged roundabout increases the probability of a bicyclist feeling unsafe by 26%. The mode frequency independent variables had many different statistically significant categories, but this report will explain a few of them. If a bicyclist uses a normal bicycle or an e-bicycle everyday, that increases the probability of the bicyclist feeling very safe by 23% and 49% respectively. Furthermore if a person responded that they use a cargo bicycle everyday, the likelihood of a bicyclist feeling very safe increases by 27%. An interesting elasticity value was if a bicyclist uses a cargo bicycle only 1 to 3 days per week, then that decreases the probability of the bicyclist feeling very safe by 16%. Additional discussion and interpretation of these results can be found in Chapter 7.

6.5. Reported crashes

This section starts to address sub-question five by analyzing the publicly available crash data for the eight study locations that were used in the survey. This way, a link can be made between locations that had many reported crashes and those that ranked low in the comfort and/or perception of safety ratings. In total, six crashes occurred at three roundabouts over a 10 year period. A request to SWOV for more detailed information on these and other reported crashes within the Randstad was not fulfilled at the completion of this research.

The information from Table 6.10 shows that the survey roundabout with the highest number of reported crashes was Meerzichtlaan/Berglaan in Pijnacker. Note that the crash data filter called BEBKOM could not be used since there was some mislabeling of where crashes occurred (e.g. the police officer incorrectly marked that roundabout X was located outside of an urban area).

Table 6.10: Crash data for the study roundabouts–from 2013 to 2022

Location	Date/time	Additional info
Dierenselaan/ Apeldoornselaan	2020	Collisions with a fixed object–Material damage only –eastbound direction–dry conditions–daytime
Neherkade/ Slachthuisstraat	N/A	N/A
Putsebocht tram stop	N/A	N/A
Planbaan/Kernbaan	N/A	N/A
Amstelplein	N/A	N/A
Gordelweg/ Rodenrijsestraat	N/A	N/A
Meerzichtlaan/ Berglaan	2017	Broadside collision–Material damage only–nighttime–dry conditions—southbound
	2017	Rear-end collision–Injury collision–daytime–dry conditions—southbound
	2017	Rear-end collision–Injury collision–daytime–dry conditions—southbound
Delftlandplein	2017	Injury collision–Sideswipe/broadside collision–eastbound–dry conditions–daytime
	2022	Material damage only–Unknown collision type–southbound-dry conditions–daytime–collision into right outer curb of roundabout

6.6. Summary of Quantitative analysis results

This Chapter outlined the model variable selection, explained a descriptive statistic and multicollinearity analysis, and presented the multivariate ordinal model results that were used to analyse the survey data regarding bicyclist comfort and perception of safety. The model results showed the complexity of the dataset and depicted how each model equation (safety vs comfort) captures different beta values due to its unique model parameters. The following roundabout attribute variables were found to be statistically significant for both latent variables: bicycle yielding priority, bicycle volumes, and number of legs of a roundabout. In addition, the following independent variables were also found to be significant: bicycle crash history, location of respondent, the normal and e-bicycle modes, and the CBQ violation subgroup variables. The age variable was statistically significant for the safety latent variable. If a person responded that they use a cargo bicycle either everyday or a few times per week, then the perception of safety latent variable was statistically significant. Overall, the final model presented a good fit for the data and there was a high positive correlation between the two latent variables that was statistically significant. The elasticities of the final model show that the more often a bicyclist rides bicycles or cargo bicycles, the higher the probability is that the bicyclist will feel safe at a roundabout. Finally a crash analysis was performed using publicly available data from the past 10 years. There were very few crashes reported at the roundabout locations used in this analysis. More information on the interpretation of the results and a corresponding discussion is addressed in the next Chapter.

7

Interpretation and discussions

7.1. Interpretation of results

The results presented in Chapters 5 and 6 show that both roundabout bicycle infrastructure design and behavioural factors have an impact on a bicyclist's perception of safety and comfort, with some factors having more or less importance. Notably, in terms of perception of comfort towards roundabouts, one's frequency of use of an e-bicycle or normal bicycle was found to be more important than the design feature of yielding priority. Another important finding was that roundabouts that have a strong attractor at one corner and a high bicycle volumes had a lower perception of safety and comfort. This is intuitive since a strong attractor such as a grocery store or a geographic barrier will cause more turning movements which causes friction amongst bicyclists and between bicyclists and other modes. This would cause lower perceptions of safety and could lead to more actual crashes. The following subsections will discuss these factors aswell as modeling and research decisions, and answer the research sub-questions.

7.1.1. CROW design guidelines

This section will answer sub-question four: *Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?* This was done by analyzing the 8 roundabouts used in the survey, comparing them to CROW design guidelines, and then examining the random effects ordered probit model results. The aim of the model was to have independent variables predict safety and comfort, and whether they positively or negatively impacted the latent variables. Roundabouts four, five , and six (Planbaan/Kernbaan, Amstelplein, and Gordelweg/Rodenrijsestraat respectively) did not follow CROW design guidelines as they did not provide yielding priority to bicyclists. At these locations there was a noticeable drop in the percentage of respondents who answered favorably (i.e. either neutral to high feeling of safety or comfort). The average neutral-positive ratings for comfort were 65.2% compared with the average of 80.4% at the other roundabouts where bicyclists have yielding priority. The average neutral-positive ratings for perception of safety were 74% compared with the average of 86.1% at the other roundabouts. Roundabout three (Putsebocht tram stop) also had a low percentage of neutral-positive ratings, which could be explained by the yielding priority being given to cars or the other characteristics of the roundabout. Roundabout three (Putsebocht tram stop) does not go against CROW design guidelines, however, since there are special public transport movements that allow designers to decide which mode receives yielding priority (CROW–Kennisbank, 2014c; CROW, 2024c). Given the elasticity for the lack of yielding priority increases the probability of a bicyclist feeling very uncomfortable by 18%, it can be said that deviating from the CROW guidelines does negatively impact bicyclists' subjective safety, in terms of the yielding priority design factor. This is in line with past studies that looked at yielding behaviours in urban areas and found that yielding priority that is consistent with local guidelines increases comfort levels and compliance (Zhang and Ma, 2015; Lawton et al., 2003).

7.1.2. Design characteristics

Certain roundabout design characteristics were found to be statistically significant, which is consistent with prior studies (Distefano et al., 2019). The findings of the random effects ordered probit model for the legs at a roundabout and yielding priority roundabout attribute variables are in line with past study that concluded that limiting the number of legs at a roundabout and providing bicycles with yielding priority increases perceived safety (Poudel and Singleton, 2021; ARUP, 2022). It is notable that there is a higher probability that someone feels safe than super safe with a roundabout that has yielding priority for bicycles (15.8% vs 12.9% in Table 6.9). This means that there is still hesitancy and doubts about yielding priority being ultimately effective for overall safety at a roundabout. Bicyclists find that other design factors contribute to their perception of safety.

Regarding the bicycle volumes variable, the findings are consistent with past studies (Pulvirenti et al., 2021; Dabbour and Easa, 2008 Cantisani et al., 2021): the higher the bicycle volumes are, the less a bicyclist feels safe or comfortable; more bicycle traffic means more conflicts at bicycle crossing points and other critical decision areas such as entering/exiting a roundabout. During the field observations, car drivers did not grow impatient waiting for a large number of bicyclists to cross, thus it is more likely that the lower perceptions of safety and comfort are caused by the friction created by other bicyclists and overall crowdedness of the bicycle path itself. When bicyclist numbers are low, past studies have found that there is a ”safety in numbers” philosophy (Cantisani et al., 2021; Møller and Hels, 2008), but at a certain threshold bicycle volumes start to cause reductions in perceptions of safety and comfort. Given the binary nature of this and other variables, it is impossible to pinpoint the bicycle volume threshold at which there is a shift in perception. Further research could expand on this. Overall, this section answers sub-question one: *What bicycle infrastructure design and behavioural factors at urban roundabouts in the Netherlands affect bicyclists' perceptions of safety and comfort?* This was done by discussing the various roundabout infrastructure items that were found to have been statistically significant.

The final design characteristic worth noting, even though it was not statistically significant in the model, was that of bi-directional bicycle paths, which were found to negatively impact perceptions of comfort. Whilst no other research has studied comfort levels for this particular roundabout design feature, a objective safety multivariate regression analysis performed in 2019 concluded that bi-directional bicycle paths had lower accident rates than those with only one-way direction (CROW, 2019b). This is confirmed with this reports' qualitative analysis findings, during which it was often mentioned by experts and survey respondents that a bi-directional bicycle path allows for more direct paths of travel, which is in line with the studies by Sakshaug et al. (2010) and van der Leeden (2012). More discussion on this design characteristic can be found in Sections 7.1.3, 7.1.4 in this Chapter.

7.1.3. Compliance and behaviours

The vast majority of observations found bicyclists obeying the traffic laws and going in the correct direction in the bicycle path. There was some confusion at locations where yielding priority was not for bicyclists. In addition, some bicyclists did not yield to the public transport vehicle (tram or bus), which caused a risky situation. The bicyclists were in fact disobeying the audible/flashing warning signs and in essence running a red light. The elasticities of the final model result showed that when people considered themselves as traffic violators (CBQ violations variable), the probability of them feeling very comfortable decreases by 25%. The Errors and Positive behaviour CBQ variables were negatively and positively correlated with perceptions of comfort, respectively. These findings are intuitive, since if you are always making errors, your perception of comfort will decrease. The opposite applies if you are always doing positive behaviour motions.

By combining the qualitative and quantitative analysis sections, this report can partially answer sub-question two: *What bicycle infrastructure design and behavioural factors affect bicyclists' compliance with traffic laws?* This report is able to conclude that the more a bicyclist demonstrates risky behaviour, the more likely they will break traffic laws and have a lower sense of perceived safety/comfort. In addition to this, the following design characteristics studied in this research do have an impact on a person's compliance:

- Yielding priority: Many respondents reported that it should be universal that bicycles have yielding priority inside urban areas and that they will assume that vehicles will stop for them regardless (even at locations where bicycles do not have yielding priority). This is supported by past studies that showed a clear increase in crash rates when yielding priority was unclear due to motorist behaviour and faded signage and lane markings (CROW, 2019a; Sakshaug et al., 2010; S. Jensen, 2013).
- Bi-directional bicycle path: This design feature was the one most commented on by survey respondents and was a topic of long debate at the CROW design workshop. Some bicyclists believe that it should be at every roundabout and that they use every roundabout as such, even if that means going against the law. Some bicyclists indicated that for simplicity and homogeneity, there should not be any bi-directional bicycle paths at roundabouts. This variable was already discussed above and was found to negatively impact a bicyclist's perception of safety and comfort, even though some bicyclists may prefer it for routing simplicity, as it could lower the number of required vehicular crossings.

This research does recommend further study into the subject of compliance as the survey only asked about a person's general compliance by means of the 12 CBQ questions. The survey did not investigate specific compliance with regards to a certain roundabout design and associated design features.

In addition to compliance, a person's history and familiarity with bicycling were found to have significance in the results. The cargo bicycle independent variable was found to be statistically significant in the model for the perception of safety latent variable but not for the comfort variable. Since the error structure between the two latent variables is positive and strongly correlated, this implies that the cargo bicycle variable has an indirect effect on perceptions of comfort. The justification for this could be that another independent variable that was not included in the model, such as bicycle path pavement quality, would help explain the effect of cargo bicycle frequency on perception of comfort. What is noteworthy from the ordered probit model is that the sign of the coefficient for cargo bicycle changes if someone uses a cargo bicycle everyday versus only a few times per week. This change in sign is noteworthy because it means that as one uses a cargo bicycle more often, one becomes more comfortable at riding them. Cargo bicycles have wide turning radii, poor balance at low speeds, and are generally bulky. Bicyclists using these bicycles may feel more cramped in the existing bicycle paths as normal or e-bicycles pass them and must take turns more cautiously. This explains why the occasional use of a cargo bicycle decreases the probability of a bicyclist feeling comfortable by 30%. The finding about the sign of the cargo bicycle usage variable, along with the CBQ questions, align with past studies that concluded that the more people bicycle, the more confidence and perceived control they may have, which leads to higher perceptions of comfort and safety (Marín Puchades et al., 2018; Sanders, 2015).

7.1.4. Different population groups

This section makes an attempt at answering sub-question three: *How do different bicyclist groups perceive the safety of roundabouts?* This also helps answer sub-question one from the behavioural perspective. Sub-question three is not fully answered since the gender variable was not statistically significant, which was most likely due to the low number of responses received. The results of the ordered probit model were that older adults are more sensitive to perceptions of safety, which aligns with the general premise that older adults are more risk-averse (Schepers et al., 2017). When comparing the non-Dutch respondent results with those of the Dutch respondents, it is notable that the betas are statistically significant and positive in sign. This indicates that non-Dutch people feel less comfortable or safe at roundabouts, when controlling for yielding priority, bi-directional bicycle paths, and the other attributes. Many countries, besides the Netherlands, force bicyclists to use the vehicle lane at roundabouts. Non-Dutch respondents often have to deal with no horizontal protection when bicycling which naturally would equate to a lower level of bicyclist comfort and safety at roundabouts, regardless of their design features.

7.1.5. Conceptual model hypotheses

The results found that certain hypotheses were at least partially correct. These include: higher traffic volumes lead to higher perceived risk by bicyclists; and females and elderly bicyclists will have a higher perception of risk. Note that the gender variable from the model run was not statistically significant and so this hypothesis can only be partially confirmed. On the contrary, the hypothesis that yielding priority for cars does not increase perceived risk was found to be false by the findings of the model. Yielding priority for bicyclists does increase the perception of comfort and safety.

In addition the hypothesis that less experienced bicyclists have a lower perception of safety could not be answered due to the removal of the bicycle skill variable in the modeling process. The variable was removed due to an uneven distribution of survey responses (nearly 75% of survey respondents stated that they are highly skilled). The hypotheses that poised that good visibility and a buffer width of 4-5 meters away from the vehicular lane would increase perceptions of comfort and safety was unsubstantiated. Finally, the question of whether bi-directional bicycle paths do not increase bicyclists' perceived risk was also inconclusive.

7.2. Discussion of survey creation

Due to limits on research resources, the photos used for the roundabout locations were taken from an Iphone X, using the panorama photo function. This resulted in additional photo editing due to the elongation of moving persons or objects. This research either removed or hid those elongated items by superimposing photos of bicyclists or other vehicles. During the research period, a GoPro camera was ordered which has a built-in fish-eye lens that can take 180 degree photos that will not elongate objects. It was decided to proceed with the survey before the GoPro camera could be used, since it would have delayed the project due to the required editing/processing period. Image processing and editing for the eight roundabouts took 10 days to complete due to the addition of vehicles and bicycles and modification of the roundabout characteristics. Figures 7.1 and 7.2 show images at two different roundabout locations, with each location photographed twice (first by Iphone X and second by a GoPro camera). Future research using photos should use a GoPro or a similar professional action/motion camera to gain more realism.

(a) GoPro camera image.

(b) Iphone camera image

Figure 7.1: Camera comparison of Putschbocht tram stop roundabout, from the same northerly viewpoint.

(a) GoPro camera image.

(b) Iphone camera image

Figure 7.2: Camera comparison of Gordelweg/Rodenrijsestraat roundabout, from the same westerly looking angle.

In addition, some respondents noted that it was difficult to fully understand the traffic situation and context via only photos which made it more difficult to answer the questions. Having short video segments instead of photos may provide more information for respondents, enabling them to answer more easily. Video was not done for this research as it would require extensive post-footage editing to blur people's faces and add the additional features for each roundabout.

7.3. Discussion of model selection

Initially, this research chose to perform two models (an Ordinal SEM and an ordered probit model) which would have allowed this research to be able to compare the results given each model's limitations. However issues arose when trying to run the models and the estimation processes underlying each of the two models. After careful consideration of the computational time impacts related with implementing the Ordinal SEM model, that model was discarded. The models that were available for this research were limited, particularly robust marginal maximization likelihood, which is currently only available in Mplus software (Newsom, 2023b). This research could not use Mplus and thus was not able to perform a more in-depth analysis of the ordinal variables. Further research should look at using these advanced methods which are built to handle a mix of numerical, binary, and categorical data in order to analyse more variables and associated variable levels.

7.4. Modeling discussion

Even before modeling, the data set needed to be scrubbed so that the ordered probit model could interpret the data correctly. Notably, the socio-demographic data had to be altered so that the age variable did not have any blanks or non-integer entries (e.g. one respondent wrote ”born in 1967”, which needed to be transformed to read ”57”). Blanks were filled in with the median value. These blanks were not included in the descriptive statistics. Other notable dataset categories were the self ascribed bicycling skill level and the scooter mode frequency variables. No respondents replied that were incompetent in using a bicycle and none replied that they use a scooter 1 to 3 days per week, or more frequently. Future research could reword the survey questions in order to garnish a more even distribution of responses (in particular for the scooter and public transport frequency questions which received answers in only one category).

Due to the binary nature of the roundabout design attributes and the fact that all models are a simplification of reality, there is limited interpretation that can be done in terms of what respondents believe is safe or less safe. Perceptions (whether of safety or comfort) are psychological and can't be fully explained by the simplicity of this model. This had some consequences with the model results, notably with the legs of a roundabout attribute variable, where the research hypothesis was that the fewer the legs, the higher the perceived comfort and safety would be. However this research included one roundabout with 5 legs and three roundabouts with 3 legs, thus potentially causing model instability. In addition, the survey showed respondents an aerial image of each roundabout which made respondents more aware of the number of legs at a roundabout than normal (normally as a bicyclist, one would care most about the legs that one must cross which could only be one or two but never all of them). This had an impact on this variable. A model that included a continuous age variable and roundabout attribute variables that are not binary in nature (especially for the number of vehicular exits/entrances, bicycle volumes, or buffer width variables) would have provided a model that offer more detail as to whether a roundabout with 3 entrances causes more discomfort versus a roundabout with 4 or 5 entrances. This would have provided more information for designers and municipal governments regarding specific design features for urban roundabouts. However, it is also important to consider where each bicyclist is headed; if they are making the first right turn, then additional entrances/exits at a roundabout will not necessarily affect their perceptions of safety or comfort.

7.5. Correlations between crash data and model results

This report looked at the crash statistics from the 2013 to 2023 period to see if there are any similarities or differences with the model results. This will answer the final sub-question: *”What type of correlation is there between a bicyclist’s perceived risk level versus actual crashes at roundabouts?”*

Due to underreporting of Dutch crash data, there were not a lot of points of comparison. This is in line with past studies that found that many bicycle crashes do not involve a motor vehicle, thus making it unlikely that a police investigation will occur and a report will be filed (L. B. Meuleners et al., 2019). Unfortunately, researchers were not able to access key details of the available crash data either, meaning that elements such as precise location within the roundabout, modes involved in the crash, and how many persons were injured are unknown. In addition, the eight roundabouts used in the survey were modified, so they did not exactly mimic reality, making it impossible to link the survey respondents’ responses to Dierenselaan/Apeldoornselaan with any crash statistics that may have actually occurred there. In addition, two of the eight roundabouts used in the survey were modified due to a planned construction project during the 10 crash data period (Delftlandplein and Amstelplein). According to the results of the survey, the Gordelweg/Rodenrijsestraat roundabout in Rotterdam was marked as the most uncomfortable and the most unsafe. However, there were no reported collisions at this location in the 10 year dataset. Municipalities may have more collision information via sources such as resident complaints, traffic studies, and other safety reports. The Metropoolregio Rotterdam Den Haag (MRDH) ”Ontwerpbegroting 2024 en meerjarenbegroting 2025-2027” document states that the region has allocated 1.5M euros for small projects such as mobility hubs, bicycle paths, and roundabout safety improvements (Haag, 2024).

Sub-question five is only partially answered and further research is needed, for example looking at other sources of collision data such as hospital records, before any quantitative correlations can be made.

This research advanced the understanding of how roundabout design features and a person’s behavioural characteristics do influence their perceptions on safety and comfort. This research used a novel approach to simultaneously look at both latent variables and unique roundabout design characteristics such as bi-directional bicycle paths and bicycle volumes in the urban roundabout. Whilst certain roundabout attribute variables were not found to be statistically significant for both comfort and safety (presence of art/advertising in the center island, bi-directional bicycle path, and buffer width), the other variables provide valuable information regarding how people behave in and react to various urban roundabout scenarios.

8

Conclusion

Despite being a world leader in bicycle infrastructure, the Netherlands must continue to improve its infrastructure in order to accommodate the diversity of bicycle types and the growing number of people who choose to use sustainable transport modes. Roundabouts are a proven intersection type that has been used for centuries and are simple to install as they do not require traffic signals (except for newer types of roundabouts such as turbo-roundabouts). There is growing concern from citizens and designers alike that the current roundabout design features are no longer adequate for the current and projected bicycle volumes and the new types of bicycles that are growing in popularity (e.g. e-bicycles). This research looked at how bicycle infrastructure design at urban roundabouts affects bicyclists' perceptions of safety and comfort by performing a stated choice experiment and analyzing the data via a random effects ordered probit model. The underlying aim of this study was to provide conclusive support for design features that provide a higher level of comfort and greater perceived safety from a bicyclist's viewpoint.

This study used modified images from eight real-world Dutch roundabouts located in the Randstad and asked respondents to rate each one based on a 5-point Likert scale, considering comfort and perception of safety separately. Not all design characteristics could be observed. The seven design characteristics studied were: buffer space between the cars and the bicycle path, yielding priority, presence of art/advertisements, bicycle volumes, bicycle path shapes, number of vehicular legs or entrance/exit points, and bi-directionality of the bicycle path. The total number of respondents was 239. There was a good distribution of respondents throughout the socio-demographic variables that were asked the following: age, gender, income, education, self-ascribed bicycle skill level, transport mode frequency, recent bicycle crash history, and cyclist behavioural questionnaire (CBQ) questions.

A strong correlation was found between the two dependent variables and roundabout design factors such as bicycle volumes, yielding priority, and the number of legs at the roundabout. In addition, the bicycle mode frequency independent variables (cargo bicycle, normal bicycle, and e-bicycle) and the CBQ violations independent variables were found to be significant.

There is a positive correlation between providing bicyclists with yielding priority and perceptions of comfort and/or safety, which also applies whether respondents ride a normal bicycle, e-bicycle, or cargo bicycle everyday.

Certain factors were found to have no or little effect or were not statistically significant, such as buffer width, bi-directional bicycle paths, bicycle path shape, or income. Further data would be needed in order to provide reportable results for these factors.

This conclusion answers the main research question: *What factors contribute to bicyclists' perceptions of safety at roundabouts?* It was found that people who: are older, or have had a recent bicycle crash, or commit violations whilst bicycling (part of the CBQ error group), or sometimes ride a cargo bicycle, or do not reside in the Netherlands have lower perceptions of comfort and/or safety at roundabouts. Regarding infrastructure, bicyclists had lower perceptions of safety and comfort at roundabouts with high bicycle volumes and more vehicular entrance/exit points. General consistency with roundabout bicycle designs is desired by both designers and survey respondents. The conceptual model was followed in the statistical assessment of the variables and most hypotheses were answered, either being asserted or debunked.

9 Recommendations

This Chapter takes the results and discussion described in Chapters 6 and 7 and provides recommendations for practitioners, researchers, and other interested parties. In addition, further research and procedural topics will be discussed that could be addressed in a new study.

9.1. Practical Recommendations

This research shows the importance of giving yielding priority to bicyclists at all urban roundabouts. This supports the statement that was made in the expert insights in Section 5.1, regarding uniformity in design. In general uniformity in the design of urban roundabouts is preferred and should be undertaken whenever geometric constraints and funding availability allows. Other design recommendations include:

- Building roundabouts in such a way as to limit current and future bicycle congestion. This should be done by looking at current and future bicycle volumes. Too many bicycles at roundabouts lead to a greater discomfort and a perceived decrease in safety, especially in bicyclists using cargo bicycles and special bicycles.

- Following the CROW guidelines as much as possible, as the design features they recommend are positively correlated to bicyclists' perceptions of safety and comfort.

- Minimizing the number of vehicular legs entering/exiting the roundabout, to the extent possible, given adjacent land-uses and roadway networks.

Whilst the inconclusive result of this research was that bi-directional bicycle paths at roundabouts decrease perceptions of comfort and safety, this report recommends following the guidance of the CROW design guidelines. CROW guidance suggests carefully assessing whether a bi-directional bicycle path would provide better accessibility and connectivity based on adjacent land uses and the nearby bicycle network and if so, that may countermand a bicyclists' subjective safety. When designers choose to build a bi-directional bicycle path, this report recommends making all the crossings bi-directional (i.e. make a bi-directional bicycle path on 100% of the roundabout) to avoid bicyclist confusion and traffic violations. This recommendation is based on the field observations done at roundabouts that had partial bi-directional bicycle paths.

9.2. Further research: goals and objectives of interest

The results show that certain design and behavioural factors contribute to a bicyclist's perception of safety and comfort at roundabouts but that these perceptions are not fully explained by the independent variables studied. Future research at roundabouts could explore several avenues, including:

- Extending the data collection to include more roundabouts as well as studying the differences in urban and rural roundabouts.

- Working with hospitals to examine objective safety records of bicycle crashes at urban roundabouts in order to make more inferences between subjective and objective bicycle safety.
- Using ordinal SEM models to compare results.
- Looking at other design features such as width of the bicycle path, visibility, or presence of public transport.
- Studying the correlations that could exist between individual characteristics and the CBQ factors.
- Considering external factors, such as weather or lighting. The field data collection and survey preparation for this research paper was done in the middle of April, when thunderstorms and odd weather patterns made it difficult to control for the weather. The desired effect was to simulate a cloudy/partially wet day but some pictures used in the final survey ended up looking less wet. Pavement wetness could affect bicyclists' perceptions of comfort and safety, due to the increased possibility of slipping.
- Exploring the various types of bicycles used and how the speed differences and maneuverability between the different bicycle types affect bicyclists' perceptions.
- Researching further to determine the thresholds of bicycle volume at which it starts to feel uncomfortable or unsafe for bicyclists.
- Performing research into bicyclist's subjective safety perceptions at bi-directional bicycle paths at or near roundabouts whilst including adjacent land uses and local bicycle network.
- Focusing solely on cargo or special bicycles to better understand why there is a shift in perceptions of comfort and safety when riders use those bicycle types more frequently.
- Isolating various modal sub-groups, such as electric bicyclists or transit users, to see if there are different beta coefficients and differences in their perceptions of safety and comfort compared to the entire sample population.
- Performing an ordinal factor analysis of the cyclist behavioural questionnaire (CBQ) variables, which allows for a more detailed interpretation of those independent variables.
- Collecting respondent data on "intention to comply" in order to have statistical information that could link compliance with subjective safety at a particular roundabout. This would allow for a multivariate analysis, looking at intention, safety, and comfort.
- Studying the impacts of the independent variables of vehicle speed and bicyclist/motorist eye to eye contact. This could further explore yielding behaviour.
- Performing a study focused on ethnicity and gender of bicyclists to determine the underlying reasons for why certain roundabout features are more or less positively received.
- Providing more levels for the roundabout attribute variables, in order to check for linearity and avoid odd beta value signs, such as the sign for the buffer width attribute.

9.3. Further research: procedural aspects

The timeframe of this research and the computational power available to it, limited how many variables could be modelled. Notably, this research had to remove latent variables and some independent variables in order to make the survey manageable for respondents whilst still addressing the research question and its sub-questions. Future research could:

- Produce the survey in multiple languages in order to reach a more diverse range of bicyclists.
- Make use of a GoPro camera (or similar) for the 180 degree photos and possibly short video clips in order to help survey respondents visualize the roundabout locations and features more realistically. This would allow further research to look at roundabout attributes such as raised bicycle/pedestrian crossings, which are practically impossible to convey to respondents via a photo-only survey.
- Locate roundabouts that do not require modifications in order to fit the attribute characteristics.

A

Research paper

This paper can be found on the next pages.

BICYCLISTS' PERCEPTIONS OF URBAN ROUNDABOUT SAFETY

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ABSTRACT

Past bicyclist subjective safety studies have evaluated different intersection types and bicycle facilities at roundabouts. None have focused on the different design elements of a dedicated bicycle facility and analyzed both perceptions of safety and comfort of bicyclists in a single model. To address this, this study focuses on the subjective safety and comfort perceptions of bicyclists at Dutch urban roundabouts, focusing on certain bicycle design elements. Infrastructure evaluated included: bi-directional bicycle paths; yielding priority; bicycle volumes; the presence of art or advertisements in the center island; buffer width between the bicycle path and the vehicle lane; and the number of vehicular entrance/exit points. Using a multivariate random effects ordered probit model, the results revealed that roundabouts where cars have to yield to bicycles and fewer vehicular legs are perceived as safer and more comfortable by cyclists. Conversely, high bicycle volumes and increasing age negatively impacted perceptions of safety. The study found that bicyclists' place of residence, their likelihood to commit traffic violations, their recent crash history, and the type of bicycle used (e.g., cargo bicycle, e-bicycle, etc.) significantly affect their perceptions of safety. The results suggest that consistent adherence to Dutch design guidelines can enhance bicyclists' sense of comfort and safety at roundabouts. The findings highlight the need for designers to consider bicyclists' perspectives in roundabout design. To improve perceived safety and comfort for bicyclists recommendations include: ensuring bicycle yielding priority; designing roundabouts to reduce bicycle congestion to the extent possible; and maintaining uniformity in bicycle infrastructure.

Keywords: Subjective safety, Roundabouts, Bicyclists, Comfort, Random effects ordered probit

INTRODUCTION

Roundabouts have existed for over a century and it is now known that roundabouts offer high levels of safety, in particular to motor vehicle traffic (*1*). Many countries have installed roundabouts for their proven reduction in vehicle crashes, but studies have noted that more attention must be given to bicyclists and pedestrians as the major safety benefits for motorists may not necessarily translate to these more vulnerable modes (*2*). Recent Dutch crash data also indicates this trend, with 12% of all bicycle crashes occurring at roundabouts (*3*). The Netherlands is experiencing increasing congestion in bicycle facilities as new types of bicycles (e.g., fat-tire bicycles, e-bicycles, cargo bicycles, etc.) are becoming increasingly popular. Roundabouts with bi-directional bicycle facilities and bicycle yielding priority (i.e. vehicles have to yield to bicycles), can be particularly challenging. Identifying bicycle infrastructure characteristics and bicyclist behavioural factors that influence both objective and subjective bicycle safety at roundabouts should inform roundabout design guidelines (*3–5*).

Perceived safety versus objective safety

One's intention to ride a bicycle relates to one's comfort levels, perception of safety, and history as a bicyclist (*6*). A recent focus of research on understanding a bicyclist's risky behaviour, Useche et al. (7, 8), led to development of the bicyclist behavioural questionnaire (CBQ) which has been verified in Belgium, the United States of America, and Spain. The CBQ makes the link between bicyclists' behaviours and their socio-demographic background, allowing for roadway design changes that better match bicyclists real-world actions (*7*). Studies have shown that if bicyclists' underestimate the risks of cycling, they are more likely to be involved in a crash and to suffer severe injuries as a result (*9*). If bicyclists take on too much perceived risk, they may become mentally fatigued, which leads to mistakes and potentially crashes (*10*). This becomes a self balancing feedback loop: the occurrence of bicycle crashes raises a bicyclist's subjective risk perception; this leads to decreased risky behaviour, and potentially less crashes (*11*). The interrelationship between perception of safety and actual safety is often politicized. When residents perceive a roundabout as unsafe, they demand that the local government make design changes, even when that location has a good objective safety record (*12*).

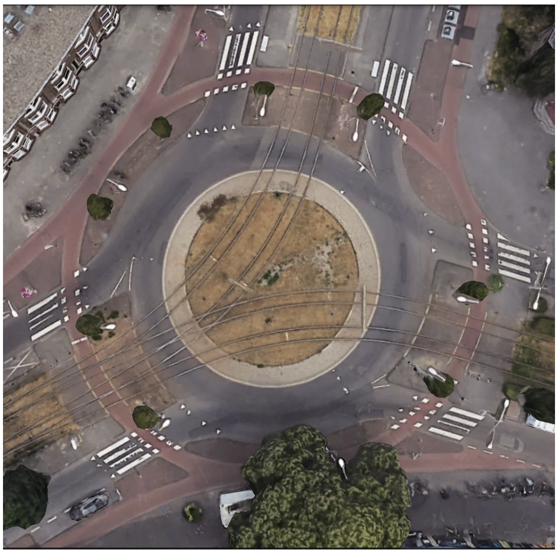
Research Aim and Contribution

The research aim is to determine what behavioural factors and infrastructure design elements influence a bicyclist's perception of safety and comfort at urban roundabouts. The practical contribution of this research is to provide recommendations to governments regarding bicycle safety at urban roundabouts and propose design alterations to maximize compliance and perception of safety. The scientific contribution of this research is the novel use of a bivariate random effects ordered probit model to investigate bicyclists' perception of comfort and safety simultaneously, against roundabout attribute and socio-demographic independent variables.

LITERATURE REVIEW

Design factors and uniformity

Urban roundabouts have significant differences compared to rural ones, such as daily traffic volumes, crash rates, complexity, and dimensions (*4, 13*). Design factors such as number of legs or roads feeding into and out of the roundabout impacts how both motorists and bicyclists yield to one another (*14–17*). This research focused on urban roundabouts with a separate bicycle facility, as shown in Figures 1a and 1b, due to their prevalence in the Netherlands. It is important to note that different countries have different design and cultural preferences (*14*).



(a) **Aerial view of Dierenselaan/Apeldoornselaan, The Hague, where the bicycle facility is in light red. Note that there are only three legs.**

(b) **Aerial view of Putsebocht tram stop in Rotterdam, where yielding priority is given to vehicles. In addition, there were some wrong way bicycling observed at the southern and western crossings.**

FIGURE 1: **Aerial photos of both types of bicycle paths at roundabouts, with one being circular and one being a bent shape. Images courtesy of Google Earth.**

Bi-directional bicycle paths at roundabouts allow bicycles to have a more direct path of travel. One Swedish study found that 38% of bicyclists travel in a clockwise direction, against the vehicular circulating direction (*18*). In Sweden, both bicyclists and motorists must yield even when shark teeth yield markings are present. That same study noted that when there are no clear traffic rules pertaining to who has yielding priority, confusion and conflicts can occur. A study by Rijkswaterstaat found that there were significantly lower crashes (0.18 vs 0.73 crashes per roundabout over 3 years) at roundabouts where bicyclists did not have priority (*19*). This was also the conclusion of a study in Denmark (*20*). However there are many Dutch roundabouts that give yielding priority to bicyclists and Dutch design guidance recommends this at all urban roundabouts (*21*). A SWOV (Foundation for Scientific Research on Road Safety) study found that certain design features, such as circular or bent bicycle paths (see Figure 1) may not give clear indication of which mode (i.e. motor vehicle or bicycle) has right of way whilst enabling higher speeds due to roundabout geometry (*16*).

An Italian study used a Poisson's law probabilistic model to study traffic volumes and design configurations in order to lower bicyclists' risk of conflict (*22*). Only minor modifications of bicycle volumes (10% and 30% more than the initial option) were performed but the study found that too little a distance of separation between the bicycle path and the vehicle path (a four meter reduction, compared with the base roundabout layout) increases the probability of bicyclist crashes. A recent Dutch study concluded that too great a distance of separation (more than six meters) increases chances of bicyclist crashes (*19*).

Clarity and consistency in roundabout characteristics is important. The Center for Regulation and research in civil, water and Road Construction and traffic technology (CROW) develops guidelines, training, and practical tools for infrastructure, public urban spaces, traffic, public transport, and bicycle infrastructure in the Netherlands (*23*). Their bicycle publications pertaining to roundabouts exist in multiple sources (*16, 21, 24*), but most of them are in the roundabout chapter of the Kennisbank. Recent CROW research has found that at roundabouts that give yield priority to bicycles, it is four times more likely that bicycle crashes will occur than at those that give priority to cars (*25*), which is counter to what current CROW guidance states regarding yielding priority (*21*). There is ambiguity in other sections such as Section 6.4.2, regarding dimensioning bicycle facilities, where there is simply an acknowledgement that bi-directional bicycle facilities at roundabouts require additional consideration and "extra attention from the designer" (*21*).

Perceptions of bicyclists

Actual traffic safety issues, such as a high incidence of left hook crashes, are not necessarily how bicyclists perceive safety issues (*26*). The study by Richard Mantona et al. (27) used mental mapping with a Generalised Linear Mixed Model (GLMM) statistical analysis and found similarities between perceived and real traffic risks for bicyclists at roundabouts. Significant variables included: segregated bicycle infrastructure, road width, vehicle volumes, past cycling experience, and gender. Many studies found that a bicyclist who has experienced a conflict or crash, has a more heightened perception of risk and safety (*28–33*).

The study by Poudel and Singleton (*29*) concluded that respondents' preferences between two different roundabouts (with varying characteristics) are motivated by their perceptions of comfort and safety. Most recent models use either a structural equation (SEM) type model (*1, 6, 26, 31*), or a form of regression analysis (*6, 27, 32, 34, 35, 35–38*) to see if there are significant correlations between variables and the indicator variable of comfort or perception of safety. Amongst the studies that used regression analysis, three studies used a form of logit or probit regression (ordered probit (*31*), cumulative logit (*34*), and non-linear least squares (*39*)). No study was found to have performed a multivariate ordered probit regression on bicyclists' subjective safety and comfort levels.

Discussion, gaps, and research question

The link between perceived comfort and safety and objective safety is ambiguous, with many studies focusing on just one form or the other (*31, 32, 34*). Subjective safety studies using advanced discrete choice theory have only been used within the past 10 years. Few have been dedicated to researching urban roundabout characteristics with a dedicated bicycle facility. For these reasons, it was decided to use an ordered probit model to evaluate Dutch bicyclists' perceptions of safety and comfort at urban roundabouts with various bicycle facility features. This paper can recommend design factors most appreciated by bicyclists to aid Dutch governments and CROW in providing updated design guidance. This research will reach this goal by answering the following main research question: *What factors contribute to bicyclists' perceptions of safety at roundabouts?*

This question is jointly answered by the following sub-questions:

1. What bicycle infrastructure design and behavioural factors at urban roundabouts in the Netherlands affect bicyclists' perceptions of safety and comfort?
2. What bicycle infrastructure design and behavioural factors affect bicyclists' compliance

with traffic laws?

3. How do different bicyclist groups perceive the safety of roundabouts?
4. Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?

CONCEPTUAL FRAMEWORK

This study aims to gain insights into how roundabout design features influence bicyclists' perceptions of safety and comfort. Thus two dimensions were considered: roadway infrastructure design and individual factors.

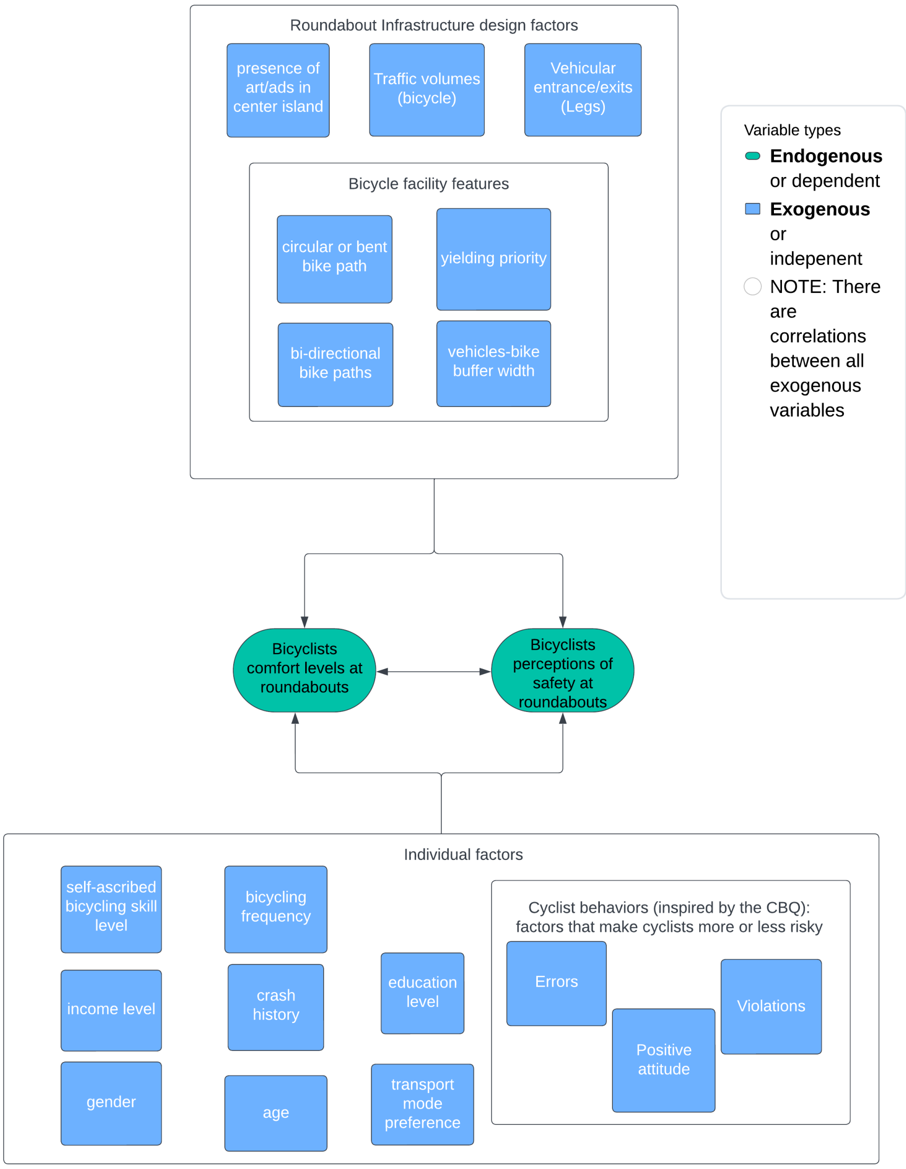


FIGURE 2: **Conceptual model showing the two dependent variables in green and measured independent variables in blue. Model created via Lucid.**

This research defines the measurement of a bicyclist's comfort level as overall level of ease as one cycles around a roundabout and perception of safety as one's sense of risk whilst cycling around a roundabout. Building on the literature review, main research question and sub-questions, Figure 2 illustrates this research's conceptual framework.

Conceptual framework and survey attributes

This conceptual framework makes use of a group of "bicyclist behaviour" variables, measured from 12 independent variables modified from the study by Useche et al. (7, 8) that used 42 independent variables (only 29 were significant), called the cyclist behavioural questionnaire (CBQ). Some of the original 42 questions will not apply as many Dutch bicyclists perform actions such as allowing a rider on their bicycle rack or carrying cumbersome objects such as beer crates, plywood, and more. Since this research is focused on design elements and different types of bicyclists, the questions presented in Table 1 reflect only the questions that had the strongest correlations to the latent variables found in the Useche et al., Useche et al. (*7, 8*) studies.

TABLE 1: **Cyclist behavioural questionnaire (CBQ), showing questions and scales/levels/categories of the indicators**

Label	Question Formulation	Scale
	Violations latent variable group	
2	Cycling under the influence of alcohol and / or other drugs or hallucinogens.	1=Never - 5= Always
3	Going against the direction of traffic (wrong way).	1=Never - 5= Always
10	Crossing what appears to be a clear crossing, even if the traffic light is red.	1=Never - 5= Always
	Errors latent variable group	
17	Unintentionally, crossing the street without looking properly, making another vehicle brake to avoid a crash.	1=Never - 5= Always
18	Colliding (or being close to it) with a pedestrian or another bicyclist while cycling distractedly.	1=Never - 5= Always
20	Brake suddenly and be close to causing an accident.	1=Never - 5= Always
22	Not braking on a "Stop" or "Yield" sign/marking and being close to colliding with another vehicle or pedestrian.	1=Never - 5= Always
30	Failing to be aware of the road conditions and therefore falling over a bump or hole.	1=Never - 5= Always
31	Mistaking one traffic signal for another, and maneuvering according to the latter.	1=Never - 5= Always
	Positive Attitude latent variable group	
36	I try to move at a prudent speed to avoid sudden mishaps or braking.	1=Never - 5= Always
38	I keep a safe distance from other bicyclists or vehicles.	1=Never - 5= Always
39	When I use the bicycle path (or bicycle-lane), I use the indicated lane.	1=Never - 5= Always

In essence, if bicyclists take more risk under various typical situations encountered whilst bicycling, they are likely to have a higher tolerance for what is considered an unsafe situation.

During the model run stage, an ordinal factorial analysis of these 12 questions was discarded; an averaging of each respondents' responses for each category (Violations, Errors, Positive Attitude) was performed instead. This was done in order to simplify the overall model and run times, while maintaining detailed information about these three aspects of the CBQ.

As there are no studies looking at the correlation between comfort and perception of safety for bicyclists, this research is setting a precedent by looking at both latent variables within one dataset. Further expanding on the conceptual model, this research chose various levels or categories for each independent variable, as shown in Table 2.

TABLE 2: **Model attributes and levels/categories of the indicators**

Label	Variable	Definition	Categories
Buffer	Buffer width between vehicles and bicycles	This space is critical for clear separation of modes and allows for reaction time for yielding behaviour	0-5.07, 5.07-11.92 meters
Yield	Yielding priority for bicycles	Roundabouts with yielding priority for bicycles are more common in urban areas and where the separation between cars and bicycles is $\leq$ 10 meters	No, Yes
Art	Presence of art in the center island	The center island features can help focus drivers on the immediate approach in front of them but also could add distractions	No, Yes
Direction	Is the bicycle path uni-directional?	Roundabouts can have bicycle paths that are partially bi-directional on certain legs or all around the circle. This adds complexity but allows for better accessibility and route choice for the bicyclists	No/hybrid, Yes
Flow	Bicycle volumes	This criteria relates to roundabouts that have bicycle volumes above or below 480 bicycles per hour (PM peak hour)	Below 480, Above 480
Shape	Bicycle path shape	Separated bicycle facilities come in two different shapes: circular (mimicking the vehicular lane) and bent (resembling more of a polygon shape)	Circular/hybrid, Bent
Legs	Vehicular entrance points	This criteria is whether or not the roundabout has 4 entrance/ exit points for vehicles which can reduce or add complexity to the roundabout	No, Yes
		Socio-demographic questions	
Mode	Most common mode of transportation	What is your primary transport mode to commuter to your work/studyplace?	Bicycle,E-bicycle,Scooter, Bus/Metro/Tram, Train,Auto/Motorcycle, Walking, Cargo bicycle, Special bicycle
TR_DAYS	Travel frequency	In the past year, how often have you used the modes mentioned in the previous question?	Never, Less than once a month, 1-3 days per month, 1-3 days per week, 4-6 days per week, Always
Crash	Crash history	Have you had any crashes or near misses in the past 3 months?	Yes, No, Prefer not to say
Education	Highest education level attained	What is the highest degree or level of school you have completed?	Primary, Secondary, University (Bachelor, Graduate or professional)
Gender	Gender of the respondent	What is your gender?	Female, Non-binary, Male, Prefer not to say
Age	Age of the respondent	What is your age?	18 - 24, 25 - 34, 35 - 44, 45 - 54, 55 - 64, 65 - 74 $\geq$ 75, prefer not to say
Income	Income range	What is your monthly income?	<1,000, 1,001 - 4,000, $\geq 4,000$, prefer not to say
Skill	Self-ascribed cycling skill	What would you qualify your level of expertise in bicycling?	[inexperienced/competent/highly skilled], prefer not to say
Risky	Risky behaviour as a bicyclist	This gets at how risky someone is when they are bicycling since the assumption is that influences their perceptions of safety and comfort	see Table 1

METHODOLOGY

The first part of this research is a qualitative analysis, focusing on literature research, expert insights, field observations, and open feedback from survey respondents regarding traffic safety at roundabouts. The expert insights were performed to better understand the nuances associated with following or not following CROW design guidelines and what designers and government officials are currently concerned about regarding roundabout design. 15 minute field observations were performed during the weekday rush hour periods (between 16h00 and 18h30) to get the busiest traffic volumes, which may add stress for bicyclists and increase the probability of crashes (*36*). Scooters were counted in the bicycle volumes, as well as anything legally using the bicycle facility during the observation period. The field observations allowed the researchers to classify roundabouts based on bicycle volumes and to observe bicyclist behaviour and compliance with local traffic regulations. After the expert insights and field observations were analyzed in order to garnish information for the survey, the second part of this research presents the quantitative analysis of data provided via a survey of bicyclists' perceptions using two methods: a descriptive analysis of the survey results and an ordered probit model.

Survey

At the beginning of each survey, participants were asked to provide socio-demographic data as shown in the bottom of Table 2. In addition, each participant was asked the 12 CBQ questions, as shown in Table 1. Participants were then shown four images (from various perspectives) at each of the eight urban Dutch roundabouts chosen (32 images total), followed by a short prompt, and then Likert scale questions for the indicators of perception of comfort and safety. As an even-numbered Likert scale leads to a "forced choice" situation (*40*), this research chose a 5-point scale, thus allowing respondents to express a neutral opinion on a roundabout and its specific characteristics. The final question in the stated preference survey allowed participants to freely express their thoughts and concerns regarding traffic safety at roundabouts.

Photos of the eight roundabouts were slightly modified to showcase particular characteristics of each roundabout as shown in Table 2. The survey was created in English and Dutch and was made available via a QR code link which allowed for greater distribution to TU Delft students, bicyclists who use the selected roundabouts, and the general public via social media channels. A combination of non-physical and physical survey collection was used to increase the number of responses. By directly asking random bicyclists, a more even distribution of the Dutch population was achieved, which reduced bias in the results.

Locations

Determination of the roundabout locations started by considering only Dutch cities with a

TABLE 3: **Location characteristics table**

Label	Location	City	art/ads in center	bicycle yielding priority[1]	uni-directional	4-legged[2]	separation from vehicle lane	bicycle volumes[3]	facility style
1	Dierenselaan/Apeldoornselaan	Den Haag	✗	✓	✓	✗	3.79m	80	Circular
2	Neherkade/Slachthuisstraat	Den Haag	✗	✓	✓[4]	✓	5.13m[5]	90	Circular
3	Putsebocht tram stop	Rotterdam	✗	✗	✓	✗	11.39m	83	Bent
4	Planbaan/Kernbaan	Zoetermeer	✗	✓	✓[6]	✓	4.45m	13	Bent
5	Amstelplein	Amsterdam	✗	✓	✓[7]/[8]	✗	5.76m	559	Circular
6	Gordelweg/Rodenrijsestraat	Rotterdam	✓	✓	✓[9]	✓	5.00m	193	Circular
7	Meerzichtlaan/Berglaan	Zoetermeer	✓	✓	✗	✗	4.81m	39	Bent
8	Delftlandplien	Delft	✓	✓	✓	✓	9.55m	341	Bent

[1] Do other modes have to yield to bicycles?
[2] for cars
[3] 15 minute counts
[4] No crossing possible on the north side
[5] This includes the truck aprons
[6] Southside of intersection is bi-directional
[7] except the west side
[8] No crossing possible on the east side
[9] The northern side is bi-directional

population over 300K (Utrecht, The Hague, Rotterdam, and Amsterdam). Since there are roundabouts found in urban, dense environments that have small population sizes, such as Delft and Zoetermeer, those cities were also included. Utrecht was excluded due to logistical reasons. The field observations explored 50+ roundabouts in Delft, The Hague, Pijnacker, Zoetermeer, Rotterdam, and Amsterdam. The real-world location characteristics used in the survey are shown in Table 3.

Model Choice

Regression models have been used in objective traffic safety studies, comparing crash rates with variables such as road design, traffic volumes, time of day, and other factors (*4, 13, 15, 41–44*). With an ordinal regression analysis, an ordinal dependent variable is predicted with the aid of one or more independent variables (*45*). A bivariate random effect ordered probit model was chosen for this research. This model is best matched to handle a cross-sectional study with panel data sets via the incorporation of an additional error term that only changes between respondents, thus preventing overfitting of the model (*46, 47*). The generic formula for this model is:

$$Y_i^* = X_{ij}\beta + \lambda_{0ij} + \varepsilon_i \tag{1}$$

$$\lambda_{0ij} \sim N(0, \sigma_\lambda^2) \tag{2}$$

$$\varepsilon_i \sim N(0, \sigma_\varepsilon^2) \tag{3}$$

where the Y_i^* is a continuous latent variable that is assumed to underlie the observed ordinal data for the i th individual. X_i is a $(1xj)$ vector of observed independent variables; and β is a $(jx1)$ vector of coefficients for the independent variables (*43*). λ_{0ij} is the effect term of the i th individual at the j th roundabout location, and ε is the error term (person level random effects). This error term links the two latent variables. Equations 2 and 3 both have a mean of 0 and variance of either σ_λ^2 or σ_ε^2 respectively. A normal discrete distribution is assumed, and the estimated value of the variance refers to the volatility between clusters (local variables) (*46*).

Due to the normalization of the error terms, the two error terms are assumed to be normally distributed (*42*). Equation 1 shows the latent variable whereas what is gathered in the survey are observed ordinal data, Y. The observed values (1,2,3,4,5) are presented via indicator variables, but these latent variables have cut-off points that will be estimated (*43*) via the following format:

$$Y_f = s \qquad \text{if} \qquad \mu_{s-1} < Y_f^* \leq \mu_s \tag{4}$$

where μ_s are thresholds or cut-off values of the continuous scale of Y^*, used to determine the comfort levels and perceptions of safety of bicyclists (*41*). f symbolizes either the comfort or safety variable whilst s is the category that the Y is observed in when the latent variable falls in the μ_s interval. In other words, Y_f is observed to be in category 1 when the latent variable falls in the interval between μ_0 and μ_1 (*48*). In order to validate the model and ensure the correct variable type assignment, the Maximum Likelihood (ML) estimation method will be used for the model parameters (e.g. β and Y). In order to test the goodness of fit, the Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC) will be used as they correctly penalize every additional independent variable that is added to the model (*49*).

Elasticities

Due to the nonlinear nature of Equation 1, the β coefficient values can't be directly interpreted as increases or decreases in the latent variables (*47*). As such, the elasticities will be calculated to show the percentage of contribution that each independent variable has on each dependent variable (*50*). Equation 5 represents the elasticity calculation where i is the individual at the j th roundabout location:

$$\text{Elasticity}_{sp|X_{jp}} = \frac{X_{jp}}{P(Y_{ij} = k|X_{ij})} \cdot \left[f(\mu_{s-1} - X'_{ij}\beta) - f(\mu_s - X'_{ij}\beta) \right] \cdot \beta_p \quad (5)$$

s represents the index for the ordinal categories of the dependent variables and p is the index for the independent variables.

RESULTS AND DISCUSSION

In total, 260 respondents completed the survey. Out of those, 239 rode a bicycle (any type) and were used as the ordered probit model input. The average survey respondent age was 40. 52.5% of respondents were male which is representative of other bicyclist surveys. Most respondents (85%) replied that they did not have a bicycle crash within the last three months. Each respondent had to rate their perception of safety and comfort for bicycling through all eight roundabouts. In total, 1912 perception ratings were collected. Most (78.1%) answers for the indicator questions (comfort and safety) are in the range from 3 (neutral) till 5 (very comfortable or very safe). Table 4 depicts the results of the mode choices that were asked in the survey.

TABLE 4: **Transportation mode usage**

Mode of transportation	Walk	Normal bicycle	E-bicycle	cargo bicycle	special bicycle	scooter	motorcycle/ car	public transport
Everyday (5)	39.5%	29.9%	5.1%	1.1%	1.7%	3.9%	2.8%	5.3%
4-6 days per week (4)	20.3%	25.9%	4.5%	1.7%	0.6%	6.8%	12.9%	12.3%
1-3 days per week (3)	29.4%	21.5%	11.3%	1.7%	2.8%	17.5%	35.6%	34.6%
1-3 days per month(2)*	5.6%	9.0%	5.1%	5.6%	4.5%	27.1%	38.9%	36.1%
Never/I don't own one(1)	5.1%	13.6%	74.0%	89.8%	90.4%	44.6%	9.6%	11.5%

* Reference case for categorical variables.

Ordered Probit Model Results

The coefficients of the roundabout characteristics on the safety and comfort perception ratings, according to the random effect ordered probit model equation (1), can be found in Table 5 below.

TABLE 5: Random effects ordered probit model results, showing confidence intervals and estimated beta coefficients.

Thresholds	Estimate	Std. Error	z value	Pr(>|z|)	CI Upper	CI Lower
Comfort: Very uncomfortable -uncomfortable	0.0000	0.0000	NA	NA	NA	NA
Comfort: Uncomfortable-neutral	1.2395***	0.0560	22.134	0.0000	1.3493	1.1297
Comfort: neutral-comfortable	1.8956***	0.0608	31.158	0.0000	2.0148	1.7764
Comfort: comfortable -very comfortable	2.9098***	0.0688	42.317	0.0000	3.0446	2.7750
Safety: Very unsafe-unsafe	0.0000	0.0000	NA	NA	NA	NA
Safety: unsafe-neutral	1.0791***	0.0617	17.495	0.0000	1.2000	0.9582
Safety: neutral-safe	1.9703***	0.0690	28.541	0.0000	2.1055	1.8351
Safety: safe-very safe	3.4187***	0.0814	41.991	0.0000	3.5782	3.2592
Coefficients:						
(Intercept) (Comfort)	1.7921***	0.0918	19.517	0.0000	1.6121	1.9721
(Intercept) (Safety)	1.9548***	0.0979	19.961	0.0000	1.7628	2.1467
Bike_Volumes (Comfort): Yes	-0.1221*	0.0496	-2.464	0.0137	-0.2192	-0.0250
Bike_Volumes (Safety): Yes	-0.1427**	0.0501	-2.852	0.0044	-0.2408	-0.0446
Bike_Yielding_Priority (Comfort): Yes	0.5601***	0.0502	11.167	0.0000	0.4618	0.6584
Bike_Yielding_Priority (Safety): Yes	0.5291***	0.0509	10.386	0.0000	0.4292	0.6289
Bi_Directional (Comfort): Yes	-0.0347	0.0347	-1.000	0.3174	-0.1027	0.0333
Buffer_width (Comfort): Large	0.0084	0.0498	0.168	0.8663	-0.0892	0.1059
Buffer_width (Safety): Large	-0.0362	0.0498	-0.727	0.4671	-0.1338	0.0614
Art_Ads_in_Center (Comfort): Yes	-0.0437	0.0348	-1.256	0.2093	-0.1119	0.0245
Four_legs_entrance_points (Comfort): Yes	-0.1456**	0.0496	-2.933	0.0034	-0.2428	-0.0483
Four_legs_entrance_points (Safety): Yes	-0.1222*	0.0501	-2.439	0.0147	-0.2204	-0.0240
Respondent residence (Comfort): Netherlands	0.4155***	0.0595	6.981	0.0000	0.2989	0.5322
Respondent residence (Safety): Netherlands	0.4864***	0.0604	8.049	0.0000	0.3680	0.6049
Age_Category (Comfort): 40+	-0.0175	0.0513	-0.341	0.7328	-0.1182	0.0831
Age_Category (Safety): 40+	-0.1813***	0.0527	-3.439	0.0006	-0.2847	-0.0780
Gender (Comfort): Male	0.0167	0.0519	0.322	0.7474	-0.0850	0.1184
Gender (Safety): Male	-0.0259	0.0526	-0.492	0.6229	-0.1290	0.0773
Bicycle_crash_history (Comfort): Recent	-0.3817***	0.0846	-4.514	0.0000	-0.5475	-0.2160
Bicycle_crash_history (Safety): Recent	-0.3108***	0.0845	-3.681	0.0002	-0.4764	-0.1453
Violations (Comfort): Most of the time 1	0.2683*	0.1118	2.401	0.0163	0.0493	0.4874
Violations (Safety): Most of the time	0.3352**	0.1090	3.074	0.0021	0.1215	0.5490
Errors (Comfort): Most of the time	-0.5355*	0.2591	-2.067	0.0387	-1.0433	-0.0277
Positive_behaviour (Comfort): Most of the time	0.0786*	0.0361	2.180	0.0293	0.0079	0.1493
Normal_bicycle_Freq (Comfort): Everyday	0.2926***	0.0645	4.539	0.0000	0.1662	0.4189
Normal_bicycle_Freq (Safety): Everyday	0.1383*	0.0639	2.163	0.0306	0.0130	0.2636
E_bicycle_Freq (Comfort): Everyday	0.3494**	0.1157	3.021	0.0025	0.1227	0.5761
E_bicycle_Freq (Safety): Everyday	0.3388**	0.1133	2.991	0.0028	0.1168	0.5607
Cargo_bicycle_Freq (Comfort): Sometimes	-0.0948	0.1675	-0.566	0.5716	-0.4232	0.2336
Cargo_bicycle_Freq (Safety): Sometimes	-0.6931***	0.2081	-3.330	0.0009	-1.1010	-0.2852
Cargo_bicycle_Freq (Comfort): Everyday	0.9700	0.8478	1.144	0.2526	-0.6917	2.6318
Cargo_bicycle_Freq (Safety): Everyday	1.2085**	0.3895	3.102	0.0019	0.4450	1.9720
Error Structure:						
corr Comfort Safety	0.8089***	0.0094	86.013	0.0000	0.8273	0.7905
Measure	**Value**					
Log-likelihood	-4315.395					
Akaike information criterion (AIC)	8710.415					
Bayesian information criterion (BIC)	8931.607					
Number of observations	239					

*, **, *** indicate significant at 90%, 95%, 99% confidence level, respectively.

The parameters in this model output consist of four thresholds denoted by the five categories in the Likert scale. Due to the calculation of an intercept for each latent variable, the first threshold is 0 and is only a reference. All the other threshold estimates were statistically significant at the 99% confidence level, which symbolizes a good model fit for the categorical data. In addition, the intercepts for both latent variables and the correlation estimates of the random terms for the two latent variables are also statistically significant at the 99% confidence level. There was a statistically significant high positive correlation between the two latent variables. A coefficient with a positive sign indicates that the corresponding parameter is directly associated with higher perceptions of safety or comfort, whereas a negative sign implies a reverse impact.

The yielding priority independent variable of positive sign and was significant at 99% confidence level. This means that if there is yielding priority for bicycles (i.e. cars have to yield to bicycles), respondents' perceptions of safety and comfort will increase. On the contrary, higher bicycle volumes showed a negative sign, indicating that respondents' perceptions of safety and comfort decreased when roundabouts with that feature were presented. This was backed by the survey respondent answers which noted that increased bicycle congestion makes it uncomfortable to ride, especially when turning. The CBQ Violations variable is marginally significant for comfort but is more statistically significant for safety; this is intuitive as violations would affect the perception of safety latent variable more (*51*). The model results found that Dutch respondents perceived higher safety and comfort levels, when compared with respondents who do not live in the Netherlands. The Age variable was negative, which is intuitive: older cyclists perceive less comfort and safety; this suggests that an older population has greater sensitivity to a roundabout whilst controlling for certain design features such as yielding priority, compared with a younger population (*3, 4, 31, 52*). The bicycle crash history variable was negative in sign and very statistically significant. This is also intuitive and aligns with past studies showing that if one has been in a recent crash, one will have a lower perception of safety and comfort (*36*). The final group of independent variables were the mode frequency variables. The normal bicycle and e-bicycle mode variables (comparing a frequency of 1 to 3 days per month to everyday) were statistically significant and positive of sign. This is intuitive: as people bicycle more, they have higher perceptions of comfort and safety. The results of the model follow the conceptual model shown in Figure 2 with exception of certain independent variables that were dropped due to low explanatory value (self-ascribed bicycling skill level, income, and education).

Elasticities

Due to the nonlinear nature of random effect ordered probit equations (Equation 1), one can not directly read the beta coefficients (estimate values). As such, elasticities are calculated for every level of each latent variable. Presenting the elasticities of the estimated parameters helps interpret the practical effect of each variable on the likelihood of a comfort level or perceived safety ranking in which the parameter estimates of the ordered probit model alone are not sufficient to explore the impacts of each factor on the likelihood of different comfort level or perceived safety categories (*47*). In essence, it is how many percentages you obtain towards falling in a certain category when you change 1% of the independent variable. The greater the elasticity, the more important that independent variable is for the latent variables. Tables 6 & 7 show the elasticities from the ordered probit model for each category of each latent variable.

TABLE 6: **Elasticities table - comfort latent variable**

Variable	*Comfort variable* Very uncomfortable	uncomfortable	neutral	comfortable	very comfortable
Bike_Volumes: High	0.390	0.250	0.010	-0.020	-0.304
Bike_Yielding_Priority: Yes	-0.180	-0.160	0.010	0.204	0.098
Bi_Directional: Yes	0.310	0.210	-0.010	-0.250	-0.270
Buffer_width	-0.350	-0.240	0.010	0.270	0.380
Art_Ads_in_Center	0.320	0.220	-0.010	-0.322	-0.250
Four_legs_entrance_points	0.390	0.240	0.010	-0.420	-0.108
Respondent_residence: Netherlands	-0.470	-0.300	-0.010	0.523	0.312
Age_Category: 40+	0.390	0.280	-0.020	-0.404	-0.324
Gender: Male	-0.490	-0.330	-0.020	0.548	0.297
Bicycle_crash_history: Recent	0.120	0.080	-0.020	-0.094	-0.158
Violations: Most of the time	-0.190	-0.387	-0.240	0.497	0.253
Errors: Most of the time	0.338	0.194	-0.248	-0.258	-0.018
Positive behaviour: Most of the time	-0.410	-0.097	-0.305	0.328	0.411
Normal_bicycle_freq: Everyday	-0.286	-0.119	0.038	0.204	0.308
E_bicycle_freq: Everyday	-0.119	-0.284	-0.096	0.429	0.198
Cargo_bicycle_freq: Sometimes	0.237	0.169	0.056	-0.295	-0.167
Cargo_bicycle_freq: Everyday	-0.036	-0.429	-0.033	0.444	0.299

bold indicates a independent variable that is statistically significant at least at the 90% confidence level.

According to the elasticities, the presence of yielding priority for bicycles (e.g. vehicles have to yield to bicycles) increases the probability of a bicyclist feeling comfortable by 20%, whereas the lack of yielding priority increases the probability of a bicyclist feeling very uncomfortable by 18%. The probability of a bicyclist feeling very comfortable is only 10%, which means that there may still be hesitancy and doubts about yielding priority being fully effective or safe. In terms of perception of comfort at roundabouts, the importance of bicyclists having yielding priority is the same as if a bicyclist were to sometimes ride a cargo bicycle.

TABLE 7: **Elasticities table - perception of safety latent variable**

	Perception of Safety variable				
Variable	very unsafe	unsafe	neutral	safe	very safe
Bike_Volumes: High	0.390	0.250	-0.040	-0.259	-0.348
Bike_Yielding_Priority: Yes	-0.180	-0.140	-0.020	0.158	0.129
Bi_Directional: Yes	NC	NC	NC	NC	NC
Buffer_width	0.350	0.230	-0.040	-0.422	-0.298
Art_Ads_in_Center	NC	NC	NC	NC	NC
Four_legs_entrance_points	0.390	0.260	-0.040	-0.189	-0.287
Respondent_residence: Netherlands	-0.470	-0.280	-0.040	0.479	0.349
Age_Category: 40+	0.390	0.230	-0.030	-0.277	-0.314
Gender: Male	0.490	0.250	-0.020	-0.399	-0.467
Bicycle_crash_history: Recent	0.120	0.170	0.040	-0.245	-0.097
Violations: Most of the time	-0.248	-0.316	-0.094	0.469	0.149
Errors: Most of the time	NC	NC	NC	NC	NC
Positive behaviour: Most of the time	NC	NC	NC	NC	NC
Normal_bicycle_freq: Everyday	-0.359	-0.186	-0.249	0.456	0.228
E_bicycle_freq: Everyday	-0.306	-0.149	0.068	0.265	0.487
Cargo_bicycle_freq: Sometimes	0.117	0.059	-0.368	-0.088	-0.159
Cargo_bicycle_freq: Everyday	-0.358	-0.296	-0.049	0.198	0.269

NC: not calculated due to removal of this independent variable.
bold indicates a independent variable that is statistically significant at least at the 90% confidence level.

The elasticities of the final model show that the more frequently people ride bicycles or cargo bicycles, the higher the probability is that a bicyclist will feel safe or comfortable at a roundabout. The sign of the coefficient for cargo bicycle changes if someone uses a cargo bicycle everyday versus only a few times per week. This change in sign means that as an individual uses a cargo bicycle more often, they become more comfortable at riding them. Cargo bicycles have wide turning radii, poor balance at low speeds, and are generally bulky. Bicyclists using these bicycles may feel inhibited in the existing bicycle paths and must turn more cautiously. This explains why if a bicyclist uses a cargo bicycle only sometimes, the probability of feeling comfortable decreases by 30%. The finding about the sign of the cargo bicycle usage variable, along with the CBQ questions, aligns with past studies that concluded that the more people bicycle, the more confidence and perceived control they may have, which leads to higher perceptions of comfort and safety (*32, 33*).

CROW design guidelines

By outlining the expert insights, model results, and field observations, this section will answer sub-question #4, *Why does deviation from CROW design guidelines occur and does that affect bicyclists' subjective safety?* The expert insights revealed that deviation from the CROW design guidelines occurs due to politics, geometrical constraints, private land boundaries, trees, water management or, in rare cases, funding challenges. The general design framework, which must be followed for all roadway projects, details how CROW deviations should be clearly documented (*53*). However, there is no official review board since CROW publications are not standards, only guidelines to assist designers in project development. Many times common sense (e.g. a tram lane cutting through the center of the roundabout means bicycles and vehicles must yield to the tram) and unique local characteristics (such as the entire city having bi-directional bicycle paths) are valid reasons to deviate from the CROW design guidelines.

Roundabouts #4, #5, and #6 presented in the survey, (modified roundabouts based on Planbaan/Kernbaan, Amstelplein, and Gordelweg/Rodenrijsestraat respectively from Table 3) purposely did not follow CROW design guidelines as they did not provide yielding priority to bicyclists. At these locations there was a noticeable drop in the percentage of respondents who answered favorably (i.e. either neutral to high rating of safety or comfort). The average neutral-positive ratings for comfort were 65.2% compared with the average of 80.4% at the other roundabouts. The average neutral-positive ratings for perception of safety were 74% compared with the average of 86.1% at the other roundabouts.

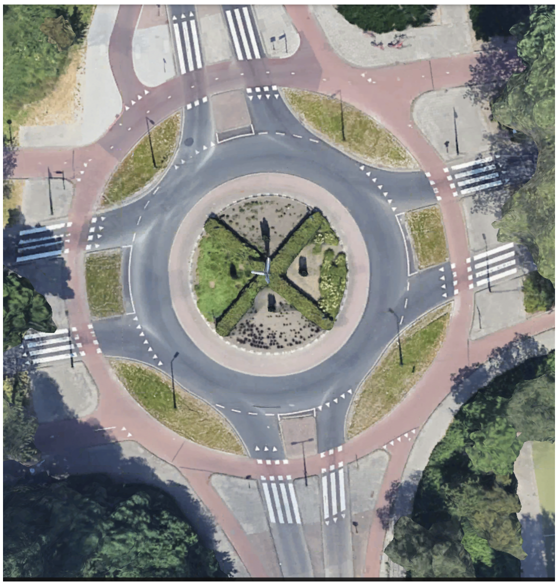
A design change that gives yielding priority to vehicles increases the probability of a bicyclist feeling very uncomfortable by 18%. Deviating from CROW guidelines does negatively impact a bicyclist's subjective safety; which is in line with past studies that looked at yielding behaviours (*54, 55*).

Design characteristics, compliance, and behaviours

The findings of the random effects ordered probit model regarding the legs at a roundabout and yielding priority roundabout attribute variables are in line with past studies that found that limiting the number of legs at a roundabout and providing bicycles with yielding priority increases perceived safety (*1, 14, 56*). The model results for yielding priority correlate with the open-response question respondents answered, stating that Dutch drivers almost always yield to bicyclists, especially at roundabouts with a small buffer width between the vehicle lane and the bicycle path. Most respondents agreed that bicycles should always have the right-of-way (yield priority) at urban roundabouts, with a few noting that it's much more difficult for a bicyclist to stop and start again compared to a car. Many respondents reported that it should be universal that bicycles have yielding priority inside urban areas and that they assume that vehicles will stop for them regardless of who has the right-of-way. Past studies showed a clear increase in crash rates when yielding priority was unclear (*19, 20*). Field observations support that yielding priority should be given to bicycles, as there were many illegal bicycle movements observed at Putsebocht tram stop (Figure 1b), where bicycles must yield to all other traffic.

Regarding the bicycle volumes variable, the findings are consistent with past studies: the higher the bicycle volumes are, the less a bicyclist feels safe or comfortable. More bicycle traffic means more conflicts at bicycle crossing points and other critical decision areas such as entering or exiting a roundabout (*22, 57, 58*). Due to the binary nature of this and other variables, it is impossible to pinpoint at what bicycle volume threshold a shift in perception occurs. Further research could expand on this.

Another important finding from the field observations and the model run was that roundabouts with a strong attractor at one corner and high bicycle volumes were perceived as less safe and less comfortable. This is intuitive since a strong attractor, such as a grocery store or a geographic barrier, generates more turning movements which causes friction amongst bicyclists and between bicyclists and other modes. This would cause lower perceptions of safety and could lead to more actual crashes. Locations with busier traffic, more public transport and where there were stores along the entire street (Dierenselaan/Apeldoornselaan, The Hague or Hugo de Grootplein, Amsterdam (Figure 1a) didn't show a visible relationship between the location of the grocery store and bicycle movements. Some roundabouts, such as at Gordelweg/Rodenrijsestraat, Rotterdam (Figure 3a) or Amstelplein, Amsterdam (Figure 3b) were observed to have significant bicycle volumes only on one side due to natural barriers.



(a) **Aerial view of roundabout on Gordelweg, where the Noorderkanaal and A20 highway to the north are the reason for many north/south and southwest corner to northeast corner bicycle movements**

(b) **Aerial view of roundabout in Amstelplein, Amsterdam, where NS train tracks and a canal pose barriers , translating to a lot of North to East and South to East movements**

FIGURE 3: **Roundabouts that have strong directionality due to geographic barriers. Images courtesy of Google Earth.**

Overall, this section answered sub-question #1: *What bicycle infrastructure design and behavioural factors at urban roundabouts in the Netherlands affect bicyclists' perceptions of safety and comfort?* and attempted to answer sub-question #2: *What bicycle infrastructure design and behavioural factors affect bicyclists' compliance with traffic laws?*. This report only partially answered sub-question #2 as the survey only asked about a person's general compliance by means of the 12 CBQ questions. It did not explore specific compliance with regards to a certain roundabout design and associated design features. This report is able to conclude that the more bicyclists demonstrate risky behaviour, the more likely they will break traffic laws and have a lower sense of perceived safety and comfort at roundabouts.

Population groups

Research sub-question #3: *How do different bicyclist groups perceive the safety of roundabouts?* is not fully answered since the gender variable was not statistically significant; this was likely due to the low number of responses received. The results of the ordered probit model demonstrated that older adults are more sensitive to perceptions of safety. This aligns with the general premise that older adults are more risk-averse (*44*). According to the model results, non-Dutch people feel less comfortable or safe at roundabouts, when controlling for yielding priority, bi-directional bicycle paths, and the other attributes. This is logical, as there are fewer roundabouts with dedicated bicycle facilities outside of the Netherlands, so respondents not residing in the Netherlands are more cautious when bicycling near conflict points such as an urban roundabout.

CONCLUSION AND RECOMMENDATIONS

Despite being a world leader in bicycle infrastructure, the Netherlands must continue to improve its infrastructure in order to accommodate the diversity of bicycle types and the growing number of people who choose to use sustainable transport modes. This research looked at how bicycle infrastructure design at urban roundabouts affects bicyclists' perceptions of safety and comfort by performing a stated choice experiment and analyzing the data via a random effects ordered probit model. The underlying aim of this study was to provide conclusive support for design features that make bicyclists feel comfortable and safe navigating roundabouts.

This research found a strong correlation between the two dependent variables of comfort and perceived safety and roundabout design factors such as bicycle volumes, yielding priority, and the number of legs at the roundabout. In addition, the bicycle mode frequency independent variables (cargo bicycle, normal bicycle, and e-bicycle), age, crash history, respondent residence, and the CBQ violations independent variable were found to be statistically significant.

This conclusion answers the main research question: *What factors contribute to bicyclists' perceptions of safety at roundabouts?* It was found that people who: are older, or have had a recent bicycle crash, or commit violations whilst bicycling (part of the CBQ error group), or sometimes ride a cargo bicycle, or do not reside in the Netherlands have lower perceptions of comfort at roundabouts. Regarding infrastructure, bicyclists had lower perceptions of safety and comfort at roundabouts with high bicycle volumes and more vehicular entrance/exit points. This research shows that it is important to give yielding priority to bicyclists and to maintain uniformity in design of urban roundabouts. In addition, future designs should follow CROW guidelines, and work towards limiting congestion and minimizing the number of vehicular legs entering or exiting roundabouts.

Certain factors were found to be statistically insignificant. These include: buffer width, bi-directional bicycle paths, bicycle path shape, and bicyclist's income. Further data is needed to provide reportable results for these factors. Future research could: extend the data collection to more roundabouts, both urban and rural, as well as more attributes (e.g. width of the bicycle path, visibility, or presence of public transport); consider weather or lighting as additional independent variables; provide more levels or categories for the roundabout attribute variables, in order to check for linearity, have better threshold precision, and avoid odd signs, such as the sign for the buffer width attribute; perform an ordinal factor analysis on the CBQ variables; and include short video clips in order to make the survey more accessible for a wider range of respondents.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Maria Salomons, Haneen Farah, Ian Trout; data collection and processing: Ian Trout; analysis and interpretation of results: Ian Trout, Amir Afghari; draft manuscript preparation: Ian Trout. All authors reviewed the results and approved the final version of the manuscript.

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REFERENCES

1. Distefano, N., S. Leonardi, and F. Consoli, Drivers' Preferences for Road Roundabouts: A Study based on Stated Preference Survey in Italy. Springer, 2019, Vol. 23, pp. 4864–4874.
2. Werner, B. and S. Birgit, Capacity and safety of roundabouts in West Germany. *Conference of the Australian Road Research Board*, 1990, pp. 275–281.
3. Wegman, F. and P. Schepers, Safe System approach for cyclists in the Netherlands: Towards zero fatalities and serious injuries? *Accident Analysis and Prevention*, Vol. 195, 2024, pp. 30–37.
4. Shen, J., T. Wang, C. Zheng, and M. Yu, Determinants of Bicyclist Injury Severity Resulting from Crashes at Roundabouts, Crossroads, and T-Junctions. *Journal of Advanced Transportation*, Vol. 2020, 2020.
5. de Waard, D., A. Prey, A. K. Mohr, and F. Westerhuis, Differences in cycling performance of Dutch and non-Dutch students in the Netherlands. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 68, 2020, pp. 285–292.
6. Fernandez-Heredia, A., A. Monzon, and S. Jara-Diaz, Understanding cyclists' perceptions, keys for a successful bicycle promotion. Science Direct, 2014, pp. 1–11.
7. Useche, S. A., L. Montoro, J. M. Tomas, and B. Cendales, Validation of the Cycling Behavior Questionnaire: A tool for measuring cyclists' road behaviors. *Transportation Research Part F*, Vol. 58, 2018, pp. 1021–1030.
8. Useche, S. A., P. Philippot, T. Ampe, J. Llamazares, and B. d. Geus, "Pedaler en toute securite": The Cycling Behavior Questionnaire (CBQ) in Belgium – A validation study. *Transportation Research Part F*, Vol. 80, 2021, pp. 260–274.
9. Han, L., Perceived risk of interaction with e-bikes. Delft University of Technology, 2023.
10. Chaurand, N. and P. Delhomme, Cyclists and drivers in road interactions: A comparison of perceived crash risk. *Accident Analysis & Prevention*, Vol. 50, 2013, pp. 1176–1184.
11. Useche, S. A., F. Alonso, L. Montoro, and C. Esteban, Explaining self-reported traffic crashes of cyclists: An empirical study based on age and road risky behaviors. *Safety Science*, Vol. 113, 2019, pp. 105–114.
12. Duivenvoorden, K., The effects of intersection design and road users' behaviour on the interaction between cyclists and car drivers. Delft University of Technology, 2021.
13. Jensen, S. U., Safe roundabouts for cyclists. *Accident Analysis and Prevention*, Vol. 105, 2017, pp. 30–37.
14. Poudel, N. and P. A. Singleton, Bicycle safety at roundabouts: a systematic literature review. *Transport Reviews*, 2021.
15. Silvano, A., X. Ma, and H. Koutsopoulos, A Hierarchical Modelling Framework for Vehicle-bicycle Interactions at Roundabouts. *International Cycling Safety Conference*, 2014.
16. CROW-Kennisbank, 4.1 Achtergronden–rotonde. *CROW*, 2014.
17. Fietsberaad CROW. Verkenning verbetering verkeersveiligheid fietsers op rotondes. 2019. Available at: https://fietsberaad.nl/Kennisbank/Verkenning-verbetering-verkeersveiligheid-fietsers?URLReferrer=searchtext Accessed on: 2023-11-21.
18. Sakshaug, L., A. Laureshyn, Svensson, and C. Hydén, Cyclists in roundabouts—Different design solutions. *Accident Analysis and Prevention*, Vol. 42, 2010, pp. 1338–1351.

19. Fietsberaad CROW. Hernieuwde aandacht voor de veiligheid van fietsers op rotondes. 2019. Available at: https://fietsberaad.nl/Kennisbank/Hernieuwde-aandacht-voor-de-veiligheid-van-fietser?URLReferrer=searchtext Accessed on: 2023-11-21.
20. Jensen, S., Safety effects of converting intersections to roundabouts. *Transportation Research Record*, Vol. 2389, 2013, pp. 22–29.
21. CROW-Kennisbank, 6 Rotonde. *CROW*, 2014.
22. Cantisani, G., C. Durastanti, and L. Moretti, Cyclists at roundabouts: Risk analysis and rational criteria for choosing safer layouts. *Infrastructures*, Vol. 6, 2021.
23. CROW-Kennisbank, Overzicht CROW kennisproducten op het gebied van Verkeer en Vervoer (2018-2020). *CROW*, 2020.
24. CROW-Kennisbank, 3.6 Afwikkeling fietsers and voetgangers. *CROW*, 2014.
25. Fietsberaad CROW. Tilburg past voorrangssituatie op 23 rotondes aan. 2021. Available at: https://fietsberaad.nl/Kennisbank/Tilburg-past-voorrangssituatie-op-23-rotondes-aan?URLReferrer=searchtext Accessed on: 2023-11-21.
26. Kummeneje, A.-M., E. O. Ryeng, and T. Rundmo, Seasonal variation in risk perception and travel behaviour among cyclists in a Norwegian urban area. Elsevier Ltd, 2019, Vol. 124, pp. 40–49.
27. Richard Mantona, R., H. Rau, F. Fahy, J. Sheahan, and E. Clifford, Using mental mapping to unpack perceived cycling risk. Science Direct, 2016, pp. 138–149.
28. Bösehans, G. and G. M. Massola, Commuter cyclists' risk perceptions and behaviour in the city of Sao Paulo. *Transportation Research Part F*, Vol. 58, 2018, pp. 414–430.
29. Poudel, N. and P. A. Singleton, Preferences for roundabout attributes among US bicyclists: A discrete choice experiment. *Transportation Research Part A*, Vol. 155, 2022, pp. 316–329.
30. van der Leeden, E., A comparison between the pleintje, priority intersection roundabout. Delft University of Technology, 2012.
31. Poudel, N. and P. A. Singleton, Bicycling comfort at roundabouts: Effects of design and situational factors. *Transportation Research Part F: Traffic Psychology and Behaviour*, Vol. 94, 2023, pp. 227–242.
32. Sanders, R., Perceived traffic risk for cyclists: The impact of near miss and collision experiences. Science Direct, 2015, pp. 26–34.
33. Marín Puchades, V., F. Fassina, F. Fraboni, M. De Angelis, G. Prati, D. de Waard, and L. Pietrantoni, The role of perceived competence and risk perception in cycling near misses. *Transportation Research Part F*, Vol. 105, 2018, pp. 167–177.
34. Jensen, S., Pedestrian and Bicycle Level of Service at Intersections, Roundabouts and other Crossings. *Transportation Research Record*, 2012, pp. 0–19.
35. Aldreda, R. and A. Goodman, Predictors of the frequency and subjective experience of cycling near misses: Findings from the first two years of the UK Near Miss Project. *Accident Analysis and Prevention*, Vol. 110, 2018, pp. 161–170.
36. Møller, M. and T. Hels, Cyclists' perception of risk in roundabouts. *Accident Analysis and Prevention*, Vol. 40, 2008, pp. 1055–1062.
37. Wang, K. and G. Akar, Street Intersection Characteristics and Their Impacts on Perceived Bicycling Safety. Science Direct, 2018, Vol. 2672, pp. 41–54.

38. Zeuwts, L. H., E. Iliano, M. Smith, F. Deconinck, and M. Lenoir, Mental fatigue delays visual search behaviour in young cyclists when negotiating complex traffic situations: A study in virtual reality. Elsevier Ltd, 2021, Vol. 161.

39. John Parkin, J., M. Wardman, and M. Page, Models of perceived cycling risk and route acceptability. *Accident Analysis and Prevention*, Vol. 39, 2007, pp. 364–371.

40. Verita HR services. Question Scales Part 1: Should I use an even or odd number of response options? 2023. Available at: https://veritaengage.com/odd-or-even-number-of-response-options/. Accessed on: 2024-04-20.

41. Chen, F., M. Song, and X. Ma, Investigation on the Injury Severity of Drivers in Rear-End Collisions Between Cars Using a Random Parameters Bivariate Ordered Probit Model. *Internation Journal of Environmental Research and Public Health*, 2019.

42. Xiao, D., Q. Yuan, S. Kang, and X. Xu, Insights on Crash Injury Severity Control from Novice and Experienced Drivers: A Bivariate Random-Effects Probit Analysis. Hindawi, 2021, pp. 0–13.

43. Lee, J., M. Abdel-Aty, Q. Cai, and L. Wang, Effects of emergency medical services times on traffic injury severity: A random effects ordered probit approach. *Traffic Injury Prevention*, Vol. 19, 2018, pp. 577–581.

44. Schepers, P., D. Twisk, E. Fishman, A. Fyhri, and A. Jensen, The Dutch road to a high level of cycling safety. Science Direct, 2017, pp. 264–273.

45. Laerd Statistics. Ordinal Regression using SPSS Statistics. 2018. Available at: https://statistics.laerd.com/spss-tutorials/ordinal-regression-using-spss-statistics.php. Accessed on: 2024-05-10.

46. Sungjun, L., P. Seongmin, P. Juneyoung, and C. Junhan, Severity Analysis for Children-Related Crashes in School Zones Using Random Effects Ordered Probit Models. *Journal of Korean Society of Transportation*, 2022, pp. 599–611.

47. Jafari Anarkooli, A., M. Mehdi Hosseinpour, and A. Kardar, Investigation of factors affecting the injury severity of single-vehicle rollover crashes: A random-effects generalized ordered probit model. *Accident Analysis Prevention*, Vol. 106, 2017, pp. 399–410.

48. Zheng, Z., Z. Liu, C. Liu, and N. Shiwakoti, Understanding public response to a congestion charge: A random-effects ordered logit approach. Science Direct, 2014, Vol. 70, pp. 117–134.

49. Washington, S., M. G. Karlaftis, F. Mannering, and P. Anastasopoulos, *Statistical and econometric methods for transportation data analysis*. Chapman and Hall/CRC, 2020.

50. Hirk, R., K. Hornik, and L. Vana, Mvord: An R package for fitting multivariate ordinal regression models. *Journal of Statistical Software*, Vol. 93, 2020, pp. 1–41.

51. Friel, D., S. Wachholz, T. Werner, L. Zimmerman, O. S. Schwedes, and R. Stark, Cyclists' perceived safety on intersections and roundabouts – A qualitative bicycle simulator study. Science Direct, 2023.

52. Kazemzadeh, K., A. P. Afghari, and C. R. Cherry, For whom is sharing really scaring? capturing unobserved heterogeneity in perceived comfort when cycling in shared spaces. Elsevier, 2024, Vol. 103, pp. 306–318.

53. Rijkswaterstaat. Documenten richtlijnen autosnelwegen. 2024. Available at: https://www.rijkswaterstaat.nl/zakelijk/werken-aan-infrastructuur/bouwrichtlijnen-infrastructuur/autosnelwegen. Accessed on: 2024-04-07.

54. Zhang, B. and Z. Ma, *Revolutionise roundabout design on bicycle routes*. Australian Institute of Traffic Planning and Management (AITPM) National Conference, 2015.
55. Lawton, B. J., P. J. Webb, G. T. Wall, and D. G. Davies, Cyclists at 'continental' style roundabouts: report on four trial sites. *ARRB*, 2003.
56. ARUP, Design recommendations for bicycle roundabouts–Expert session, 2022.
57. Pulvirenti, G., T. DeCeunynck, S. Daniels, N. Distefano, and S. Leonardi, Safety of bicyclists in roundabouts with mixed traffic: Video analyses of behavioural and surrogate safety indicators. *Transportation Research Part F*, Vol. 76, 2021, pp. 72–91.
58. Dabbour, E. and S. M. Easa, Evaluation of safety and operational impacts of bicycle bypass lanes at modern roundabouts. *Canadian Journal of Civil Engineering*, Vol. 35, 2008, pp. 1025–1032.

B

Qualitative analysis

B.1. Expert insights

During a CROW-led meeting on February 28th, 2024 about roundabouts, which took place in Utrecht, representatives of various local city, provincial, and federal agencies and transport consultants met to discuss the new CROW guideline called: Everything about roundabouts. This was the second workshop meeting, with the 1st meeting being held in November 2023. The next paragraphs present the detailed findings from the 1st meeting and topics and discussion points from the second meeting. The following paragraphs are broken down by the group of person, aka a consultant or local city official. In addition, this section has the unabridged version of the expert survey responses.

DTV, Turbo Traffic Solutions, and SWECO consultants

The senior advisor from Turbo Traffic Solutions was there and presented their thoughts on a variety of topics, namely how the guidelines should present the design steps clearly but try to minimize the amount of text as much as possible. Safety is primordial in all designs and there should be a transition to emphasize slower traffic speeds in general. He stated that it should be simply that inside an urban area, there will be bicycle yielding priority and outside there will not be. Other members contested this and said it can't simply be like that since there are situations (such as with public transport), where it makes sense to not give priority.

The SWECO consultants were leading the main discussion and the mini breakout group that occurred. In the recap of the 1st meeting, SWECO mentioned how a lot has been done to slow down motor vehicles in the design guidelines but little has been done for users in the bicycle path. There also seems to be not a lot of thought put into the visibility of the bicyclist, which results in some hazards. SWECO noted that there should be threshold bicycle volumes where a certain design is no longer adequate for an application. The 1st meeting had discussions regarding bending out the bicycle path so that there's more room for motorists to anticipate fast moving bicyclists' turning movements. That 1st meeting also raised issues regarding pedestrian safety and clear guidelines regarding how giving bicyclists yielding priority grants them more safety. The 1st meeting also went over how there are now many different varieties of bicycles and that this causes friction between modes (do not forget public transport and also pedestrians). Unfortunately crash recordings are under-reported so making a proper safety assessment on roundabouts is difficult and doesn't help designers go from analyzing an intersection to determining design features. The 1st meeting ended with a small discussion on art/advertising at roundabouts but it was inconclusive (no strong opinions for or against art/advertising).

At the beginning of the second meeting, the draft contents page of the new CROW guideline was shown for approval. It focused on compiling a lot of information from other CROW publications, with a focus on the different modalities (e-bicycles, scooters, cars, public transport, etc) and road safety. This new guideline will cover all the basic design information and then also develop more detailed information about the bicycle-roundabout (e.g. Zwolse), single lane roundabout, and the turbo-roundabout (no mention of a regular multi-lane roundabout was made and it is not recommended by existing CROW guidelines). SWECO mentioned that there could be a section on how to optimize existing roundabouts as well. They asked the group what kinds of conclusions do they want to make in the new guidelines; what things can the entire group agree on?

In the breakout group, one of the advisors mentioned how Groningen uses speed bumps in the bicycle path (brom-drempel) to slow people down within the roundabout. One of the SWECO consultants stated that maybe the 5 meter space between the exit of the vehicular roundabout and the bicycle crossing is not enough. There is a grey zone between 5 and 10 meters and maybe 7 meters is better for always giving yielding priority to bicycles. At the end of the second workshop, SWECO advisors mentioned that there has yet to be a conversation regarding bicycle to bicycle conflicts at roundabouts or how roundabouts handle wrong-way driving or the detailed design of the bicycle crossing points (e.g. using chicanes to slow down vehicle traffic).

RWS–Rijkwaterstraat

Though the agency did not say much (they only partook online via Teams), they were receptive to the debate about yielding priority, and ultimately controlling for speed at roundabouts. The participant from RWS did mention that slowing down vehicles is probably easier to achieve than bicyclists as bicycles are more maneuverable. Clear, consistent signage and markings should be included in the new CROW publication.

TU Delft, SWOV

These two groups participated in the debate as they are research experts that have done studies on roundabouts in the past. The SWOV employee brought up a DTV study that looked at one or 2-way bicycle paths and noted that the conclusion came down to the crossing points. Certain cities have only two-way bicycle paths but no yielding priority. The SWOV employee also brought up how bicyclists have a lot to concentrate on when entering and navigating through a roundabout. She stated that the new Zwolse bicycle roundabout is proving to be mentally challenging on drivers and bicyclists since they both need to anticipate the other whilst the bicyclist can make more turning movements than the motor vehicle and those types of roundabouts have limited buffer space between the bicycle path and the vehicular lane. The SWOV employee also agreed with the advisor from Zaanstad, stating that actually about only 4% of single-bicycle crashes receive an official police report. In the discussion during the second hour, the SWOV employee mentioned how there could be a third option in the guidelines that states: yielding priority for cars unless the city wants to offer priority to bicycles. This makes the decision political instead of an engineering issue but that could have serious congestion and delay issues at busy crossing points where bicycles may have to wait for minutes in order to cross. Their final statement was that there has to be a balance between tolerating illegal behaviour and accepting and facilitating it (e.g. by converting a roundabout to be bi-directional).

Provincial governments (Fryslan, Noord-Holland, Brabant, Zuid-Holland)

The senior advisor from Friesland noted that many times, it doesn't matter what the yielding priority is at a roundabout, if there is a zebra markings for the pedestrian crossing, then it's almost certain that bicycles will have priority or think they do. Nowadays, there is a need for wider bicycle paths as there are more e-bicycles, scooters, recumbent bicycles, and cargo bicycles (bakfiets) which is causing congestion on the busier links in the bicycle network. However, at the same time, people need to slow down when needed, and a roundabout with many different possible turning movements is one of those places. The advisor from Brabant reminded everyone that designs should be understandable and comfortable for children as they understand safety also. The fact that bicyclists are now often being passed by e-bicycles or other things in the bicycle path is scary and there should be more attention paid to these interactions. The advisor from the province of Zuid-Holland brought up that pedestrians and bicyclists are linked, in particular at zebra crossings/bicycle crossings. He stated that everyone starts out as a pedestrian and that there needs to be more respect for them (bicyclists often do not stop for pedestrians).

Noord Holland advisor mentioned that we should incorporate relevant old CROW publications aswell as new publications such as the bicycle roundabout, with the example from Lieden, as new changes that can be considered for this CROW publication. This new CROW publication should replace the old

CROW publications, so as to not confuse designers. One advisor mentioned that comfort and road safety are used interchangeably but in reality, they differ and are subject to the individuals bicycling. One advisor from a provincial government suggested that yielding priority should not be recommended for or against but the new publication should state the various factors and considerations associated with making that design decision. The consequences of that decision should also be detailed to the maximum extent possible.

Gemeente/City (Breda, s-hertogenbosch, Enschede, Zaanstad)
The employee from s-Hertogenbosch was very vocal about how two-way bicycle paths motivated the city to invest in a lot of signage to sufficiently warn motorists to look both ways. Drivers are accustomed to look right and not left when exiting roundabouts. The city staff from Enschede chimed in about looking more closely at speed humps in the bicycle path before vehicular crossing points, as a way for slowing down bicycles and e-bicycles, which allows for more reaction time for drivers to be able to stop for bicyclists. The advisor from Den Bosch said that we should be constructing bicycle paths farther away from the vehicular lanes, so that there is more reaction time for both motorists and bicyclists as well as more clarity on which direction the bicyclist is going (straight versus turning).

The advisor from Zaanstad noted that they were very alarmed when they started using ambulance data and found that there are nearly twice as many crashes than what was reported in the official police database. They reason that designers can no longer simply look at only official crash data since you're going to be missing high crash or "near miss" locations. The advisor from Enschede brought up the bicycle roundabouts (Zwollse) and how this is really a new type of roundabout and deserves it's own chapter in the new CROW guidelines. There should also be a chapter on traffic analysis and how to choose the optimal roundabout for the traffic volumes and transport needs of the area. One of the advisors from a city raised the point that the raised bicycle crossings and center island aprons have generated a lot of complaints from public transport companies due to bad ride quality causing driver back injuries.

The advisor from s-Hertogenbosch stated that consistency within a municipality is an important consideration and that even though the current CROW guidelines state that bicyclists should by default have yielding priority, more attention and focus needs to be put into this subject. It is better to have a good balance between all modes from analysis through design, otherwise you may end up with a design that has a strong negative effect on one mode (e.g. motorized traffic).

Expert survey responses
In addition, the people that were at the workshop were asked the following questions via a Google form survey and provided their responses and shown in the Table below. Note that some of their responses were in Dutch. The summary of the responses were translated into English and can be found in Section 5.1.

1. In section 4.1 Achtergronden, it states that "Within built-up areas, spatial limitations are often the cause of the diversity in roundabouts." Is this the only consideration that changes roundabout design? What are other factors that may force a city or consulting firm to propose something different (such as not the 5 meters for the distance between the bicyclists and the road users)?
2. How does the option to deviate from the CROW guidelines work and constitutes a strong motivation? What considerations are taken into account (e.g. directness for bicyclists, complex transit operations)?
    - Haarlemmermeerstation in Amsterdam [rebuilt in 2019 with the priority for cars (uitvoorang) established] is a good example where it doesn't follow the Pursuant to Article 18 of the RVV 1990 [artikel 18 van het RVV 1990], which states that bicyclists should have priority at exit points if there is less than 10m separation (or if the cycle path is considered part of the roadway).
    - CROW-publicatie 230 'Ontwerpwijzer fietsverkeer'–recommends to not do bi-directional roundabouts but there are many examples where they exist (even new ones such as Stieltjesweg/ Schoemakerstraat in Delft in early 2022).

3. To which extend do the CROW guidelines grant safety (e.g. designing for lower vehicle speeds)? Are there guidelines (regarding safety) that should be reconsidered?
4. Are the CROW guidelines (such as Section 6.4.1) clear enough?— a visual connection between the roadway and the cycle path for the comfort of the bicyclist as well as safety— “This can easily be achieved by providing the intermediate verge of the cycle path and roundabout with a hard surface (clinkers or tiles).”
5. Why is there not a hard requirement to have physical separation at roundabouts that have more than 6000 movements per day (vehicle ,bicycle, truck)–Section 6.4.1?
6. Recent research has found that wider cycle paths are good for preventing bicycle crashes due to the increasing variety of types of bicycles and bicycle congestion in general. Roundabouts however, tend to be points of conflict, so have you considered narrowing the cycle path in roundabouts, to force bicyclists to go single file (narrower than 2 meters)?

Name & company/organization /	In section 4.1 Achtergronden, it states that “Within built-up areas, spatial limitations are often the cause of the diversity in roundabouts.” Is this the only consideration that changes roundabout design? What are other factors that may force a city or consulting firm to propose something different (such as not the 5 meters for the distance between the cyclists and the road users)?	How does the option to deviate from the CROW guidelines work and constitutes a strong motivation? What considerations are taken into account (E.G. directness for bicyclists, complex transit operations)? Example : Haarlemmermeerstation in Amsterdam [rebuilt in 2019 with the priority for cars (uitvoorang) established] is a good example where it doesn’t follow the Pursuant to Article 18 of the RVV 1990 [artikel 18 van het RVV 1990], which states that cyclists should have priority at exit points if there is less than 10m separation (or if the cycle path is considered part of the roadway). Another example: CROW-publicatie 230 ‘Ontwerpwijzer fietsverkeer’–recommends to not do bi-directional roundabouts but there are many examples where they exist (even new ones such as Stieltjesweg/Schoemakerstraat in Delft in early 2022).	To which extend do the CROW guidelines grant safety (E.G. designing for lower vehicle speeds)? Are there guidelines (regarding safety) that should be reconsidered, given the existence of a mixed fleet of bikes (bakfiets, e-fiets, brooms)?	Are the CROW guidelines clear enough?— Example from Section 6.4.1— a visual connection between the roadway and the bikeway for the comfort of the cyclist as well as safety— “This can easily be achieved by providing the intermediate verge of the cycle path and roundabout with a hard surface (clinkers or tiles).”	Why is there not a hard requirement to have physical separation at roundabouts that have more than 6000 movements per day (vehicle ,bike, truck)–Section 6.4.1?	Recent research has found that wider fietspads are good for preventing bicycle crashes due to the increasing variety of types of bicycles and bike congestion in general. Roundabouts however, tend to be points of conflict, so have you considered narrowing the fietspad in roundabouts, to force cyclists to go single file (narrower than 2 meters)?	Anything else you would like add about the CROW design guidelines regarding roundabouts and cyclists(in of uit voorrang, snelheid, etc)?
Gemeente 's-Hertogenbosch	Mostly the reason. There are plenty of other aspects that make it necessary to adapt a roundabout design. Consider, for example, plot boundaries, trees, water management or political reasons for retaining other functions that require space. Money is not always the issue for us, only in extreme conditions.	If we have a good reason to deviate, we will do so. We don't have much trouble with that. A guideline is not a law. We use common sense and sometimes some guts to strengthen the position of cyclists and weaken the position of the car.	The GOW30 is a hot item at the moment. We are reserved. Sounds good, doesn't work. In our view. We would like a good investigation into how you can create a well-functioning GOW30 with today's resources.	Yes.	I don't know the considerations. But I would rather have a roundabout without separation than a regular intersection, if that influences the choice.	It rarely happens that we narrow cycle paths. We broaden them where possible.	Please give priority to cyclists and pedestrians.
Rijkswaterstaat	No it also depents on if there is a free bicycle path or bicycle suggestie strook	This not an ordinairy roundabout this because of public transport that gets the right of way first. So if Public transport gets the right of way first on cars it have to get it on bicycles as well otherwise they will we be run over by public transport	According to me we have to make sure that all bicycles are going to cross with the same volicity	yes this section 6.4.1 is for me clear enough. It al depend on who has got the right of way.	If traffic intensity is to low the speed will go up and by mixing traffic the speed will be reduced because of the bicycle	It is a good idea to go small at roundabouts that way you can reduce the speed of the bicycle.	One clear thing for me is that roundabouut option you realy do not want outside. can not be included in the design guide otherwise they will be used.
ManEngenius	Politics can have an opinion, local (outdated) guidelines/standards	Available space and different traffic flows may give reason to deviate from the CROW guidelines.	Behavior among slow traffic participants is much more difficult to influence with infrastructural measures. CROW has little recommendation for influencing behavior that cannot be achieved through infrastructural measures.	More substantiation (in brief) for each recommendation is desirable. For example, why a paved surface?	Everything is included in guidelines/recommendations, nothing is legally established when it comes to the design and design of public space. This makes more possible, even with less available space or less money. And what is the limit of 6000 mvt/day?	No, I've never thought of that. Interesting.	I am a big fan of the microtonde, especially in the case of the GOW30 with mixed traffic and little space, this can be a good and safe intersection solution. Furthermore, lighting should be included more clearly in the guidelines, as should signage.
Rijkswaterstaat	There are many variables, and they must be carefully considered to arrive at the best intersection design. See also my answer to the next question.	"In order to deviate from the normal design, there are many variables that can play a role. In order to be able to properly assess all of these variables, the correct knowledge must be available. The most important consideration should be whether the understandability and clarity for road users is sufficient, because a different design should certainly NOT be at the expense of road safety. With regard to the examples you indicated: The traffic situation at the Haarlemmermeer station is NOT a roundabout. It is in fact a "normal" intersection where the Amstelveenseweg is the priority road. It's just a bit strangely designed. The only thing that is not clear at this intersection is that when crossing the Amstelveenseweg, cyclists do NOT have priority, while there is a VOP for pedestrians. And I wonder where the mopeds should ride, on the road?? Regarding the roundabout in Delft. This is a fairly simple standard roundabout and the bi-directional traffic is well designed. I am not a fan of a two-way cycle path at such a simple small roundabout. It is not difficult for cyclists to cycle 3/4 of the way around."	"The CROW guidelines are excellent tools for achieving a traffic-safe road design. However, deviating from these guidelines often results in an unknown and therefore unclear situation for the road user with negative consequences for road safety. The road design process framework provides guidance how to deal with any deviations from the guidelines. See: https://www.rijkswaterstaat.nl/zakelijk/werken-aan-informatie/bouwgids-informatie/autosnelwegen I do agree with you that the guidelines for bicycle traffic need to be revised because bicycle traffic has become so much busier and more diverse. The sooner that revision takes place, the better, because a guideline will then be available to road authorities that ensures clarity for road users. And.........what do you mean by brooms on the cycle path?"	I don't think it makes any difference to road safety whether the separation between cyclists and other traffic in Figure 13 is paved or not. See, for example, the example of the roundabout in Delft with a grass verge in between. What can make a difference is a physical separation on the roundabout (with bicycle lane) between cyclists and other traffic as in figure 12.	"In my opinion, it is a strict requirement to provide a physical separation at 6,000 mvt or more. Either with separate cycle paths (fig. 13) or cycle lanes with a narrow physical separation (fig. 12). For less than 6,000 mvt, you should consider omitting physical separation. However, the cyclist must then share the road with other traffic. Make this lane as narrow as possible so that cyclists, as it were, ride between the vehicles and not next to them. And to ensure a low speed. By the way, I would not advise that at a roundabout where there is regular freight traffic."	"I would definitely NOT do this for three main reasons."I would definitely NOT do this for three main reasons. 1. This means that one of the cyclists has to slow down to ride one behind the other. This increases the risk of accidents and bicycle traffic jams. This is negative for road safety. 2. Because other traffic now has to wait longer for cyclists to pass, this is at the expense of the capacity of the roundabout. 3. Motorists having to wait longer is also detrimental to road safety because motorists are prepared to take more risks the longer the wait lasts. As a result, the situation may be misjudged, resulting in accidents. There may be more reasons, both for and against. This could perhaps be weighed against each other in a very specific situation to arrive at this narrow variant."	Above all, do not change too much in the design of roundabouts, certainly not with regard to the priority situation within built-up areas. It is better to ensure that this is applied correctly everywhere in the Netherlands, including in terms of the design of (the cycle paths). around) the roundabout. See also the CROW publication CROW publication 126a – Bicycle crossings on roundabouts and see the fact sheet: road safety at single-lane roundabouts: https://www.kennisnetwerkspv.nl/getmedia/1d6e9ef2-12c8-46cf-b3c4-d1c220b06af6/Factsheet_SPV-4_vvh-bij-enkelstromensrotondes_WEB.pdf.aspx

B.2. Site selection

This section provides more details why certain roundabouts were chosen to be shown in the final survey and provides more detail mentioned in Section 4.3. This research started by casting a wide net, looking for roundabouts within urban areas (classified as Binnen in the NWB dataset column called BEBKOM). Then there was manual Google Map satellite checks to see if the roundabout was not controlled by a traffic signal and that there was indeed a dedicated bicycle facility. After those filters were performed, then cities were chosen to show the most populated cities and other smaller cities within the Randstad. The Randstad was chosen as it was assumed that more reported crashes would be found in the BRON dataset and the Randstad is the location where the researcher resided, which simplified field observations and data collection. This left the research with the initial list of over 50 roundabouts that is shown in Table B.1. Note that there were more roundabouts in Pijnacker but those were removed due to significant green space around them, which is a different (6 of them in total) adjacent land use type compared to a more urban setting such as The Hague or Amsterdam.

The next step was to physically observe each roundabout on Table B.1, in order get the 15 minute bicycle volumes but also to see if reality was reflective of the office research thus far achieved. Further roundabouts were eliminated since they did not fit within the constraints set by this research, notably:

- Mosplein/Distelweg was removed since it is under construction (the city is rebuilding the entire roundabout to remove space for cars)
- Any roundabouts that had less than 10 bicyclists in the 15 minute observation period.

At this stage of the process, certain studied attributes were removed as explained in more detail in Sections 4.3.2 and D.2. This in turn meant that certain locations no longer represented study characteristics and were removed. The final site locations are shown on Table 4.3 and were used in the stated choice experiment. Note that only one roundabout matched exactly any of the eight unique roundabouts studied in the stated choice experiment, Delftlandplien in Delft. During the survey development process, all roundabouts were modified (even Delftlandplien) slightly to better match what was dictated by the orthogonal fractional factorial design, by altering the photos to make the roundabout fit exactly the required characteristics (e.g. uni-directional and with no bicycle yielding priority). For more information on this process, please refer to Appendix D.3.

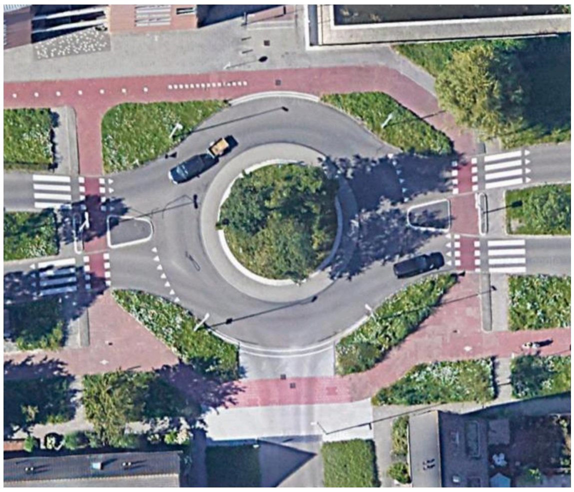
Table B.1: Initial location characteristics table. Note that this list was used for the field observations.

Label	City	art/ads in center	bicycle yielding priority[1]	uni-directional	4-legged[2]	separation from vehicle lane	bicycle volumes	visibility	facility style	transit presence[3]
Warande/Vondelweg	Rotterdam	✗	✓	✓	✗	4.82m	103	Good	Circular	✗
Boezemlaan/Karmelweg	Rotterdam	✓	✓	✓[4]	✓	2.29m	100	Good	Circular	✗
Karlingseweg/Plaszoom	Rotterdam	✓	✓	✓[4]	✓	3.07m	111	Good	Both	✗
Zuiderparkweg/Hijkerveld	Rotterdam	✓	✓	✓[5]	✓	4.53m	32	Good	Circular	✗
Groene Tuin/Reyerdijk	Rotterdam	✗	✗	✗	✓	7.51m	38	OK[28]	Circular	✓
Olympiaweg/Sportlaan	Rotterdam	✗	✓	✗	✓	5.05m	63	Good[20]	Both	✗
Olympiaweg/Buitendijk	Rotterdam	✗	✓	✗[6]	✗	4.90m	79	Good[20]	Circular	✗
Olympiaweg/Adriaan Voikerlaan	Rotterdam	✗	✓	✗	✗	6.31m[32]	89	Good	Circular	✗
Kreekhuizenlaan/ Groeninx van Zoelenlaan	Rotterdam	✗	✓	✗	✗	6.58m	118	Good	Circular	✗
Slinge/Spinozaweg	Rotterdam	✗	✗	✗	✗	9.20m	130	Good	Bent	✓[18]
Slinge/Langenhorst	Rotterdam	✓	✓	✓	✓	4.49m[32]	74	Good	Circular	✗
Putsebocht tram stop	Rotterdam	✗	✗	✓	✗	11.39m	83	Good[20]	Bent	✓
Pieter de Hoochweg/ Willem Buytewechstraat	Rotterdam	✓	✓	✓[7]	✓	0.46m	105	Good	Circular	✗
Burgemeester Meineszplein	Rotterdam	✓	✓	✓	✓	4.29m	202	Poor[23]	Circular	✗
Beukelsdijk/Heemraadssingel	Rotterdam	✓	✓	✓	✓	4.71m	305	Good	Circular	✗
Jacques Dutilhweg/Jinnahsingel	Rotterdam	✓	✓	✓[4]	✓	0.48m	42	Good	Circular	✗
Jacques Dutilhweg/ Nancy Zeelenbergsingel	Rotterdam	✗	✓	✗[22]	✗	4.79m	40	Good	Circular	✓[24]
Prinsenlaan/Jacob van Campenweg	Rotterdam	✓	✓	✓[9]	✓	6.73m	45	Good	Bent	✗
Prinsenlaan/Michelangelostraat	Rotterdam	✓	✓	✓	✓	4.89m	96	Good	Circular	✗
Gordelweg/Rodenrijsestraat	Rotterdam	✓	✓	✓[4]	✓	5.00m	193	Good[20]	Circular	✗
Gordelweg/Vroesenlaan	Rotterdam	✓	✓	✗	✓	4.44m	138	OK[23]	Circular	✗
Meerzichtlaan/Zalkerbos	Zoetermeer	✗	✓	✗	✗	5.66m	22	Good	Bent	✗
Meerzichtlaan/Berglaan	Zoetermeer	✓	✓	✗	✗	4.81m	39	Good	Bent	✗
Van Leeuwenhoeklaan/ Jacob Leendert van Rijweg	Zoetermeer	✓	✓	✗	✓	6.39m	47	Good	Bent	✗
Bredewater/Meerzichtlaan[33]	Zoetermeer	✓	✓	✗	✗	7.86m	50	Good	Bent	✗
Brechtzijde/Toneellaan	Zoetermeer	✗	✓	✗	✗	5.29m	32	Good	Circular	✗
Planbaan/Lijnbaan	Zoetermeer	✗	✓	✓[9]	✗	4.04m	16	OK	Bent	✗
Planbaan/Kernbaan	Zoetermeer	✗	✓	✓[9]	✓	4.45m	13	Good	Bent	✗
Planbaan/Ruimtebaan	Zoetermeer	✗	✓	✗	✓	5.05m	8	Good	Bent	✗
Meerzichtlaan/Kerkenbos	Zoetermeer	✗	✓	✗	✗	5.72m	51	Good	Bent	✗
Van Leeuwenhoeklaan/Clauslaan	Zoetermeer	✓	✓	✗	✓	4.80m	66	Good	Circular	✗
Zwaardslootseweg/Aidaschouw[33]	Zoetermeer	✓	✓	✗[8]	✗	5.88m	78	Good	Bent	✓[10]
Delftlandplien	Delft	✓	✓	✓	✓	9.55m	341	Poor[28]	Bent	✓[11]
Stieltjesweg/Schoemakerstraat	Delft	✗	✓	✗[12]	✓	3.73m	77	Good	Circular	✗
Westlaan/Europalaan	Pijnacker	✓	✓	✗	✓	5m	81	Good	Circular	✗
Vrouwenrecht/Klapwijkseweg	Pijnacker	✗	✓	✗[17]	✗	4.81m	91	OK[23]	Bent	✗
Ade/Klapwijkseweg	Pijnacker	✓	✓	✗	✓	6.24m	65	Good	Circular	✗
Rietlanden/Klapwijkseweg	Pijnacker	✓	✓	✗	✓	4.7m	27	Good	Circular	✗
Oostlaan/Emmastraat	Pijnacker	✓	✓	✓	✓	2.48m	123	Good	Both	✗
Duikersloot/Klapwijkseweg	Pijnacker	✓	✓	✗[17]	✗	3.30m	60	Good	Circular	✗
Dierenselaan/De la Reyweg	Den Haag	✗	✓	✓	✓	6.88m[32]	81	Poor[23]	Circular	✓[15]
Vlaskamp/Diamanthorst	Den Haag	✗	✓	✓	✓	5.24m	30	Good	Circular	✗
Sportlaan/De Savornin Lohmanlaan	Den Haag	✗	✓	✓	✓	4.99m	55	Good	Circular	✗
Sportlaan/Wildhoeflaan	Den Haag	✗	✓	✓	✓	4.86m	78	Good	Circular	✗
Sportlaan/Segbroeklaan[34]	Den Haag	✓	✓	✓	✓[34]	4.36m	79	Good	Circular	✓[34]
Neherkade/Slachthuisstraat	Den Haag	✗	✓	✓[19]	✓	5.13m[32]	90	Good	Circular	✓
Dierenselaan/Apeldoornselaan	Den Haag	✗	✓	✓	✗	3.79m	80	OK[28]	Circular	✓[13]
Hugo de Grootplein	Amsterdam	✗	✓	✓	✓	4.67m	646	Good[29]	Circular	✓[15]
Mosplein/Distelweg	Amsterdam	✗	✓	✗[19]	✓	2.32m	XX	OK	Bent	✗
Meeuwenlaan/Johan van Hasseltweg	Amsterdam	✗	✓	✓[30]	✓	6.55m[32]	146	OK[20]	Bent	✓[21]
Amstelplein	Amsterdam	✗	✓	✓[22/31]	✗	5.76m	559	Good	Circular	✗
Aalsmeerplein	Amsterdam	✗	✓	✓	✓	4.17m	111	Poor[23]	Circular	✓[24]
Hoofddorpplein	Amsterdam	✓	✓	✓	✓	4.19	310	Poor[25]	Bent	✓[14]
Haarlemmermeerstation[33]	Amsterdam	✗	✗[26]	✓	✗	2.52m	747	OK[27]	Circular	✓[14]

B.3. Field observations

Each roundabout in Table B.1 had to undergo a 15 minute observational period, in order to observe bicyclist behaviour, compliance, and to obtain bicycle volume data. This Appendix section supplements Section 5.2 with more pictures of the roundabouts that had notable bicyclist behavioural patterns.

(a) Aerial image of Haarlemmermeerstation in Amsterdam with 747 bicyclists per 15 min

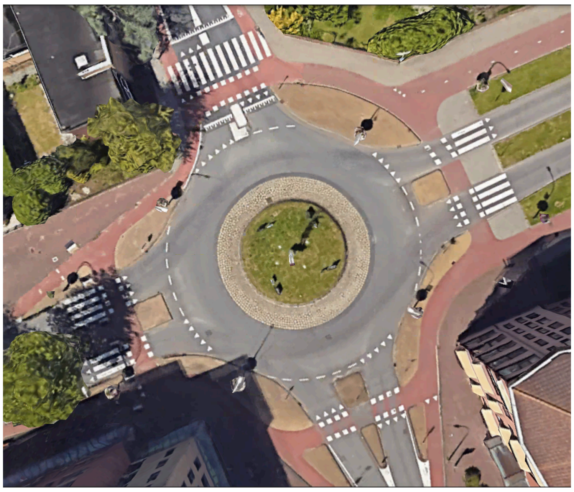


(b) Planbaan/Ruimtebaan in Zoetermeer with 8 bicyclists per 15 min

Figure B.1: Two different urban roundabouts with drastically opposite bicycle volumes.

[1]do bicycles have priority
[2]for cars
[3]X if only a bus goes through it and uses the regular car lane; I.E. there is not special transit cut-thru
[4]the northern side is bi-directional
[5]the eastern side is bi-directional
[6]bi-directional except for the east leg
[7]the cyclepaths leading away on the south side are two-way (but not in the roundabout)
[8]there are only bicycle crossings on the south and east side of intersection
[9]southside of intersection is bi-directional
[10]southbound bus lane that bypasses the roundabout itself
[11]bus lane that crosses north-south and the tram line that enters north and exits via the west
[12]except for the north and south legs
[13]two tram tracks diverging in intersection
[14]tram line goes around the roundabout aswell
[15]tram/bus lane thru roundabout
[16]the north/south crossing does not have a separate bicycle facility
[17]there is only a crossing on the east side
[18]the tram has priority through the intersection
[19]No crossing possible on the north side
[20]bushes in the center island
[21]bus lane that bypasses roundabout from north to the west
[22]except the west side
[23]large bushes in center and on sides
[24]bus lanes on the north side of intersection
[25]alot of traffic, parked cars, square in the middle
[26]the east and west side does though
[27]alot of lanes, bus lanes, many conflict points
[28]trees between bicycle and vehicle roundabout, large sweeping curves for vehicles to exit roundabout with high speeds
[29]trees present but white pavers are used 5m before the vehicle exit points for visibility
[30]the western side is bi-directional
[31]No crossing possible on the east side
[32]This includes the truck aprons
[33]Roundabout has dedicated turn lanes within roundabout circle and has multiple approach lanes on one or more legs.
[34]Roundabout has a forced eastbound right turn for cars (buses are exempt via a bus land) and the 4th arm of this roundabout is a one-way street, coming from the north.

B.3.1. Presence of grocery store



(a) Image of roundabout in Pijnacker with AH located at the SW corner

(b) Image of roundabout in Rotterdam with AH located at the NE corner

Figure B.2: Two urban roundabouts that have grocery stores located at one corner.

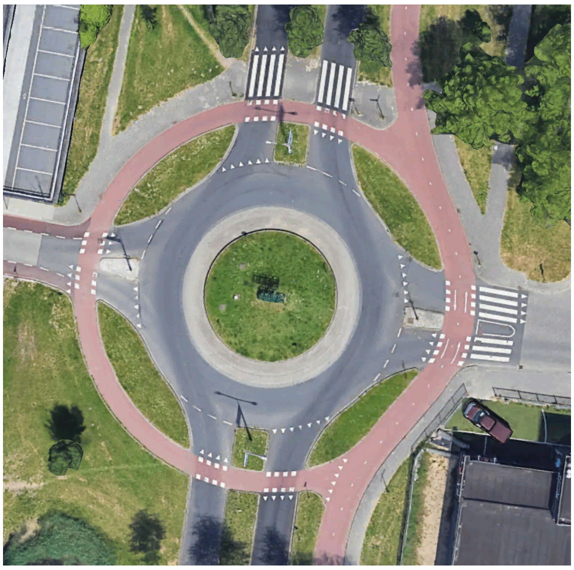
B.3.2. Strong directionality

(a) Aerial view of roundabout on Prinsenlaan, where one can note the heavy westbound right turn during evening rush hour

(b) Aerial view of roundabout on Karlingseweg, where one can note the strong connection from Kralingsebos

Figure B.3: Rotterdam roundabouts that have strong specific directional movements.

(a) Aerial view of a Rotterdam roundabout with a shopping centre located at the NW corner.



(b) Aerial view of a roundabout in south Rotterdam with a strong north/south directionality

(c) Aerial view of a roundabout in Zoetermeer with a strong north/south directionality

Figure B.4: Aerial images of roundabouts with strong bicycle volume directionality (continued)

B.3.3. Wrong way bicycle riding

(a) Aerial view of Boezemlaan, showing the bi-directional bicycle path that connects to the Crosswijk neighborhood on the left side of the image.

(b) Aerial view of Prinsenlaan roundabout, where bicyclists were observed going the wrong way on the northside of the roundabout to access the apartments located on that side.

Figure B.5: Roundabouts that had non-compliant bicyclist behaviour

B.3.4. Preference for one side of roundabout

During the field observations, it was noted that even though the bicycle facility may have been two-way on all sides, there was a clear side that had the most bicyclists. Notably, the north side was preferred at the following locations in Rotterdam:

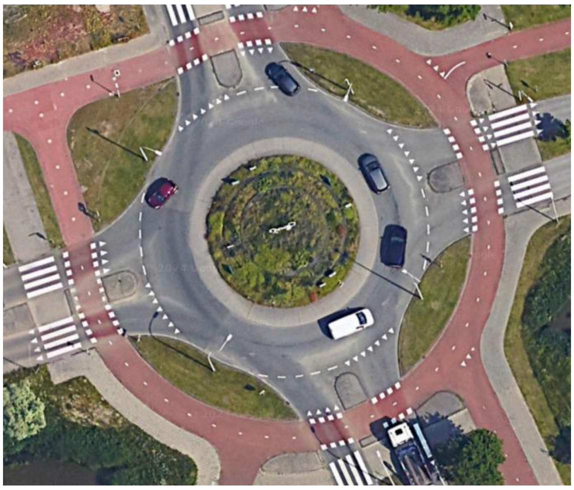
1. Boezemlaan/Karmelweg (Figure B.5a)
2. Jacques Dutilhweg/Jinnahsingel (Figure B.6a)
3. Gordelweg/Vroesenlaan (Figure B.6b)
4. Groene Tuin/Reyerdijk(Figure B.4a)

Whilst the east side was preferred at Ade/Klapwijkseweg and Rietlanden/Klapwijkseweg locations in Pijnacker (Figures B.7a and B.7b) because of the continuation of the bicycle facility on that side to the north and south with a connection to the neighboring town of Berkel en Rodenrijs.

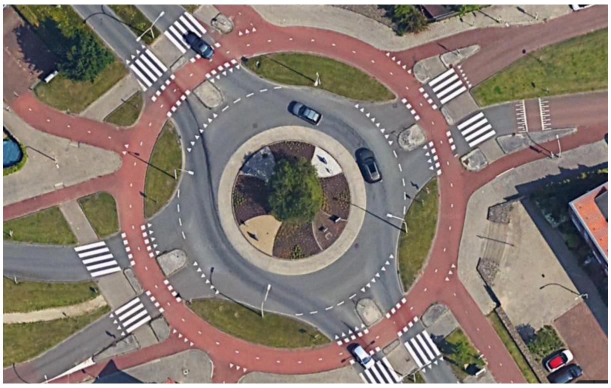
(a) Aerial view of a roundabout on Jacques Dutilhweg where the north side had more bicycle traffic

(b) Aerial view of a Rotterdam roundabout where the north side goes along a canal and has fewer road crossings

Figure B.6: Aerial images of roundabouts with notably higher bicycle volumes on one section.



(a) Aerial view of a roundabout on Ade in Pijnacker with the bi-directional bicycle path on the east side



(b) Aerial view of a roundabout on Rietlanden in Pijnacker with the bi-directional bicycle path on the east side

Figure B.7: Aerial images of roundabouts with notably higher bicycle volumes on one section (continued)

B.4. Survey comments

During the survey collection process, many respondents provided additional comments on their thoughts about roundabouts in general and the survey setup in particular. Below are the exact comments that people left directly on Ouders.nl forum and via email to the main researcher. In addition, Table B.2 shows the responses to the last question of the Qualtrics survey, which was:

Is there anything else you would like to mention regarding safety at roundabouts?

Table B.2: Qualtrics survey roundabout comments

#	**Comments**
1	[Experimental]Design sometimes become confusing. The direction signs are unclear.
2	A drawback of roundabouts is that they can be confusing for inexperienced drivers, leading to increased hesitation and potential for accidents.
3	Sometimes, when crossing the roundabout, it seems better to have a convex mirror so that you know which vehicle is coming from behind.
4	As a foreigner I can say that cars in the NL are very respectful of bicycles, and basically always stop for example at roundabouts, well in advance, even if they are not sure whether you're going to cross or proceed
5	Motorists don't look enough. It is and remains confusing that there is not always priority for cyclists
6	I believe the safety of the roundabout could be affected by where it is located and what kind of drivers drive on them
7	Mostly dutch roundabouts seems safe to me.
8	It would be more comfortable to have 2 directions on the circular bike path in order to avoid to circumnavigate the roundabout if I have just to turn left. Then it is more important for bicycle to have priority (not cars) when crossing roads, because it is physically more difficult for cyclists to reach again the speed. Cars can easily do so and also the should regardless decelerate more than bikers while approaching the roundabout. However, this may lead to higher pollution/emissions.
9	Not too high vegetation and not too large objects, plus good lighting is nice and traffic lights with sound for the disabled.
10	The bigger the more dangerous it looks to me. If there are multiple lanes, I find it less comfortable to drive.
11	I think the balance between road users is important: when cars are in the majority, all roundabouts are unsafe. When there is a good mix of cyclists, pedestrians and cars, all roundabouts feel safe and comfortable
12	Uniformity is important
13	I don't think it's a problem if you feel a little bit uncomfortable at a roundabout/intersection. This creates a certain level of alertness
14	I usually find roundabouts very annoying, especially because drivers often do not see that a cyclist is approaching (and as a motorist I also have that, even though I really consciously pay attention).
15	Timing and high traffic hours are to be kept in mind and possibly avoided
16	I believe yielding doesn't make much difference for me in terms of fear, because I don't trust the car anyway. I'm always cautious when the car is around. The most comfortable I feel when I have a lot of space for cycling and large buffer from cars. Dense cyclists do not stress me much, but scooters yes.
17	Uniform priority rules are important, multi-lane roundabouts are a risk, two-way cycle paths are nice but less safe.
18	The experience at a roundabout largely depends on where you have to go and how much crossing traffic you have.
19	It's bizarre that cyclists don't have priority at many roundabouts [in the study]
20	Here in Alkmaar it is customary to extend your left hand so that motorists know that you are using the priority at a roundabout. There is too much distraction at roundabouts and crossings, extending a hand can clarify a lot.
21	Due to the unpredictable behaviour of motorists and other cyclists, no roundabout is safe anymore. The roundabouts where cycling is allowed in two directions are absolutely terrible and have, in my opinion, ensured that cyclists will do this everywhere.
22	When convenient and safe I go the wrong way around a roundabout (like to get to the next exit when in a hurry)

Table B.3: Qualtrics survey roundabout comments (continued)

#	Comments
23	Cyclists (in priority) must be guided aside in time when they leave the roundabout, so that motorists can see in time whether or not you are going to cross. In addition, the agreed rules will finally be implemented everywhere (Inside urban areas, bikes have priority, and outside of urban area bikes do not). Uniformity is important.
24	It would be nice to have the same priority rules at every roundabout and one-way traffic for cyclists.
25	Preferably all roundabouts have priority or no priority. There should not be both. I am against 2-direction roundabouts for cyclists.
26	I prefer roundabouts with mixed traffic, i.e. without a separate cycle path, because I am then seen as a cyclist. I want priority at roundabouts; I will then check whether I get it to get across the roundabout safely. This makes for slower cars and, in my opinion, is safer for bicycles.
27	The more unpredictable, the more dangerous. Deviating from normal rules (cyclists have priority within urban areas) always causes confusion for all road users and creates dangerous situations.
28	It's helpful if something slows drivers as they enter or exit the roundabout. Like a speed hump. It's also important for the crossing distance to be short as possible. That's why I gave a poor rating to the roundabout you showed with a 2 lane-wide crossing.
29	Comfort is lower in a number of photos in the study due to conflicting priority rules. I see that they have been adjusted manually, but a cycle path from the right-of-way next to a zebra (in the right-of-way) causes confusion. I also see tram tracks in some photos that cyclists must give priority to. They are not mentioned in the explanation, but they do play a role in my assessment.
30	I like them [roundabouts]
31	I feel safe when I feel seen. Buildings close to the edge of the roundabout (like in the first question) contribute (in a negative way) to that massively.
32	Priority inside and no priority outside built-up areas, that's how it should be! This is the big risk: there is too much difference in how priority is arranged.
33	Uniformity on all roundabouts, both inside and outside built-up areas; cyclist stop and give way. Now there is a lot of false security by giving cyclists priority. As a result, cyclists no longer pay attention and cycle without making eye contact to see whether they have priority. People do not realize that priority is given and that you can take it. It also opens the door to other risky behaviour through risk compensation, risk homeostasis (Wilde). Make cyclists aware of their vulnerability and force them to pay close attention.
34	I [would] like to exchange knowledge. To learn more yourself and to give something from practice.
35	Our village has all roundabouts within the built-up area with priority for cyclists. The fact that other municipalities do not have this makes it confusing for children who learned to cycle in my village, as they have to pay close attention to how priority is arranged elsewhere.
36	Distracted road users, drivers who only look at the last minute and changing priority situations are my biggest drivers for an unsafe feeling.
37	There is a Shared Space Roundabout in my hometown of Winschoten. This is a disaster for pedestrians, cyclists and motorists. All the roundabouts I 'rated' in this survey feel and are safe compared to that monstrosity.
38	bi-directional cycle paths are often confusing for motorists
39	Being allowed to cycle in two directions is an impossibility for the motorist: giving priority to only clockwise cyclists is already difficult. Idea: have cyclists only cycle clockwise around the roundabout.
40	Lack of yielding to bikes makes them more dangerous. Driving your car should make you question your life choices. Bikes should be encouraged and always given priority. The all green [bike traffic light] from Groningen should be the country standard.
41	I prefer unsignalized or signalled intersections with cars over roundabouts. Cars tend to be moving more quickly around roundabouts than other intersections in Amsterdam. I live near the Haarlemmermeercircuit and it never feels comfortable to cross so many bus and car lanes, though the latest redesign has improved the experience somewhat.
42	I didn't realize there were so many types! That can get confusing for cars and bikes.
43	I never assume the driver will stop, so that's why I feel comfortable. I rely on my common sense, not their awareness or driving skill.

Table B.4: Qualtrics survey roundabout comments (continued)

#	Comments
44	Good lighting and overview of the traffic situation are both essential but not mentioned in this survey.
45	I live near the pictured roundabout at Leeghwaterplein and cycle there every day. There is a high volume of bicycle traffic there during rush hour, many motorbikes on the cycle path (including yellow-plated ones), and often drivers who are not paying attention. I think it's too narrow for a partial two-way cycle path on one end and that it's unnecessary in this specific location.
46	[Roundabouts are] better than a normal crossing
47	Need a clear view to anticipate when car drivers are too fast and will not yield.
48	I feel the drivers are more aware of stopping for pedestrians and cyclists in the Netherlands which makes me feel more safe
49	It's consistently hard to figure out how to ride them. Likewise many people biking on the paths seem to be biking and doing something else, leading to accidents and sometimes substantial injury or death of other cyclists.
50	As an American I hated them at first but now like them quite a bit.
51	In general, no double line [two lanes] for cars in the roundabout.
52	The priority arrangement for cyclists is still not clear to me. I always pay attention to the shark teeth, but they are sometimes worn out. So you always have to be a little careful.
53	I think that the different priority situations on roundabouts create a lot of confusion for cyclists and other users of roundabouts.
54	I accidentally chose very comfortable at first, but it must have been very uncomfortable
55	I feel safer with NO yielding preference to bikes because then I don't have to trust the car drivers. Having to trust car drivers always makes me uncomfortable because most of them don't stop (especially at the roundabout by the TU Delft) and all of my near crashes come from people who should have stopped for me and did not.
56	Yielding priority and bidirectionality are important factors
57	I generally experience roundabouts as safe. It is important to always have eye contact with car drivers to make sure they have seen me
58	Lack of priority marking for cyclists on the cycle paths around the roundabout. Short distance from the cycle path, so that motorists are too late to see whether a bicycle is turning right. Curves that are too wide for cars, causing people to drive too fast out of the roundabout. If roundabouts are too small, the driver has too little time to pay attention to cyclists when leaving the roundabout.
59	Priority for cyclists and shark teeth for cars is essential.
60	I think clarity is the most important thing. Cyclists have priority, I don't trust that. Cars might pass by [without yielding].
61	I once understood that cyclists are given extra insurance protection in the event of accidents. That gives a safe feeling.
62	I missed the presence of speed bumps for leaving cars on the roundabout just before the cycle path.
63	Too many different types of roundabouts does not benefit the assessment of the traffic situation.
64	Roundabouts never feel safe, you always need to be careful.
65	Most of the time I feel very comfortable at almost all roundabouts if cars are traveling at slower speeds which is the intention of most roundabouts because it allows me to make eye contact with drivers; at which point even if there is not a clear yield for bikers, I can determine if they will stop before crossing.
66	The type of car/bus often makes it unsafe (e.g. Post deliverers etc).
67	I want priority, we are not going to give priority to cars because they are blind
68	As a cyclist your safety on roundabouts also largely depends on automobilists' willingness to actually hit the brakes instead of the gas, which why I mostly feel uncomfortable on roundabouts.
69	Remove all that[roundabout yielding priority] nonsense

C

Literature research

This appendix gives an overview of past research reports on the subject of bicyclists' perceived safety at roundabouts, along with specific design attributes if they were studied. The overview also shows the exact method developed, where the data collection took place, what variables were included, the findings of each report, and any limitations or gaps for further research.

Literature review summary

Citation	Location	Aim	Measuring Unit/Sample Size	Method	Objective/Subjective safety	Variable/Categories	Findings	Limitations and Gaps
Bahmankhah, B., Fernandes, P., & Coelho, M. C. (2019).	Aveiro, Portugal	Evaluate the impact of larger bike volumes and conversion of a traffic light to a multi-lane roundabout on local emissions and safety	1 intersection location, 9 bikes per hour, 1650 veh per hour but then the model scenarios looked increasing bike columns up to 270 per hour and decreasing vehicle volumes to compensate for mode shift.	PTV VISSIM , with a Surrogate Safety Assessment Methodology (SSAM) model \& a Non-Dominated Sorting Genetic Algorithm for the Multi-objective optimization	Objective	Time-To-Collision, Post-Encroachment Time, initial deceleration rate, max speed, max relative speed difference, traffic count data, OD Matrices, site geometry, signal cycle time and phasing.	The roundabout option showed that it was more favorable for reducing greenhouse gas emissions and traffic performance (travel time and number of times vehicles were at a standstill) but that as more bicycles are added into the model, there are more severe conflicts as there are more vehicles that try to bypass cyclists within the roundabout itself.	VISSIM model was done for the time period of 8:20 --9:30PM; The multi-lane roundabout assumed was without any bike facility: inscribed circle diameter = 43.8 m and circulating lane width = 7.9 m. (I. E. bikes share the road with cars) thus meaning that specific design treatments to protect cyclists were not studied. Pedestrians were also not included in the VISSIM model, which could reduce the traffic performance of the roundabout and increase the number of traffic conflicts as cyclists' and motorists' would have to yield to a pedestrian.
Cantisani, G., Durastanti, C., & Moretti, L. (2021).	Italy	risk analysis for the collisions between motor vehicles and bicycles in the merging and diverging conflict points of a single-lane conventional roundabout with four arms, characterized by a permanent traffic flow.	1 intersection location, 310 to 700 vph and 40 to 120 bph per each roundabout arm (then they also did scenarios for each configuration with +10% and +30% bicycle traffic volumes due to COVID traffic flow measurements)	combined Poisson's law probabilistic model (to address the randomness associated with behaviour of the users) and a damage model (deals with the interactions of the different modes and the geometry of the roundabout)	Objective	External roundabout diameter 25m; **constant speed assumption:** 10 km/h for bicyclists and 30 km/h for motor vehicles; probabilities of conflicting movements; Number of vehicles and bikes entering and exiting each roundabout arm per hour (310 to 700 vph and 40 to 120 bph); required sight distance; 5 different roundabout layouts tested (normal without bike facility, 1 with bike facility but no bike paths approaching, 1 with reduced buffer space between bike facility and car facility (to fit within external diameter of 25m), 1 with bike facility and bike paths approaching, and 1 with reduced buffer and bike paths approaching; Yield priority for bicyclists for the bike facility configurations; No sight line issues	The roundabout with larger diameter with a bike facility (without bike path approaching) has a lower R (risk of collision) value compared with the roundabout without a bike facility or the 1 with a reduced buffer space. (0.0152 vs 0.0287 for no bike facility). The roundabout with the larger diameter, a bike facility, and approaching bike paths has an average risk of collision of 0.00909. In the scenarios where the bike traffic is increased, then there is a general increase in risk of collision but still lower than the original 'no facility, base bike volumes design option (0.0287). "The roundabike external to the current roundabout (i.e., in L1 and L3) reduces max Di compared to the current condition (i.e., L0), while the reduction of the inscribed circle radius to have the external roundabike within the area of the current roundabout (i.e., in L2 and L4) has a detrimental effect on max Di."	Did not study different yield priority and assumed perfect sight lines/visibility. They did not look into bi-directional bike path around the roundabout.
Distefano, N., Leonardi, S., & Consoli, F. (2019).	Italy	Investigate whether road user preferences are more oriented towards safer geometrical configurations or instead if the driver prefers configurations that offer better operational performance at the expense of safety.	11 different roundabout fictious layouts, 420 respondents with each respondent performing 42 different tasks/scenarios in order to determine their 'style' of driving.	Stated Preference model with a Correspondence Analysis (**CA)** (in order to compare the relations between gender, **SP** model results, and type of driver without presenting a hypothesis)	Subjective	11 attributes of geometrical-functional characteristics of the roundabout (central island diameter, channelization island, # of approach lanes, # of lanes within roundabout, presence of truck apron, painted narrowing of lanes, slip lanes, outside angle of curvature, painted channelization islands) , 3 categories of driving behavior (exemplary, OK, bad), and sociodemographic data (age, gender, mean of transport used mainly).	This data indicates that the knowledge of the type of driver explains around 37% about preferences of the roundabout's geometric elements and vice versa. This relation is weak. In addition, wider/larger central island's were deemed as more safe and were preferred by the group that had an OK or exemplary driving behaviour. In parallel, the people whom had a bad driving behaviour preferred roundabouts that have double lanes, and a truck apron; which allows them to drive more ruthlessly and fast.	Did not look at cycling infrastructure at all (this study was from the driver's perspective). Did not get respondents outside of age range (30-55).
Fernández-Heredia, Á., Monzón, A., & Jara-Díaz, S. (2014).	Ciudad Universitaria, Madrid	In order to improve better bike use policies, the aim of the study was to try and determine the structure and relationships among variables and to understand users' (University staff and students) intentions to use the bike.	Pre phase with two focus groups. Then 233 respondents for a pilot survey and the final survey had 3048 completed surveys	**Structural Equation Model (SEM)**	Subjective	Factors that promote bicycle use are: – Efficiency: avoids traffic problems such as traffic jams, easy to park, enables door to door transport and is competitive with other modes of transport over certain distances. – Flexibility: no time or frequency restrictions. – Economical: no fuel expenses, the purchase and maintenance of the bicycle are economical. – Ecological: does not emit pollutants or greenhouse gases, hardly makes any noise and takes up little space. -- Healthy: it is an active mode of transport that encourages people to exercise. – Fun: some users take pleasure in riding a bicycle. Factors that inhibit bicycle use are: – Distance: distances to be travelled if they are too long. – Danger: perception of risk in relation to accidents or falls. – Orography: mountainous or hilly topography. – Fitness: poor physical condition. – Climate: weather limitations such as rain, wind, low or high temperatures. – Vandalism: fear of the bicycle being stolen. – Facilities: need for complementary facilities for personal hygiene, bicycle parking area at the destination point, to keep the bicycle at home, etc. – Comfort: not as comfortable as other modes of transport. The existence of cycling infrastructures has not been included as a factor because, although it is believed that it plays a subjective role that would fit in this analysis, it is captured under the perception of risk factor.	Four (latent) variables are identified, namely convenience, pro-bike, physical determinants and exogenous restrictions. The main conclusion is that convenience (flexible, efficient) and exogenous restrictions (danger, vandalism, facilities) are the most important elements to understand the attitudes towards the bicycle.	They performed a perceptions survey on general bike use and was not focused on specific intersections or roundabouts.

Friel, D., Wachholz, S., Werner, T., Zimmermann, L., Schwedes, O. S., & Stark, R. (2023).	Berlin, Germany	Cyclists' perceived safety in relation to different intersection designs. In the study, we focus on the following two research questions: (1) Which intersection designs provide best perceived safety? (2) Which design elements affect subjective safety and in which way? Answering these questions, we will be able to give recommend- dations on how to design junctions to provide a high level of perceived safety for cyclists.	Virtual reality experiment; 46 participants did the bike simulator (6 non cyclists and the rest were cyclists)	Simulator followed by a Structured content analysis using MaxQDA	Subjective	Three intersections (BS: Berlin Standard, PI: protected intersection, CbC: cycle lanes between car lanes) and one roundabout. 5m offsets for the separation; bicycle priority; 2m wide uni-directional bike paths; constant traffic volume; consistent small shrubs in the buffer space between cars and bikes.	Protected Intersection ranked the safest amongst respondents with the roundabout in the middle. ---- Specific design features, such as continuous cycling infrastructure, physical separation and elements enhancing cyclists' visibility improve participants' perceived safety. On the other hand, narrow bike path width, sharp-curbs, bending of bike path around roundabout, confusion about yielding priority in the roundabout and trusting vehicles to yield, and elements obstructing visibility (too high hedges) decrease perceived safety. -----The findings also point towards a difference between overextending and manageable interactions between cars and cyclists. While manageable interactions raise attention to an appropriate extent, overextending interactions diminish the quality of the cycling experience so that some cyclists rather violate rules instead of using the designated cycling infrastructure. They also noted that perceived safety is linked with comfort and comprehension, as the roundabout is a new intersection type in Germany.	Roundabouts are not often used in Germany, thus the participants most likely ranked it less safe as they are less familiar with that type of intersection facility. There were no other cyclists or pedestrians in the simulations (due to technical difficulties). ----"Limited research on design influences on cyclists' perceived safety at intersections, there are hardly any hypotheses to confirm. Hence, a quantitative approach would result in rather limited insights. Instead, we chose a qualitative approach to exploratively investigate cyclists' assessments of cycling infrastructure and to create insights that will help to understand the underlying factors determining perceived safety at junctions. " --The use of a simulator poses reality challenges that are impossible to avoid.
Jensen, S. U. (2017).	Denmark	Evaluate bicyclists safety after conversion of intersections into roundabouts	255 intersections that were converted to single-lane roundabouts	Before-and-after study using regression-to-the-mean	Objective	accidents, speeds, traffic volumes, roundabout characteristics (no bike facility, bike lanes, and separated bike paths), central island height(0-2m or 2-10m), central island diameter(3.5-19.9, 20-39.9m), urban/rural (52%/48%)	A single-lane roundabout with a high central island, which middle is elevated 2 m or more above the circulating lane, is safer for cyclists than comparable single-lane roundabouts with lower central islands. • Single-lane roundabouts with separate cycle paths, where cyclists must yield to motorists entering or exiting the roundabout are safer than single-lane roundabouts with bike lanes. Bike lanes are the least safe type of bicycle facility at single-lane roundabouts. • Single-lane roundabouts seem to be safer for cyclists compared to intersections, if the roundabout has a high central island and/or has a separate cycle path. If the single-lane roundabout has a low central island and no separate cycle path, then the roundabout is seldom safer for cyclists than a regular intersection.	This is just an indicative study and it doesn't study the comparison between roundabout types (only comparing non-roundabout intersection with the re-designed roundabout). The applied methodology with comparison of safety effects between different roundabout designs is questionable and could lead to unreliable results. The prime reason to this is that the safety effect of conversions varies due to a great number of intersection and roundabout design features and other location characteristics. More reliable results about the safety impacts of the various roundabout design features can be obtained through before-after safety studies of roundabout redesigns.
Kummeneje, A.-M., Ryeng, E. O., & Rundmo, T. (2019).	Trondheim, Norway	Find the association between cyclists' choice to bike during different seasons and their risk perception	291 respondents	Questionnaire survey (the scale for measuring the probability assessments was a five-point Likert scale ranging from 'not at all probable' to 'very probable')., followed by a Confirmatory Factor Analysis To test the fit of the data to the regression model, additional **structural equation modelling (SEM)** was done. Then 4 hierarchical multiple regression analyses were done.	Subjective	Socio-demographic data: Gender, Age, Education, bicycling frequency. What extent they agreed or disagreed with 13 different statements and give their responses on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree). Statements= two attitudes (see figure on right)	Risk perception was an important predictor of both the decision to cycle and the frequency of cycling during wintertime. Female respondents cycled less often than male respondents during wintertime. Age and educational level were not found to be associated with whether the cyclists used their bicycle during wintertime. Attitudes towards traffic rules were found to significantly influence bicycle use when the other variables were included in the model. A further interesting finding was that women tended to tolerate risk less than did men and they were more worried and perceived the risk of accident as higher compared with men.	Low response rate (emailed out to over 4000 potential respondents) and another topic could be: the way the media, road authorities, and researchers influence cyclists' risk perceptions in general. Investigate whether the emotional state of cyclists influences their perception of risk. Perceived risk associated with rider comfort/discomfort.
Macioszek, E., Sierpiński, G., & Czapkowski, L. (2010b)	Poland	Compare different roundabouts from around the western world to see what safety measures are done	USA, Belgian, Dutch, Uk studies	Literature review	Objective	Safety factors, roundabout diameter, AADT (average annual daily traffic volume), cyclist priority, no bike facility vs separate bike facility, speed of motor vehicles	13% of cyclists in NL enter a roundabout in the wrong direction and 40% don't yield to motorists (in the case that they don't have yielding priority). Roundabouts with a 22m radius or greater should have a separate bike facility (or if there are 8000 veh/h or more).	This was just literature review, and all the studies were from pre 2010.
s, L. B., Stevenson, M., Fraser, M., Oxley, J., Rose, G., & Johnson, M. (2019).	Perth, Australia	Identify roadway features that present a risk for bike crashes (unsignalized intersection, roundabout, signalized intersection, mid-block)	400 sites in Perth with 3 years worth of crash data (100 crash sites and 300 control sites)	Crash study coupled with a naturalistic study (guestionnaires for crash victims and for 100 non-crash victims that went to the 300 control sites), followed by a conditional logistic regression	Objective	intersection approaches; intersection control; number of lanes in the direction of travel; speed limit, on-road bicycle lane; and motorised traffic volume. Crash data. Socio-demographic data: Age, frequency of riding a bike, gender, university degree, employment	Roundabouts had more than twice the risk of crashes compared to priority control/ uncontrolled intersections (unadjusted OR: 2.44, 95% CI: 1.06, 5.60). Half of the crashes occurring at roundabouts involved a motor vehicle (n = 7) and half did not involve a motor vehicle (n = 7). A larger proportion of intersection case sites involving a motor vehicle were located at roundabouts (n=7, 24.1%), compared to corresponding control sites (n = 13, 14.9%). In addition, a larger proportion of intersection case sites not involving a motor vehicle were located at roundabouts (n=7, 31.8%), compared to corresponding control sites (n = 12, 18.2%).	The study didn't have any protected bike paths at roundabouts (only bike lanes or no bike facility at all). This study only included crashes that were severe enough to result in hospitalisation. The insignificance of some results and wide confidence intervals may be due to limited power resulting from the small sample size.

Møller, M., & Hels, T. (2008).	Denmark	The study focuses on cyclists' perceived risk in specific situations, factors influencing the perception of risk and cyclists' knowledge about traffic rules regulating the interaction between road users in roundabouts.	1019 cyclists, 5 locations	Structured Interviews, followed by a Cronbach Alpha, then Chi-Square tests, and finally a Multiple Linear Regression (eliminating non-significant variables as they proceeded). Only included first order components and no interaction terms.	Subjective	Roundabout with a bike facility and without. Some roundabouts didn't have zebra crossings but all were in urban areas. Roundabouts had 3 to 5 legs (only 1 had 4 legs) and there were 480-3620 cyclists per day using them.------14 varaibles in total: bcycle facility, traffic volume car, traffic volume bike, risk perception and background factors (travel behaviour [how often do you bike], destination on day of interview, familiarity with the roundabout and use of a bicycle helmet, how many kilometers do you bike per week, drivers license, how often do you drive per week (car),bicycle roundabout accident involvement and near-accident involvement) and cyclist char acteristics (age and gender).	Underestimation of risk (Danish crash records show majority of collisions are cars entering roundabout but interviewees felt that cars exiting the roundabout posed a higher risk) and lack of kknowledge of about relevant traffic rules were found to be partial causes for car-bike collisions. Road designs with clear regulation of road user behaviour (whom has priority) is preferred. Significant factors were gender, history of a near-accident, traffic volumes (both cars and cyclists, and type of cycle facility). A universal situation was the situation in which a cyclist is circulating in the roundabout and a car is trying to exit the roundabout (posed the highest perception of accident risk and danger). Traffic volumes of more than 1000 entering cyclists per day and less than 10,000 entering cars per day were associated with increased perception of danger. In order to check for a possible interaction effect of bicycle and car traffic volumes, the analysis was rerun including this interaction. The interaction term was significant ($p<0.01$) while the car traffic volume variable became insignificant and was consequently excluded. This indicates that some of the variation in the dependent variable covered by the car traffic volume variable was also covered by the interaction term. Thus, car traffic volume influences the perception of risk, but the influence decreases as the bicycle volume increases.	Cycle facility question was binary (yes or no) and thus had no information on what type of facility was provided. The aim was to include roundabouts that were as similar as possible according to the selection criteria. However, it is possible that minor design feature differences have influenced the risk perception of the cyclists. Further studies including a larger number of roundabouts are needed. All interviews were conducted in roundabouts. Consequently cyclists who find the roundabouts too dangerous to use may be underrepresented in the sample. Further studies focusing on the relation between perceived risk and actual behaviour are needed to clarify this. Additional individual and design features such as geometry, lighting, and pavement surfaces may influence perception of risk. The results regarding the influence of car traffic volume are counterintuitive and controversial as they contradict with results found in other studies (see for instance Parkin et al., 2007).
Poudel, N., & Singleton, P. A. (2022).	USA	overall objective is to understand preferences among US 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.	613 respondents (online), 1 fictious location with 6 different choice scenarios (respondents were blocked to minimize workload and stay within 15min average survey duration)	**MNL and Panel Mixed MNL (SP) model** with no alternative specific constants (unlabeled alts) using Dummy coding. Monte Carlo integration was used aswell to reduce calculation time and memory storage. The survey was created by doing a orthongonal design that was blocked (and with dominiant alterantibes removed).	Subjective	Roundabout characteristics: central island size[80ft or 120ft diameter], number of circulating lanes[1 or 2 within the roundabout], bicycle facility type[none, bike sharrows, bikes on sidewalk, separate bike facility], motor vehicle volumes[low, medium, high], and approach speed limit[25mph or 35mph] ----socio-demographic data: age, gender, race/ethnicity, Are you a student, level of education, Are you a worker, household income, # of bikes at home, # of cars at home, # of adults in household, # of children in household, bike use frequency[Never, less than once per week, 1-3 days per week, more than 4 days per week], type of cyclist [strong & fearless, enthused and confident, interested but concerned], crash experience at a roundabout, frequency of biking thru roundabouts, route choice decision based on roundabouts	US bicyclists seem to prefer roundabouts with: smaller central islands, fewer travel lanes, lower traffic volumes, lower speed limits, and separated bicycle lanes; central island and speed limit were not significant in their model results-----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.	Additional factors potentially affecting preferences could be considered in future studies: 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), and bicycle facility type on the approaches.-- 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 this stated choice experiment may be slightly different in reality.
Poudel, N., & Singleton, P. A. (2021).	(most from Europe, some from Australia/ New Zealand, few from the US).	a systematic review of the literature on bicycle safety at roundabouts. Focus on reviewing study methodologies and operational and design-related factors associated with bicycle safety at roundabouts, also considering driver and cyclist behaviours, since behaviour responds to design and design should accommodate expected behaviours.	49 different resources with empirical findings	Literature review	N/A	Various types of methodologies used to examine bicyclist safety, focusing on crash data, video recordings, and user perceptions. Sections include: roundabout safety, including geometric, design, operational, behavioural, and perceptual characteristics and considerations. Various study methodologies – statistical modelling and analysis of longitudinal or cross-sectional crash data, observations of cyclist and driver behaviours and interactions, and surveys of road users' safety perceptions –--- Summarised evidence of factors potentially influencing bicycle safety, including operational and design characteristics (volume, speed, etc.), the presence and type of bicycle facilities, and road user behaviours.	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. Critical situations and behaviours are: visibility and yielding at separated cycle path crossings, and conflicts between entering/exiting vehicles and circulating cyclists. .	Future research should investigate more design features, socio-demographic characteristics, cyclist safety perceptions. Future research should investigate more varied factors, study roundabouts outside of Europe, and utilize naturalistic methods and stated choice experiments.----- Lower numbers of cyclists and bicycle crashes (compared to other transportation modes) further complicates this line of research, as does the underreporting of crashes involving cyclists and the relative lack of bicycle exposure data…-----There have also been few studies about cyclists' safety perceptions of roundabouts, which could be used to develop quality-of-service ratings (Jensen, 2013c), investigate avoidance behaviours and route choices, and account for awareness and experience with roundabouts. Particularly, stated choice experiments could help to understand the comfortability of users for adding new bicycle facilities, which design features cyclists prefer, which types of roundabouts they would avoid, etc.

Poudel, N., & Singleton, P. A. (2023).	USA	informs an understanding of bicycle safety at roundabouts in the US 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.	568 cyclists, 21 different hypothetical roundabout configurations but each respondent only saw 1 roundabout, 4-point Likert Scale of comfort	hypotehtical questionairre, with **ordered probit regression models**, while controlling for personal socio-demographics and cycling characteristics (including type of cyclist). **SEM was used**	Subjective	Roundabout characteristics: central island size[80ft or 120ft diameter], number of circulating lanes[1 or 2 within the roundabout], bicycle facility type[none, bike sharrows, bikes on sidewalk, separate bike facility], motor vehicle volumes[low, medium, high], and approach speed limit[25mph or 35mph] ----socio-demographic data: age, gender, race/ethnicity, Are you a student, level of education, Are you a worker, household income, # of bikes at home, # of cars at home, # of adults in household, # of children in household, bike use frequency[Never, less than once per week, 1-3 days per week, more than 4 days per week], type of cyclist [strong & fearless, enthused and confident, interested but concerned], crash experience at a roundabout, frequency of biking thru roundabouts, route choice decision based on roundabouts.--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--------------------------------------Six dependent variables (comfort) measured on an ordinal scale, thus we employed ordered probit regression. Independent variables were roundabout attributes (Table 1) and respondent characteristics (Table 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.	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. ------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. -----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. ------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. I	Not fully represetative of the US adult population. The choice of a 4-point Likert scale didn't allow for a neutral setting. The hypothetical situations didn't look at other factors, such as differences in bike and traffic volumes, large vehicles, ciruclating lane wifths, two-way cycletracks, crossing types, and lighting.---- "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)."---Also static images and text may lead to more bias as folks need to be more immersed in the scenario and use their own judgement/experiences when answering the questions.
Pulvirenti, G., DeCeuninck, T., Daniels, S., Distefano, N., & Leonardi, S. (2021)	Brussels, Belgium	Study of roundabouts with no bike facility, analysing bicyclists' behaviour and safety (by using surrogate safety indicators) on roundabouts with different diameter.	4 urban roundabouts were observed using 2 cameras placed at each location. 974 records after 3 days of recording, with 544 of which were bike-car interactions.	Video data that was then manually and automatically analyzed T-Analyst for speed, positioning, and time calculations. Then a Univariate Analysis of Variance (ANOVA) was performed to compare the independent variables (diameter of roundabout) with the dependent variables.	Objective	Roundabouts were similar except for diameter(inscribed radius) [20-32m]. Measured items: speed, lateral position (within the roundabout) and closeness of interactions [Time To Collision-TTCmin[1.5 s], post-encroachment time--PET[1 s], predicted arrival time of 2nd user--T_2min[1s], lateral overtaking proximity, and minimum distance headway	Cyclists were found to ride faster on roundabouts with a larger diameter and cut closer to the center island of the roundabout (compared to smaller diameter roundabouts). Close interactions are frequent at both small and large roundabouts. The most observed close interaction was when cyclists were entering the roundabout(whether or not they go before the vehicle already in the roundabout).	They did not do a comparision between roundabouts with bicycle lanes or separate bike facilties. The use of surrogate safety indicators can be debated since is it really objective? Short observation period.
Richard Mantona, R., Rau, H., Fahy, F., Sheahan, J., & Clifford, E. (2016).	Galway, Ireland	How negative perceptions of safety could inform measures to increase cyclist numbers and consequently improve cyclist safety.	104 mental map participants, equalling 484 percieved safety observations	mental mapping, a stated-preference**(SP) survey** and a transport infrastructure inventory to get a GIS file that can be used in a SPSS **(Generalised Linear Mixed Model)** file for percieved cycling risk	Subjective	SP survey of 28 questions (e.g. cycling frequency, trip purpose, self-ascribed cycling skill, typical infrastructure used, preferred infrastructure, involvement in cycling collisions,volume of cars passing, volume of trucks passing, roundabouts, adjacent car parking, speed limits, road lane width, cycle lane width, and number of junctions)---socio-demographic data aswell was collected: age, gender, years spent living in Galway, employment status, household composition, and car availability. ----For the SPSS model inputs, it was the following: The qualitative variables are: gender, cycling experience [inexperienced/competent/highly skilled], segregation [of cycling facility; yes/no], parking [adjacent car parking; yes/no]. The quantitative variables are: age, proportion of LV [per 1000 light vehicles per day], percentage of heavy goods vehicles, lane width, and number of junctions	There was a semi good correlation between percieved safety and actual collision stats at roundabouts. ---All of the collisions on road sections perceived as very dangerous actually took place at roundabouts, though it should be noted that the weighting system yielded just three very dangerous road sections other than roundabouts. Roundabouts were rated as very dangerous by all participants and require further research for cycling safety. ---Three of the major safety concerns were found to be traffic-related: the number of trucks passing, speed of traffic, and number of cars passing. Infrastructure proved to be less of a concern than traffic; and cyclists consider the presence of a roundabout, the width of the road lane and the presence of an adjacent car parking lane to be the most concerning characteristics of infrastructure.--Segregated infrastructure, road width, the number of vehicles as well as gender and cycling experience were significant, and interactions were found between individual and infrastructural variables.	Collisions are super under-reported. The mental mapping was qualitative and ordinal (red, yellow, green). No roundabouts had any bike facilities. Sample size was too small to make inferences for the general cycling population. Further research is recommended on bicycle suitability measures and online mapping tools.
Sakshaug, L., Laureshyn, A., Svensson, Å., & Hydén, C. (2010).	Lund, Sweden	Use quantitative and qualitative methods in traffic conflict, interaction and behavioural studies to find out how interactions and conflicts differ between the two roundabout designs.	2 types of roundabouts (1 with bi-directional separate bike facility that has some yielding priority[Sweden rules are that both modes have to yield] and 1 with no bike facility); 3 days of field observsations; 5 days of video data per roundabout	Qualitative field analysis, Automated video detection, and accident analysis	Objective/Subjective safety	center island (20m for separate bike facility and 14m for no bike facility), types of conflict situations, behaviour preceeding a conflict [Conflicting Speed and Time-to-Accident], travelling speed, traffic counts, who should yield, which road user passed first, the cyclist's behaviour (stop, adjust speed, no speed change, get off the bicycle), the motorist's behaviour (stop, adjust speed, no speed change) and, in the roundabout with no bike facility, the behaviour when catching up with another vehicle (proceeding parallel with the other or staying behind).	The roundabout with no bike facility turns out to be more complex with a higher number of serious conflicts and interaction types. The most dangerous situations are when a motorist enters the roundabout while a cyclist is circulating and when they are both circulating in parallel and the motorist exits. The yielding rules are more ambiguous in the separated roundabout, contributing to a lower yielding rate to cyclists and a lower trust in the other road user's willingness to yield. Situations in the separated roundabout with the lowest yielding rate to cyclists occur when the motorist exits the roundabout at the same time as cyclists are riding in the circulating direction and hence coming from the right. However, most of the accidents in separated roundabouts occur while cyclists are riding against the circulating direction, both when motorists enter and exit the roundabouts. ----In the separated roundabout (with bi-directional cycle path) 38% moved against the circulating direction.	There were issues with the automatic detection of pedestrians and cyclists. In addition, the non-optimal placement of the cameras made it more difficult to see the entirety of the roundabouts. Underreported accident data was another issue. There is a serious confusion about yielding rules in Sweden as both parties have to yield (even when sharkteeth are clearly present for motor vehicles).

Sanders, R. (2015).	San Francisco, CA USA	Tries to prove that people's concern regarding the risk of bicycling near traffic—namely the risk of being hit by a car—is dependant on various traffic characterisitics and types of bicyclists with differing skill levels, experiences, and behaviours.	406 respondents; 4-part Likert scale survey questions (for a range of dangerous interactions)	Cronbach's Alpha, **logistic regression with Univariate Analysis of Variance (ANOVA)**	Subjective	Socio-demographic data: age, gender, driving frequency, household income children present in household. ----Aspects of traffic risk for bicyclists, including experiences bicycling or driving near bicyclists; beliefs about bicycling in general; safe and unsafe practices of bicyclists and drivers[inattentive driver]; attitudes toward cycling in their city; opinions about potential cycling laws; and knowledge of current cycling laws.	Perceived traffic risk negatively influences the decision to bicycle for potential and occasional bicyclists, although the influence decreases with cycling frequency. Additionally, cycling frequency seems to heighten awareness of traffic risk, particularly for cyclists who have experienced "near misses" or collisions. In particular, near misses were found to be (a) much more common than collisions and (b) more strongly associated than collisions with perceived traffic risk.	No pedestrian-bicycle interactions. Issue getting women and non-white respondents for the survey (not representative of the population). Predictor variables such as geometry, lighting, speed/volume of traffic and bikes should be included in future studies could potentially better explain why, where, and how near-misses or collisions occur.
Johan Vos *, Haneen Farah, Marjan Hagenzieker (2021)	Netherlands	explorative research explores which curve cues and other variables influence drivers' speed choice in curves.	819 survey participants, choosing 4 curves (there were a total of 28 curves in the study) that they would drive faster in	Survey with pictures depicting the various highway curves. Two pictures per curve (1 at the beginning and in the middle of the curve). **Cluster analysis** performed based on similar unique word responses such as "overview" or visibility. Then a qualitative comparision with the curve characteratisitics was	Subjective	Curve characteristics: radius[60-250m], deflection angle[50-300 degress], lane width[7.21--15.44] and number of lanes[1-3]. All selected curves were right turning to prevent bias towards turning direction,----Questions: Which curve would you driver faster in? What are your reasons to drive faster in a curve?".----Socio-demographic data: gender, age and driven kilometres a week. Weather was not a factor, nor was taffic volumes.	Top three variables influencing speed choice are visibility of curve characteristics, "overview" as a holistic but as such hard to measure variable, and number of lanes. In additon, 20% of respondents mentioned that the non-presence of signage drove them to drive faster. Respondents didn't say that the curves with the larger radii were where they would drive fastest, in contrast with speed prediction models.	Under-representation of 60-80 age group. Over-representation of males. difficult to gain insights in drivers speed choice based on static pictures alone; larger curve samples and actual operating speeds could help further studies.
Jensen, s. (2012)	Denmark	develop methods for objectively quantifying pedestrian and cyclist stated satisfaction with roundabouts, signalized and non- signalized intersections, mid-block crossings, and pedestrian bridges and tunnels	180 Danes, 95 crossings (23 roundabouts or 24%), 3,998 cyclist ratings, The video clips were filmed at 46 signalized intersections, 23 roundabouts and 26 non-signalized crossings, which matched the orthogonal experimental design. In-person sessions with participants totalling 68 minutes	6-point Likert scale for satisfaction **(SP)(stated preference survey)** based on videos taken by a person walking/biking thru the intersections (it's a realistic perspective); analyzed with a **cumulative logit regression model.**	Subjective	300 variables in total for whole study. Some for the bicyclist are shown to the right in the image. Socio-demographic variables: gender, age, type of residence, weekly walked kilometers, weekly bicycled kilometers, aids for walking, and ability to bicycle without problems. The questions were "How satisfied were you as a pedestrian?" or "How satisfied were you as a cyclist"? 68 pedestrian video clips, 74 cyclist riding straight ahead video clips and 16 left-turning cyclist video clips were randomized, and rated in both forward and backward order to avoid fatigue bias.	Variables such as type, width and height of pedestrian and bicycle facility, length of crossing, size of roundabout, width of roadway, traffic volume, waiting time and speed limit significantly influence the level of satisfaction. The type of bicycle facility between arms influences cyclist satisfaction very much at roundabouts. Satisfaction improves 2-3 levels when cyclists ride on a cycle path, cycle track or colored cycle lane (blue or red) compared to riding on a bike lane or the roadway, i.e. circulating lane. A blue cycle crossing across the arm improves satisfaction about half a level. The volume of circulating traffic has a slightly larger influence on cyclist satisfaction compared to pedestrian satisfaction. Cyclist satisfaction decreases by one level when an increase of about 600 circulating motor vehicles per hour occurs. The size of the roundabout matters. The cyclist detour becomes longer the further away from the center of the roundabout that the cyclist rides, and this result in more dissatisfied cyclists. Cyclists seem to prefer large central islands over small and cyclists prefer narrow circulating lane(s) over wide maybe because of the relations to motor vehicle speed. Overall, cyclists become less satisfied as the size of the roundabout increases.	Study looked at pedestrians too and also all types of intersections (non-roundabouts). What was interesting was the roundabout variables didn't include rural vs urban but the signalized intersections did. Didn't include bi-directional cycletracks at roundabouts.
Esko Lehtonen a,⇑, Ville Havia a, Anna Kovanen a, Miika Leminen b,c, Emma Saure (2016)	Helsinki, Finland	Study risk and hazard perception of bicyclists in a city environment to help improve their traffic safety	Two groups of cyclists (19 frequent and 19 infrequent cyclists), 40 video clips on bike path and 15 clips on sidewalk	Continous video watching method (using a slider for how hazardous or safe a situation is). They tried to do eye movement capture but software malfunctioned. **ANOVA** was used to analyze the various results.	Subjective	weekly[0-10km vs >20km] and annual cycling kilometers[< 100km or >500km], gender, riding in city center vs urban area, typical cycling speed [slower, equal, faster].----The caution level[median position of the slider], rise rate and rise speed parameters[change in slider relative to it's last position] were calculated.	Caution level between frequent and infrequent groups was non-significant. Frequent cyclists (in line with other studies) were more attentive and had more frequent hazardous situations. For example, they had more caution when riding on the sidewalk. Those cyclists who reported typically cycling faster than others showed elevated overall level of caution on sidewalks compared with others, but there was no difference on bike paths.	No intersections were analyzed. Small sample size. It would be good to control how accurately the participants were able to differentiate between sidewalks and bike paths and what were their attitudes regarding cycling on sidewalks.
Gustav Bösehans a,⇑, Gustavo Martineli Massola (2018_	Sao Paulo, Brazil	investigate the risk perceptions and behaviour among current active commuter cyclists in São Paulo.	207 active cyclists (45 women, 160 men and two other, 36 years-old).	Online questionaire (qualitative and quantative). Used pure counts and means for reporting and discussion and **content analysis** for sorting comments into categories.	Subjective	Demographic data (age, gender, income, modes used other than cycling and main mode cycling yes/no). iii. Commute details (years of cycling experience, frequency of bicycle use for leisure/commuting, start/end point of commute, mean duration of commute, hilliness/weather). iv. Safety behaviour (use of protective gear, presence of working lights/breaks, severe accident history, frequency with which bicycle suffered damage through accident involvement and near-miss frequency). v. Risk behaviour (ACBQ developed and tested by Feenstra et al., 2011). vi. Risk perception (Quantitative: Overall and specific risk evaluation; Qualitative: Q1 – Memory of risky situation involving the self or other riding a bicycle, Q2/Q3 – Reactions by other road users/pedestrians towards cyclists, and Q4 – Suggestions for possible improvements to conditions for cyclists).	A higher risk perception among women and high income cyclists, although the only (marginally) significant result was found for the risk of being run over by a car, which was perceived higher among women. Cyclists themselves reported engaging in a variety of risk behaviours ranging from misjudging the speed of approaching cars to ignoring red traffic lights or swerving around pedestrians. Qualitative results suggested that road space remains contested among cyclists and other road users or pedestrians, even in the presence of cycle paths, with a minority of road users disrespecting or even trying to harm cyclists intentionally.	Highly qualitative analysis with no GPS or objective data regarding routes or collisions, etc. Heavily male (77% of respondents). High average income levels (not truly populaion representative) . There hasn't been a comparision before the 400km of cyclepaths were built (no before and after risk perception possible). Not many specific risky behaviour questions(7): 5. Feel uncertain about who had the right of way on a traffic circle 9. Almost hit a pedestrian when turning right 10. Cycle when it was slippery and you could fall easily 11. Ride so close to someone else that the handlebars touched and you almost fell 12. Forget to signal when changing directions 13. Ride in threes (i.e. three cyclists next to each other) 15. Forget to look behind when turning left

Rachel Aldred, Anna Goodman (2018)	UK	3 aims: examine the consistency of incident rates for cycling near misses across these two years. ----examine whether the incident rate is associated with how much cycling experience a participant has, with a particular focus on new cyclists.----examine what individual and incident characteristics predict perceptions of whether an incident is deliberate, whether it is a near miss, and whether it is very scary.	398 participants that completed the diaries for both 2014 and 2015 (1 day over a 2 week period)	to existing participants--a respondent's level of cycling experience; secondly, whether an incident was perceived as deliberate; and finally, whether the respondent themselves described the incident as a 'near miss' (as opposed to only a frightening and/or annoying non-injury incident). Developed a conceptual model to provide any correlations and then did a **Poisson regression model** as inidividuals or incidents as units of analysis	Subjective	Socio-demographic data: gender, age, how many years have you been cycling, their dairy of near-misses over that year, how much each participant cycled on the dairy days----many of the near-misses or scary/annoying incidents were open-field type questions (E.G. the respondent could fill in anything they want). In 2015, there was an additional ask to place the incidents into one of 8 categories.	Large male participant response but unlike kilometers biked, there was a noticable drop in incident rates--- incidents that are perceived to be deliberate are more likely to be experienced as 'very frightening', independent of their 'near miss' status. number of women and young adults reporting incidents was higher than other groups. Newer cyclists (less than 2 years of experience) reported 40% more incidents per day than more experienced cyclists. ---Most common types of incidents were 'close passes' and 'someone pulling in or out across the path of the cyclist'.	Subjective data with diaires without specific location details.----"More research is needed to understand the experiences of newer cyclists, and the extent to which near misses might contribute to discouraging new cyclists from continuing. It would be useful for future studies to collect data on cycling exposure at route-level, in order to include infrastructural correlates of near miss risk in future analysis."---Further research could helpfully explore the extent to which perceptions of cyclists and cycling incidents might differ depending on the broader local prevalence of cycling.
Nurten Akgün, a,* Dilum Dissanayake, b Neil Thorpe, b Margaret C. Bell (2018)	6 towns in Northumberland, UK	investigates which design factors (geometric design parameters as well as sociodemographic characteristics, speed limit, and meteorological variables) influence cyclist casualty severity at roundabouts with no bike facility	2011-2016 cyclist causality crash reports at roundabouts, equating to 439 cyclist casualties were recorded at 209 roundabouts (of which 69 were serious and 370 were slight casualties)--No fatal collision.	binary logistic regression method, with serious and slight casualties as dependent variables, was applied in three steps. The first Binary Logistic Regression Model (BLRM) included speed limit, sociodemographic, and meteorological conditions. The variables in the second BLRM consisted of geometric design variables. The third BLRM included the factors that were generated by dimension reduction.	Objective	The cyclist casualty data includes: date and time of occurrence, location (geographical coordinates), a general description of the accident, daylight, weather, road surface condition and sociodemographic information such as age and gender of the cyclist.---Roundabout geometrical characteristics: number of lanes on approach, half width on approach, entry path radius, number of arms, number of flare lanes on approach (existing radius from the circle in a roundabout, type of roundabout, and number of circulating lanes)---Dependent variable was cyclist causality severity. ---Vehicle drivers' apporach direction ---The categorical variables, severity of cyclist casualty (slight/ serious), gender (female/male), and lighting level (darkness/daylight) were recorded as binary numbers either 0 or 1. For variables with three categories, such as weather (fine/rain/other) and road surface condition (dry/wet/ice), these were coded as 0, 1, and 2 in the dataset	Correlation matrix revealed that the number of lanes on approach and half width on approach were statistically significantly correlated, while the variables, such as geometric design (entry path radius, number of arms, number of flare lanes on approach, type of roundabout and number of circulating lanes), sociodemographic (casualty gender and age), speed limit and meteorologically related factors (daylight, weather and road surface condition), did not show any statistical significance.---A higher speed limit reduces the safety for cyclists at roundabouts---The last regression model only had 1 significant variable; that of the # of flare lanes on the approach to the roundabout (E.G. This suggests that a unit increase in the approach capacity increases the cyclist casualty severity at roundabouts.)	No bike facility was evaluated. There is a statisitcal findings issue with nighttime and rainy weather casualities since there are less cyclists on the roads during those times. Overall there could have been more data points (casuality data) in order to improve the reliability of the statistical tests.
John Parkin a,∗, Mark Wardman b, Matthew Page (2007)	Bolton, UK	assessing perceived risk reduction of competing cycling investments, specifying the most appropriate improvements to be made at route level, in recommending least risk advisory routes and assessing accessibility for bicycle traffic based on perceived risk of routes.	144 respodents to a video survey of bike routes and intersections; 873 rated journeys	2 Risk models that are route-choice models. (2 of which are on a 10-point Likert scale).--1st one used Non-linear least squares regression to estimate relationships. --- Last model is based on a risk threshold **(dissagregate logit model)** and provides a measure of the acceptability of cycling (mode choice modelling). **RUM ML (SP) models**	Subjective	2nd model: variables for the proportion of the journey with bicycle facilities, the average volume of motor traffic and parked vehicles along the journey, and the number and type of junctions and the type of turn being made.---# of peds, # of vehicles per hour (2-way flow), parked cars [Y or N], Various other traffic situations[Traffic signals straight on with bicycle facilities, Traffic signals straight on without bicycle facilities, Traffic signals right turn with bicycle facilities, Traffic signals right turn without bicycle facilities, Roundabout straight on with bicycle facilities, Roundabout straight on without bicycle facilities, Roundabout right turn with bicycle facilities, Roundabout right turn without bicycle facilities, Mini-roundabout straight on, Right turn off main road, Residential street with parking, Residential street without parking, Traffic calmed road, Bicycle route on footway, Route through a park, City centre bicycle only route, Busy road with bicycle lane, Busy road without bicycle lane Busy road without bicycle lane and with parking, Busy road with bus and bicycle lane]---NOTE: speed was kept at 30mph---different kinds of respondents (cyclists, never, 1-3 times per month, only on holidays).	demonstrate that roundabouts add more to perceived risk than traffic signal controlled junctions and show that right turn manoeuvres increase perceived risk. Facilities for bicycle traffic along motor trafficked routes and at junctions are shown to have little effect on perceived risk and this brings into question the value of such facilities in promoting bicycle use. These models would assist in specifying infrastructure improvements, the recommending of least risk advisory routes and assessing accessibility for bicycle traffic. The acceptability model confirms the effect of reduced perceived risk in traffic free conditions and the effects of signal controlled junctions and right turns.----Although passing through roundabouts is expected to have an adverse effect on risk, the effect is larger where facilities are in place (J5 and J7 with facilities as opposed to J6 and J8 without facilities). This at first appears counter-intuitive, but might be explained by the presence of facilities suggesting to respondents that the roundabout was more risky than it might otherwise have been perceived to be. Note, however, that the imprecision of some of these coefficient estimates may have contributed to the unexpected results.	No clear definition about what bike facilities in a roundabout constitute (Google Maps survey found that they were only painted bicycle lanes in 2007). ---They initially tried to do a stated preference where nine journeys of four clips were shown randomly but the respondents got confused regarding which clips were part of the same journey or not. Thus a different method was used (whole journey takes with the participants outling their journey 1st for clarity). ---"it should be recognised that there are other attributes relevant to provision of infrastructure for bicycle traffic, such as the development of a coherent network of well signed routes that are comfortable, attractive and direct."
Schepers, P., Twisk, D., Fishman, E., Fyhri, A., & Jensen, A. (2017).	Netherlands	study analyses the evidence for policy factors present in the Netherlands and measures taken to improve bicycle safety levels (motor vehicle-bicycle crashes), in comparison with the absence of these factors and measures in other countries.	Comparision of countries; USA, Sweden, NL, Denmark, France	A conceptual framework for road safety based on several factors; literature review and statistical analysis (linear regression)	Objective	traffic volumes [car, bike], modal split, distribution over space, exposure to motor vehicles, percieved risk, injuries/fatalities, road education, cycling speed, legal liability, cycling experience, road infra (bike paths), intersection treatments (bike boxes, dedicated bike signals, lateral deflection [2-5m])	Dutch roads have a hierarchy that means that high vehicle volume/high speed roads have seperated bike facilities. Higher bike modal split, leads to less exposure to cars. The Dutch cycle more slowly than other countries, they are more experienced at cycling which helps with anticipation of driver movements and more reaction time.	Not alot of quantitative comparision.----The exclusion of single-bicycle crashes that cause almost three-quarters of all serious injuries among hospitalised cyclists was not studied. More evaluation research is needed to examine whether new designs for education programs might help improve their safety outcomes . More studies are also needed to examine if and to what extent drivers are aware of and influenced by strict liability laws that favour vulnerable road users. Increased cycling rates result in lower crashes but it's not clear why.

Schepers, P., & den Brinker, B. (2011).	Netherlands	questions the assumption that cyclists can do without a minimal level of guidance and conspicuity of (design-related) obstacles on their way	734 crash victims	Questionnaire survey (for the crash victims understanding the casues), followed by logistic regression for casual relationships. Image-degrading and edge detection (IDED)method for identifying 21 characteristics of the crash scenes	Objective	What object did they collide with, location, date/time, average bike use before the crash and afterwards, crashes and age, light condition, alcohol use, gaze direction and familiarity with the crash scene.	Visual characteristics of the bike facilities do impact single-bike crashes. Crashes involving a visual design(46% bollard and 54% curb/shoulder were related to age, alcohol use, and gaze direction before the crash. ---Some crashes were predominantly caused by deficiencies of focal vision, while others were primarily caused by problems with ambient vision.	Self-reported in terms of what happened and where (questionnaire portion). The IDED method can further be expanded and tested on intersections aswell or other large shapes "cyclists discern the course of the road by large shapes with rather low contrasts, such as the separation between the road surface and the verge."
Shen, J., Wang, T., Zheng, C., & Yu, M. (2020).	UK	analyze and compare the influences of different intersection features on bicyclist injury severities in crashes.	Bike-involved crash data (2009-2017), 42,532 crashes[roundabouts 20%, T-junction 59%, and crossroads 15%]	generalized ordered logit (GOL) model and partial proportional odds (PPO) model	Objective	bicyclist characteristics[gender, age, urban vs rural dweller, purpose of trip], intersection characteristics[central refuge, signalized, speed limit, pedestrian crossing facilities, urban area, divider, wet vs dry road], environmental conditions[month, weather, daylight, peak vs non-peak, weekend], bicyclist movement and location preceding the crash, and types of collisions[slight, serious, or fatal injury, front, back, right, left, secondary vs primary]	The testing of the 2 different models allowed for a better comparision on how the variables were associated with one another. The PPO model had a better fit with findings: male cyclists are more likely to be involved in fatal or serious injuries at crossroads and T-junctions. Older cyclists are more likely to be involved in a serious or worse injury. Lower speeds reduce crash injuries at all intersection types. In particular, on rainy days, more consideration should be paid to cycling safety at roundabouts, since the factor can increase the occurrence probability of slight injury at roundabouts by 12.01%. Individually, at roundabouts, making a right turn, changing lanes to the left, and overtaking inside the intersections are statistically significant factors related to bicyclist injury severity.	"We cannot consider the temporal heterogeneity of various influencing factors in the analysis"----Didn't get into dissagregated level of analysis pertaining to different characterisitics of roundabouts themselves. The only note was about dividers but there wasn't any further information.
Silvano, A., Ma, X., & Koutsopoulos, H. (2014).	Sweden	Determine a model for calculating vehicle-bike interactions at roundabouts (yielding behaviour)	1 intersection location, 2 hours of video data collection, PM Peak hours	Proabilistic model (hierarchel logit model)--LCCM	Objective	field of vision, speed of bike and vehicle, decision point for yielding[10m for cars and 30m for bikes], covariates: arrival time of each interaction zone, order of arrival at interaction zone.	the conflict probability is influenced differently depending on the user, cyclist or driver, arriving to the interaction zones. The yielding probability is negatively correlated with the speed of the vehicle when the driver makes decision. Lower motorist speed will yield a much higher yielding rate	Only did 1 suburban roundabout which had field of view obstructions and a downgrade slope for bicyclists. They used only 1 selected decision position for purposes of model validation. No driver or bicyclist characteristics were taken into account. "Certainly, site geometric characteristics play an important role in the yielding process (e.g., 1-lane, 2-lane facilities; raised or non-raised crosswalks; painted, non-painted bicycle lanes; angle of intersecting approaches; road and sidewalk width and gradient, etc.). However, data from different facilities are needed to account for such variability, which is limitation for this study."
Tan, T., Haque, S., Lee-Archer, L., Mason, T., Parthiban, J., & Beer, T. (2019).	Melbourne, Australia	Study the user perceptions before and afer installation of bike facilities at roundbouts	2 roundabouts; Moray Street/Coventry Street and Moray Street/Dorcas Street; 351 pre-surveys and 389 post surveys	Before-and-after study using qualitative surveys of users and quantitative video data colection for vehicle counts and user behaviour	Objective/Subjective safety	pre-construction:---- speed limit: 60km/h, traffic counts: 6-10K cars per day; no bike facility----Post construction: raised ped crossing, protected bike facility, smaller roundabout radii. -----surveys: Type of user[bicycle rider, pedestrian, or both], their perception of general safety, and their perception of roundabout safety. Cyclists were also asked whether they would recommend Moray Street to inexperienced riders.	User perceptions of safety went up 21%. However, 30% of respondents noted that: a) driver visibility of riders is reduced; b) cyclists are slowed down; c) there is occasional confusion as to who has priority; and d) there is increased potential for cyclists to crash into pedestrians.---- The evaluation also found no significant issues with near-crashes for bicycle-and-pedestrian and bicycle-and-vehicle interaction. There were no significant problems with vehicle drivers using the protected roundabout. However, it was noted that when pedestrians are crossing at the raised crossings then vehicles would sometimes stop in the middle of the roundabout thus blocking traffic.	Only 2 roundabouts were studied and there was only statistical analysis of the before/after
Thomas, L., Ryus, P., Semler, C., Thirsk, N. J., Krizek, K., & Zegeer, C. (2016).	Various places	Identify noteworthy and innovative designs that could improve bike safety and increase the rate of cycling	11 countries	Literature review	N/A	six thematic areas, with four covering infrastructure or treatments: (1) network infrastructure (including large-scale intersection design), (2) limited auto traffic areas, (3) signalization, traffic control, and intelligent transport systems, and (4) policy change; and two topic areas focusing on innovations in: (1) methods or measures for prioritizing improvements, and (2) goals and network performance measures	Good goals and proper policy go a long way. Other treatments such as grade seperation, bike signals, bike path priority at low-volume streets, lower-speed multi-lane roundabouts, and different types of bike priority streets (superhighways, "green waves", wider seperated lanes) also have a high potential for implementation.	This was just literature review, and there was only mention of a roundabout once.
van der Leeden, E. (2012).	Heerhugowaard and Purmerend, Netherlands	To study the worthiness of each of the three intersection types from the viewpoints of traffic safety, trafic fow, and emissions.	two roundabouts, two pleintjes(voorrangsplein)/bow-string intersections, two regular non-signalized intersections	Conflict observations, simulation tool to determine traffic flow and emissions, followed by an **MCA analysis (6 criteria)**	Subjective	encounters, conflicts and critical conflicts have been characterized on a few parameters like driving direction, priority rules, evasive manoeuvres, average car speed in the area. ----MCA performed the following: Number of Critical Conflicts per car, per bike. • Chance of a fatal crash based on the average speed. • CO2 emission per car. • PM10 emission per car. • Waiting time per car. • Waiting time per cyclist.	No intersection stood out as being the safest; however if there is an encounter, there is a high chance that it becomes a conflict at a roundabout; the severity of a possible crash at a roundabout is lowest due to the lower speeds at a roundabout compared with the other intersection types	Only 6 intersections in total were studied and they were all located in Noord Holland in small towns (under 12K). Priority for cyclists was not studied but it was mentioned that there should be more comparisions done.

van Bentem, L. (2022).	Haarlem, Netherlands	Develop safety performance functions that predict bike crash risks	1 city, 7 roundabouts, 80 VRI's, 173 uncontrolled intersections, road section	Safety performance functions based on a generalized linear regression model.	Objective	crash data, exposure data and data of infrastructure characteristics[lane width, speed limit, road functional class, driving direction, bridge, tunnel, speed humps, streetlights, buildings adjacent, urban area nearby [office, industrial, residential]] were used to develop the functions. Three intersecitons were assumed: traffic signals (VRI's), roundabouts and uncontrolled intersections.	Moreover, it was found that increasing the bicycle width significantly decreases the bicycle crash risk. For intersections, the results showed a higher risk for roundabouts compared to the other intersection types. Additionally, the number of traffic flows crossing the intersection was positively related to bicycle crash risk. Finally, the presence of street lights was found to be positively related to bicycle crash risk for both road sections and intersections, which was not expected.	Lack of significance made many results non conclusive.--I.E. there were only 7 roundabouts in Haarlem.--- This study did not get at percieved risk.
Wang, K., & Akar, G. (2018).	Ohio, USA	analyzing and comparing the influences of intersection features on the safety perceptions of multiple types of bicyclists	90 intersections, 1094 valid responses	**Hierarchical generalized ordered logit models (LCCM**) based on an online visual survey with a 5-point Likert scale (“Very unsafe to cross” to “Very safe to cross”). **Multiple regression analysis** was performed on the intersection features to examine the influence whilst controlling for other factors.	Subjective	4 groups were used in the model : (i) regular bicyclists[someone whom biked in the past month], (ii) potential bicyclists[someone whom has biked in the past year], (iii) non-bicyclists who are pro-drive, (iv) non-bicyclists who are pro-public transit and pro-walk.----bike infra [(1) types of intersections, (2) road traffic, curbs, and lanes, (3) bike lanes and cycle tracks, (4) intersection treatments, (5) presence of traffic diverters, (6) characteristics of the surrounding environment, (7) sidewalk environments, and (8) green space.]----bicycle infrastructure at intersections, such as bicycle boxes, bicycle crossing signs and intersection crossing markings---socio-demographic characteristics[gender, age], daily travel mode choice[Auto (drive alone), Carpool (with 1 or more people),Bus, Walking, Bicycle], and bicycling frequency and skills[cannot ride a bicycle, A novice cyclist, An intermediate cyclist, An advanced, confident cyclist, I don't know how to describe my bicycling skills]---attitude factors for why people choose to bike[23 factors]	Riding through roundabouts is statistically significant and positively associated with regular and potential bicyclists' safety perceptions.----installing two-stage turning boxes may promote the perceived safety levels of regular and potential bicyclists. However, this factor does not significantly affect non-bicyclists' perceived bicycling safety at intersections. ---The number of through auto lanes and the main traffic volume are negatively associated with the perception of bicycling safety across four types of bicyclists.	This research did not focus solely on roundabouts, but on general behavioural and perceptions of USA cyclists. The roundabouts shown are not necessarily with dedicated bike facilities. ---"Future research should focus more on how to improve the safety perceptions of non-bicyclists. "We acknowledge this study has some potential limitations. First, Google Street View (GSV) imagery presents a view of an intersection at a particular angle. It may be difficult for the survey respondents to figure out some road conditions, such as traffic speed, the width of different types of road lanes, and neighborhood types"
Wegman, F., & Schepers, P. (2024).	Netherlands	analyzing the Safe System approach to understand the causes of the unfavourable developments in road safety for cyclists in the Netherlands and which problems require a solution are examined.	data from the Netherlands since 1990 on crashes, distribution of age of cyclist and distance travelled	Qualitative Road safety model composed of a multiplication of exposure to risk, crash risk, injury risk	Objective	**exposure, crash risk**[Fundamental risk factors are inherent to road traffic and are a combination of factors such as speed and mass (and the resulting kinetic energy in a crash) combined with the vulnerability of the human body. Fundamental risk factors play a role in all crashes. In addition to fundamental risk factors we face risk-increasing factors caused by, or at least related to road users. These factors are, for example, lack of driving experience, use of psycho-active substances such as alcohol and drugs, illnesses and ailments, emotion and aggression, fatigue and distraction], **and injury risk[**they are balance machines, thus you can lose balance and fall even at low speeds/dismounting; it becomes alot more injury prone as one gets older**]**.---Boundaries: in 2050 will be a combination of motorized vehicles and active transport modes, mainly on the current road infrastruc- ture. There will be some automation existing but not 100%.	About 50% of all distance cycled is by >50 year olds and more ebikes and other special bikes are becoming prevalent. --over 80 % of all seriously injured cyclists (MAIS3+) were involved in crashes without motorized vehicles, most of these being single-bicycle crashes --serious injuries are primarily the result of single-bicycle crashes, fatal crashes are mostly crashes with motorized vehicles, and to a far lesser extent single-bicycle crashes and crashes with other vulnerable road users. Last but not least, crashes with motorized vehicles are more serious for cyclists than other crash types--cyclists are separated (in time and space) from heavy and fast-moving motorized vehicles at intersections and road sections--The Safe System will work to make cycling safer but to what extent is unknown given uncertainties with technology, potential helmet usage, and personal behavioural choices. ....In order to prevent single-bike crashes (which would be significant move towards vision ZERO): Obstacle-free, spacious and skid-resistant bicycle infrastructure: create a bicycle infrastructure that is forgiving and therefore free from slippery substances (loose sand/gravel/leaves), obstacles, and vertical edges and ridges that can cause cyclists to lose their balance, fall, and injure themselves. Additionally, create bicycle infrastructure that is wide enough to provide cyclists the space for natural lateral movement and is sufficiently skid-resistant to prevent cyclists from slipping in bends.	The paper did not touch on topics such as cost-effectiveness, implementation issues, public acceptance of interventions, political support etc. ----"we are not fully able to assess the safety effects of Safe System implementation in the last decades in terms of the reduction in the number of cycle casualties. We recommend further evaluation research to understand better how exactly to improve our performance."----And a new phenomenon can be observed: bicycle congestion. "It is not fully understood how design characteristics (such as width of a track, intersection solutions, etc.), bicycle volumes, composition of the bicycle fleet etc. are correlated to risks. It is therefore recommended to make this a topic for research."----"It is recommended to carry out more research on the adverse impacts of risky behaviour of cyclists to underpin policies to prevent risk-increasing behaviour of cyclists."
Zeuwts, L. H., Iliano, E., Smith, M., Deconinck, F., & Lenoir, M. (2021).	Ghent, Belgium	examine the influence of induced mental fatigue on hazard perception and anticipation in young cyclists using a novel Virtual Reality (VR) bicycle simulator.	48 child (under 18 years old) cyclists, simulator environment with 8 simple and 6 complex traffic situations	Mental fatigue test was Stroop colour-word task and 50% of participants did that 1st (the entire test was done twice over 2 months); followed by a VR test that had eye trackers in them. **A Linear Mixed Model (LMM)** was used since it's better than ANOVA.	Subjective	A mental fatigue test was administered to 50% of participants, with a self administered visual analogue scale for mental fatigue afterwards. ---measurement of the children's cycling speed, cadence, braking response and steering angle---14 different hazardous events [includes (1) both overt (e.g. a car in front of the cyclist starts to act dangerously) as well as covert latent hazards (e.g., vision on the intersecting street is occluded by a parked van), (2) both abrupt or acute hazards (e.g., a car door suddenly opening), and latent hazards that develop over time (e.g., a pedestrian on the sidewalk looks over his shoulder and is about to cross the bicycle path), (3) actual threats (e.g., a car is actually on collision course), and potential threats (e.g., when view is obscured on the street from the right but there is no other traffic participant emerging from the street) and (4) visual and auditory stimuli that forecast the hazardous event]--One situation involved a roundabout "The cyclist enters a roundabout where (s)he has to provide priority to a car."	mentally fatigued cyclists fixated the relevant areas of interest (AOIs) in the simple and complex later and showed delayed response times for the complex hazards. Mental fatigue, however, did not alter the speed with which participants cycled through the virtual environment and did not change the hazard perception score.	Not statistically significant sample size, but close. ---response bias to influence virtual reality simulator reports of mental fatigue in our investigation----Future studies should, therefore, consider the evaluation of different strategies to negotiate traffic situations (braking hard, swerving, stopping pedaling).
Kazemzadeh, K., Afghari, A.P., Cherry, C.R. (2024)	Lund, Sweden	This study focuses on gaining insights into cyclists' experiences, particularly their comfort levels during 'passing' and 'meeting' events with other road users in shared spaces	intercept survey involving 594 cyclists.	random effect latent class ordered probit model	Subjective	The survey encompassed three question blocks, covering socio-demographic characteristics (income, education level, age, gender, Household structure), travel habits and history (cycling experience, owner of various transport modes, preferred mode for short and long distance trips), experienced comfort concerns in shared spaces (with a 3 point Likert scale).	female cyclists generally perceive less comfort compared to their male counterparts in both scenarios. Passing events have a more negative impact on older adults, leading to less comfort compared to younger cyclists. We also found that previous cycling experience increases comfort in shared facilities, particularly for older adults.	Looked at one city and had a low amount of respondents. The study could have looked at different types of riders such as pedestrians, e-bike riders, and scooter users.

D

Quantitative analysis

D.1. Crash analysis

In order to properly do the crash analysis, a number of filters needed to be applied so that only crashes at the specific roundabouts of interest that involved a bicycle were taken into account. This process is shown step by step in the following subsections.

D.1.1. WKN and NWB datasets

This dataset comprises of all the road network and it's associated codes for the entire Netherlands. Each type of road and intersection had a unique code for asset management and maintenance purposes for Rijkwaterstraat and the provincial and local governments. By using this, we are able to filter for only the BST code indicating mini roundabouts and roundabouts (NRB and MRB) respectively. Figure D.1 shows the results of this filter, showing all the roundabouts in the entire country. In addition, another filter was applied to only look at the Ranstad, which is shown in Figure D.2. A closer analysis of the roundabouts located in Utrecht found that all but five locations either did not have a bicycle path or were controlled partially or fully by a traffic light. Based on this information, that city was excluded from this research (The five roundabouts had similar properties to roundabouts found in The Hague, Rotterdam, and Amsterdam). Afterwards, another filter was performed to only show roundabouts within the cities of Pijnacker, Delft, Zoetermeer, Rotterdam, Amsterdam, and Den Haag. This filter is shown in Figure D.3 and reduced the amount of roundabouts to 186. Finally, as this research is only studying single lane roundabouts with bicycle facilities that are not controlled by traffic lights, there was a manual filter performed which resulted in the 52 locations shown in Table B.1.

Data sources:
-Roadway network
(NWB - https://www.nationaalwegenbestand.nl/aanbieders)
-Collision data
(BRON - https://data.overheid.nl/dataset/9841-verkeersongevallen---bestand-geregistreerde-ongevallen-nederland#panel-resources)

Figure D.1: Roundabout locations for the Netherlands. Data valid as of 2024

Data sources:
-Roadway network
(NWB - https://www.nationaalwegenbestand.nl/aanbieders)
-Collision data
(BRON - https://data.overheid.nl/dataset/9841-verkeersongevallen---bestand-geregistreerde-ongevallen-nederland#panel-resources)

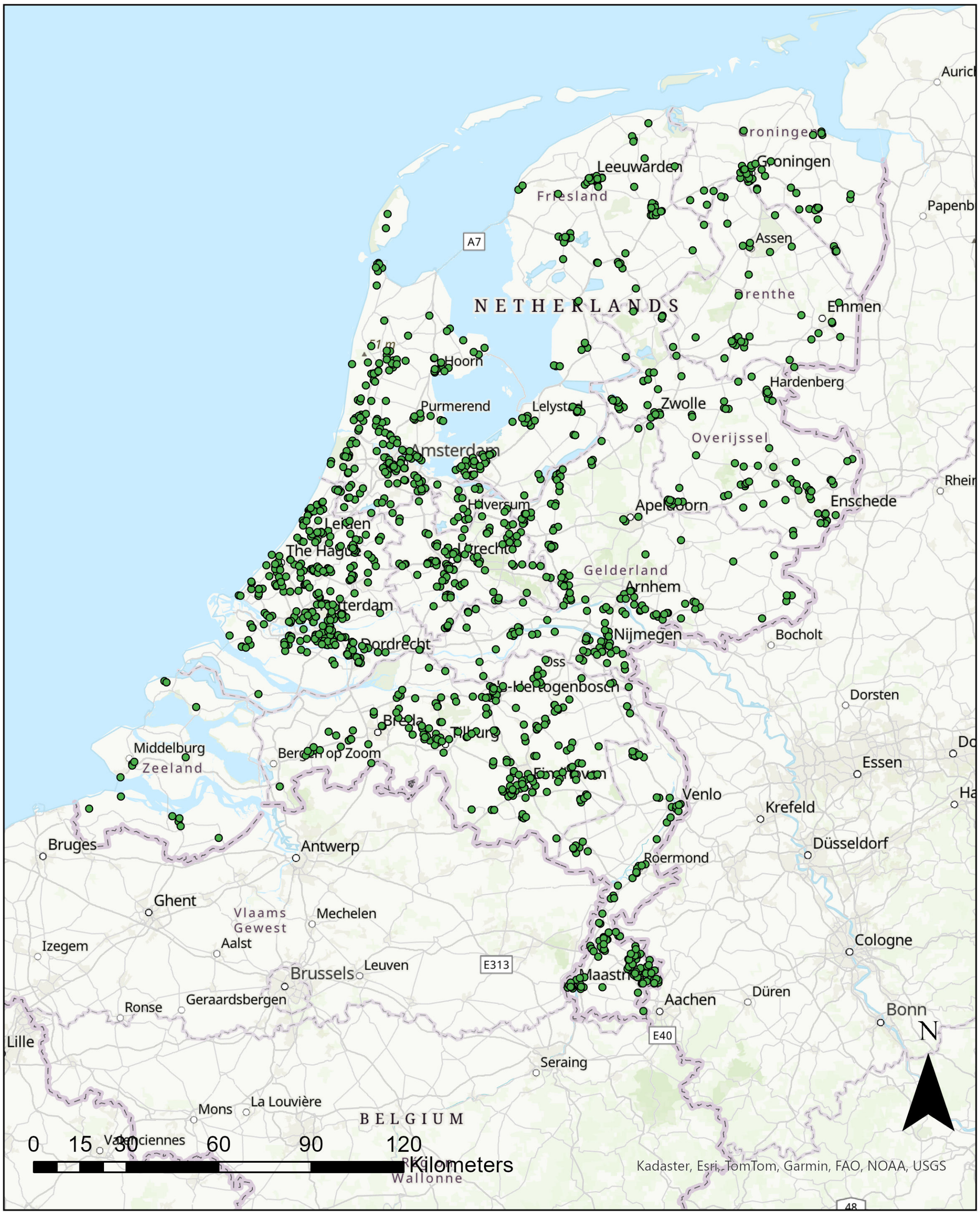
Figure D.2: Roundabout locations within the Randstad. Data valid as of 2024

Data sources:
-Roadway network
(NWB - https://www.nationaalwegenbestand.nl/aanbieders)
-Collision data
(BRON - https://data.overheid.nl/dataset/9841-verkeersongevallen---bestand-geregistreerde-ongevallen-nederland#panel-resources)

Figure D.3: Initial study roundabout locations. Note this shows the five selected cities (Den Haag, Amsterdam, Delft, Zoetermeer, Pijnacker, and Rotterdam). Data valid as of 2024

D.1.2. BRON dataset

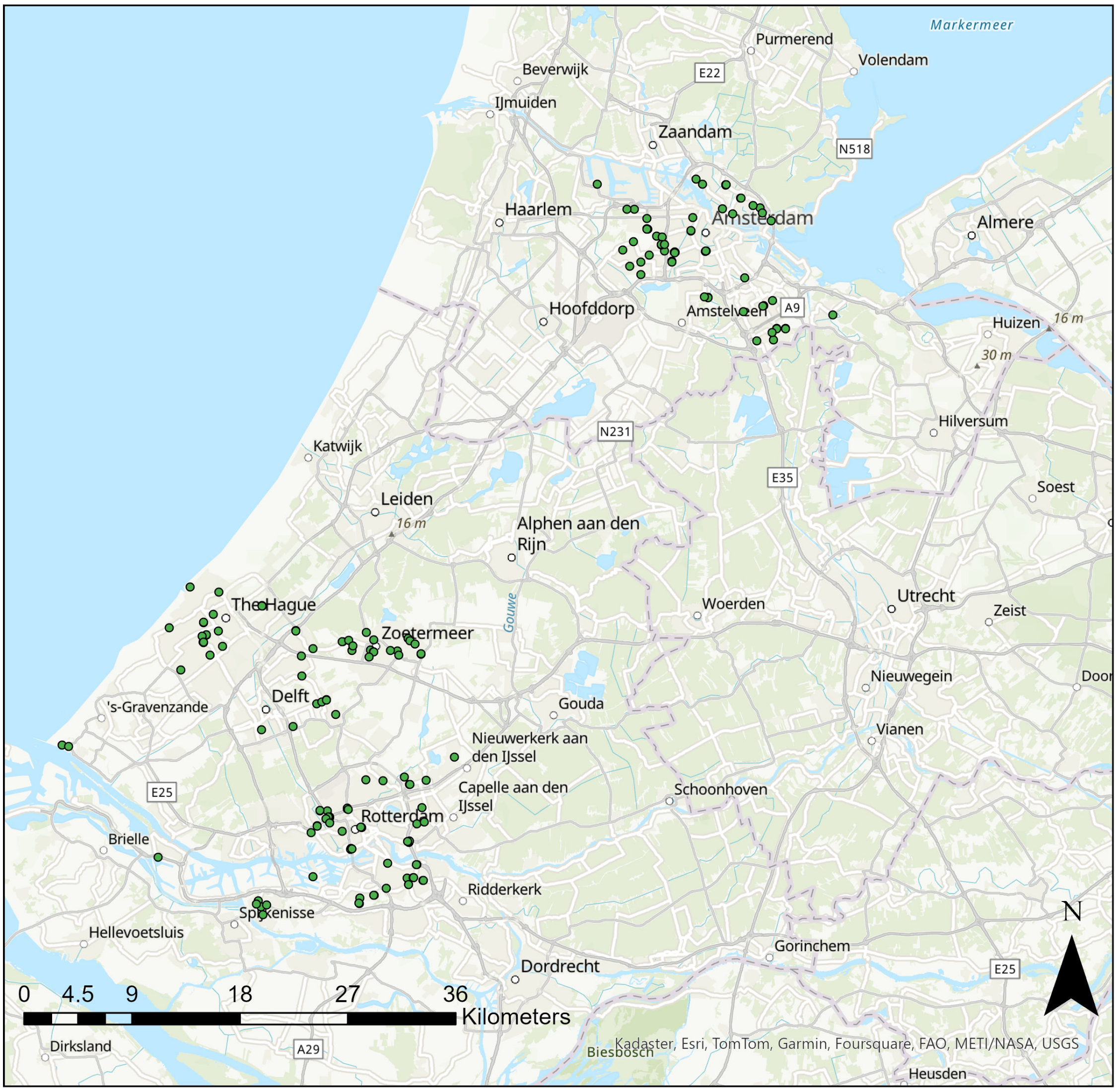
The official crash database can be linked to the road network databases mentioned in the previous subsection by using the unique WVD_{ID} or junction ID. This process was done to the entire crash database and then filtered for just the 52 sites.



Data sources:
-Roadway network
(NWB - https://www.nationaalwegenbestand.nl/aanbieders)
-Collision data
(BRON - https://data.overheid.nl/dataset/9841-verkeersongevallen---bestand-geregistreerde-ongevallen-nederland#panel-resources)

Figure D.4: Reported Dutch crashes occurring at a roundabout between 2013 and 2022.

Following that, the X and Y coordinates were converted to the latitude and longitude coordinates in order to correctly display on a GIS program. This dataset is the official reported crashes for the entire Netherlands and covers a 10 year period from 2013 through 2022. Out of the initial data set of 1.16M crashes, only 8586 crashes occurred at the roundabout locations (see Figure D.4), with Keizer Karelplein in Nijmegen having the most reported crashes with 58. Note that this roundabout is controlled by a traffic light.



Data sources:
-Roadway network
(NWB - https://www.nationaalwegenbestand.nl/aanbieders)
-Collision data
(BRON - https://data.overheid.nl/dataset/9841-verkeersongevallen---bestand-geregistreerde-ongevallen-nederland#panel-resources)

Figure D.5: Crashes occurring at a roundabout within the selected cities between 2013 and 2022

If the choice is to not consider roundabouts with traffic lights, then Groene Kruisweg/Dorpsstraat in Rotterdam is the highest with 25 reported crashes.

The next step was to perform a filter for just urban roundabouts (marked BI in the BEBKOM column). This yielded a total of 2727 reported crashes over the 10 year study period. After narrowing down to the cities of interest for this research, there were 322 reported crashes, as shown in Figure D.5. Within this final selection, a total of 14 reported crashes occurred at Groene Kruisweg/Dorpsstraat in Rotterdam, occurring in 2016 or 2019. Note that from the country-wide search, this roundabout had 25 reported crashes. These researchers believe that this discrepancy lies in the improper labelling of whether the roundabout is considered urban or rural. When filtering just by the cities of interest and not using the BEBKOM filter, there were 670 reported crashes at roundabouts. The final Table 6.10 incorporates all the collisions stated in the BRON dataset for the eight roundabouts used in the survey, including ones that were mislabelled as suburban or rural roundabouts.

In addition, there were other interesting characteristics related to the crash information, notably:

- Six reported crashes occurred at real-world roundabouts that were used in the survey (Dierenselaan/Apeldoornselaan, Delftlandplien, and Meerzichtlaan/Berglaan).
- There is very little information on who was involved in each crash.
- The data is only those crashes that were reported by the police, which is roughly about 20% of all crashes.
- ”Near misses” are not documented and thus were not captured in the data.

D.2. Conceptual framework generation and creation of attributes

D.2.1. Conceptual model overview

Taking the hypotheses mentioned in Section 3.2, this report developed a conceptual framework. Figure D.6 illustrates this conceptual framework, describing the relationship between roundabout infrastructure design factors, bicyclist type, individual factors, external factors, a bicyclists' comfort using a roundabout, bicyclists intention to use a roundabout over other intersection types, and bicyclist's perceived safety on roundabouts. Note that this Figure shows all the possible factors and as such is beyond the scope of this research report and would be a highly complex model with large computational time requirements.

What is unique about this conceptual framework is the use of a latent variable ”bicyclist behaviours”, measured from 12 independent variables modified from the Useche et al. (2018) study that used 29 independent variables, called the cyclist behavioural questionnaire (CBQ). ”Cyclist behaviours” variable is hypothesised to have a direct effect on the comfort and safety perception latent variables since if a bicyclist is more risky under various typical situations that are encountered whilst bicycling, they are likely to have a higher tolerance for what is considered an unsafe situation. The latent ”Cyclist behaviours” variable addresses one's long term aversion towards risk. More information about how the 12 variables were selected and the CBQ in general is located in Section 4.4.

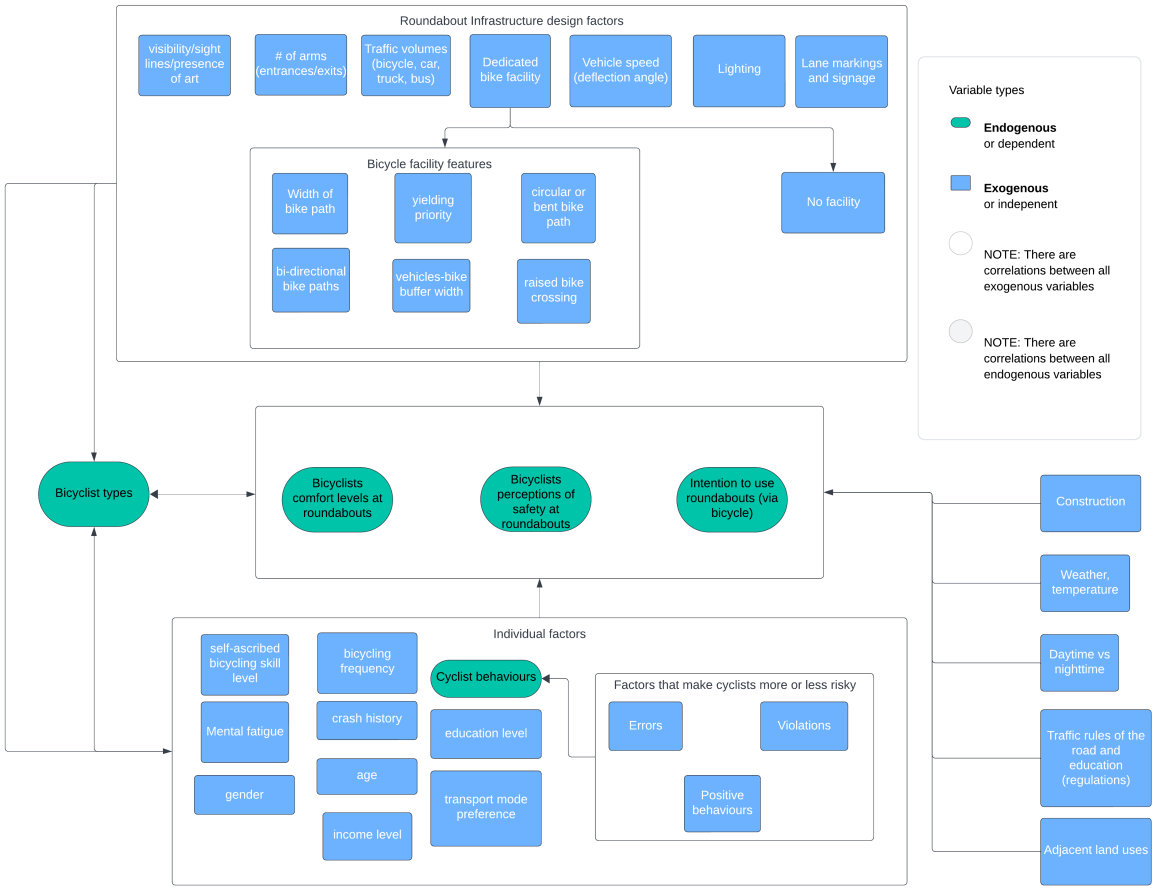


Figure D.6: Initial conceptual framework of subjective bicycle safety at roundabouts. Model created via Lucid.

D.2.2. Path diagram/Conceptual framework refinement

The conceptual framework (Figure D.8) was first modified to only include variables that will be studied in this research paper (Figure D.7) and to test the hypotheses produced in Chapter 4, thus looking at the spurious,indirect, and direct effects that one variable may have on another. After further discussions and literature research, a second round of simplification was performed in order to fit within the confines of a six month research project, the existing capabilities of regression models, and to reduce the burden placed upon survey respondents (via blocking and removal of certain questions thought to be redundant). Note that since there has yet to be any studies looking at the correlation between comfort and perception of safety dependent variables versus one that assumes there is no correlation, this research is setting a precedent by performing two model runs to test the results of one versus the other.

Figure D.7: Refined conceptual framework of subjective bicycle safety at roundabouts. Model created via Lucid.

The path diagram for this research is shown in Figure D.12. Note that the independent variables falling under the roundabout characteristic category all have correlations between them and are correlated with the variables in the individual factors category and the 'cyclists behaviour' latent variable. Note that there are correlations between the independent variables in the individual factors category and the 'cyclists behaviour' latent variable as well as between all the variables that fall into the individual factors category.

D.2.3. Refined conceptual model

By controlling certain factors and eliminating variables that are too difficult to measure, this report will only look at certain factors, as shown in Figure D.8. The key differences between the exhaustive conceptual model shown in Figure D.6 are:

- The removal of mental fatigue independent variable due to it's complexity in properly measuring it without performing a more in-depth simulator or eye-monitoring study (Zeuwts et al., 2021; Richard Mantona et al., 2016; Wegman and Schepers, 2024).
- The removal of all external factor variables such as time of day, weather, construction, adjacent land use, and knowledge of traffic regulations.
- Lane markings and signage was removed since the roundabouts all have consistent markings to delineate yielding priority as required by the CROW design guidelines.
- Due to the limited existence of urban Dutch roundabouts that have no bicycle facility at all, this research decided to focus solely on roundabouts with bicycle facilities.
- Due to the difficulty in conveying to online survey respondents that the bicycle crossing was raised or not, this independent variable was dropped.
- Due to the large range of bicycle path widths, even within a single roundabout, this variable was also excluded.
- This study is focusing on bicyclist perceptions of safety, thus the survey and photos/videos were performed during daytime hours. The lighting independent variable was removed.
- The vehicle speed variable was removed since it would be hard to convey that information via an online survey to participants and the prevailing speed at single lane urban roundabouts was all below 30km/h. In addition, past research has confirmed that the center island size increases the deflection angle, which decreases vehicle speeds, and thus decreases perception of risk (van der Leeden, 2012;Richard Mantona et al., 2016; Poudel and Singleton, 2023).
- Due to the questionable nature of the latent variable ”bicyclist type” (since it was already being indirectly asked via the independent individual factors variables), it was removed. In addition, the questions in the CBQ which influence the ’Bicyclists behaviours’ latent variable include some that describe what type of bicyclist the survey respondent is.
- The latent variable ”intention to use a roundabout” was removed since the focus on this research is on perceptions of safety and comfort. The assumption was made that bicyclists will always use the infrastructure provided to them and thus will most likely use a roundabout (even though if they dislike roundabouts in general this will impact their perception of safety and comfort level).
- The roundabout visibility independent variable was removed as it is subjective to each respondent on how bush height or tree canopy coverage can affect visibility. In addition, the eye level of bicyclists and motorists vary depending upon motor vehicle type and individual physical height.
- The transit presence independent variable was removed as it adds complexity to the roundabout and transit normally have priority over all other modes.

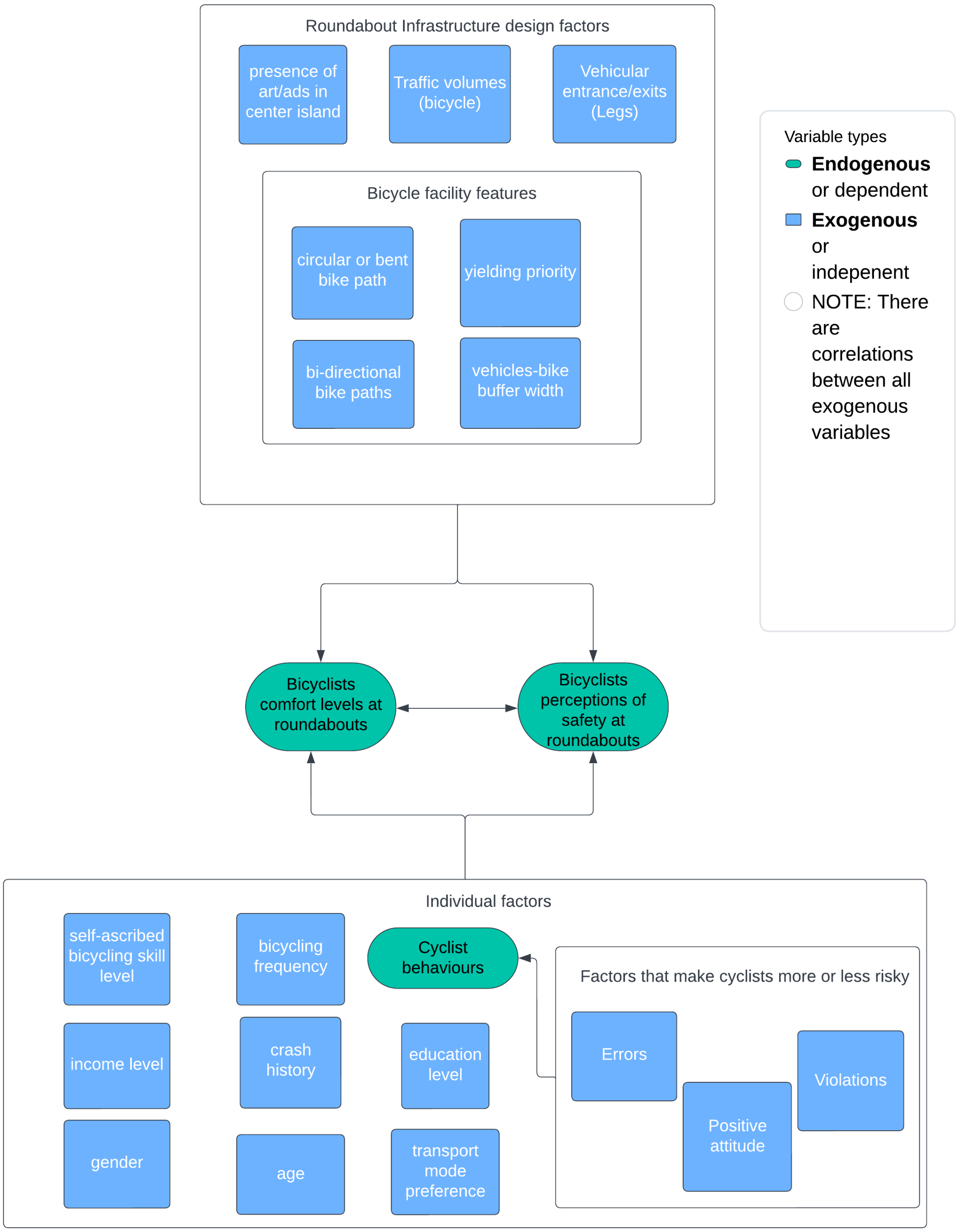


Figure D.8: Penultimate conceptual model for this research. Model created via Lucid.

The final conceptual model is shown in Figure 3.1.

D.2.4. Attributes

Following, the conceptual framework shown in Figure D.8, the task was to narrow down on the attributes and refine them to create a path diagram. In order to perform a stated choice experiment that is not too overwhelming for respondents, this research will employ an orthogonal fractional factorial design and make use of the basic plan 3 which allows for varying attribute levels (i.e. some attributes are binary such as art presence whilst some have have multiple possible values such as buffer width between vehicles and bicycles). As such, the initial number of attributes and their levels/scales was determined in order to fill a basic plan 3 (See Table D.1). These attributes focus this research to look at specific design characteristics of roundabouts that have protected bicycle facilities and that past research has found to significantly contribute to safety.

Table D.1: Initial model attributes and scales/levels/categories of the indicators

Label	Variable	Definition	Categories
buffer	Buffer space between vehicles and bicycles	This space is critical for clear separation of modes and allows for reaction time for yielding behaviour	1, 3, 5, > 7 meters
Yield	yielding priority for bicycles	Roundabouts with yielding priority for bicycles are more common in urban areas and where the separation between cars and bicycles is ≤10 meters	Yes, No
Art	presence of art in the center island	The center island features can help focus drivers on the immediate approach in front of them but also could add distractions	Yes, No
Sight	Visibility at roundabout	This criteria is related to the visibility due to shrubs, objects, poles located in the buffer space separating bicyclists and motorists and also in the center island of the roundabout	Poor, OK, Good
Direction	Is the bicycle path bi-directional?	Roundabouts can have bicycle paths that are partially bi-directional on certain legs or all around the circle. This adds complexity but allows for better accessibility and route choice for the bicyclists	Yes, Partial, No
PT	special transit movement	This criteria is whether there is a tram/bus lane present in the roundabout (often times these lanes go through the middle of the roundabout)	Yes, No
Flow	Bicycle volumes	This criteria relates to roundabouts that have bicycle volumes above or below 480 bicycles per hour (PM peak hour)	Below 480, Above 480
Legs	Vehicular entrance points	This criteria is whether or not the roundabout has 4 entrance/ exit points for vehicles which can reduce or add complexity to the roundabout	Yes, No
Shape	Bicycle path shape	Separated bicycle facilities come in two different shapes: circular (mimicking the vehicular lane) and bent (resembling more of a polygon shape)	Circular, Bent
		Socio-demographic questions	
mode	Most common mode of transportation	What is your primary transport mode to commuter to your work/studyplace?	Bicycle,E-bicycle,Scooter, Bus/Metro/Tram, Train,Auto/Motorcycle, Walking, Cargo bicycle, Special bicycle
TR_DAYS	travel frequency	In the past year, how often have you used the modes mentioned in the previous question?	Never, Less than once a month, 1-3 days per month, 1-3 days per week, 4-6 days per week, Always
Crash	Crash history	Have you had any crashes or "near misses" in the past 12 months?	Yes, No, Prefer not to say
Education	Highest education level attained	What is the highest degree or level of school you have completed?	Some primary school, Completed primary, Some secondary school, Completed secondary school, Vocational or similar, (Some university credit, no degree), University Bachelors degree, Graduate or professional degree (MA, MS, MBA, PhD,JD, MD, DDS, etc), Prefer not to say
Gender	Gender of the respondent	What is your gender?	Female, Non-binary, Male, Prefer not to say
age	age of the respondent	What is your age?	18 - 24, 25 - 34, 35 - 44, 45 - 54, 55 - 64, 65 - 74 ≥75, prefer not to say
income	income range	What is your monthly income?	<1,000, 1,001 - 2,000, 2,001 - 3,000, 3,001 - 4,000, 4,001 - 5,000, ≥5,000, prefer not to say
skill	self-ascribed cycling skill	What would you qualify your level of expertise in bicycling?	[inexperienced/competent/highly skilled], prefer not to say
risky	Risky behaviour as a bicyclist	This gets at how risky someone is when they are bicycling since the assumption is that influences their perceptions of safety and comfort	see Table 4.4

Certain variables such as vehicle speed and center island size were never considered in this research as many prior research papers have looked into that subject. Section B.1 reveals that amongst all the CROW workshop attendees, everyone agreed that speeds should be lowered (in line with the GOW30 policy at the national government). Other variables were not selected due to finite research period and the multitude of roundabout types present within the Netherlands. These are listed below:

- bicycle path width
- multi-lane roundabouts
- roundabouts without bicycle facilities
- turbo roundabouts
- micro roundabouts
- bicycle roundabouts

During the survey construction phase, additional variables were removed or altered in order to reduce the number of participants needed to start reaching t-test significance with certain variables. Those are explained individually below.

Transit Presence
This attribute adds complexity to roundabouts and is clearly coupled with the 'yielding priority' variable (see Table B.1) as all four real-world roundabouts that do not give bicycles yielding priority, have a special transit lane/movement at the roundabout. In addition, the information gleaned from the expert insights is that a special transit movement in a roundabout is precisely the location where 'yielding priority' should not be given to bicyclists.

Visibility
This attribute is highly subjective, depending upon multiple factors such as vehicle speed, weather conditions, lighting, bicycle speed, and seasonality. During the winter months, a roundabout with bushes and trees may have good visibility but in the summertime it could be bad. Good maintenance of shrubs and trees is an essential part of a city's job functions, so it visibility may depend upon city crew's trimming schedules aswell.

Buffer, Direction
These attributes were reduced down to be binary variables, in order to reduce the possible choice situation combinations that would need to be studied. The Buffer space was reduced from bins of roundabouts with 1, 3, 5, or greater than 7 meter buffer widths down to one bin that is called: "small buffer width", which equals 0 to 4.5m and a "large buffer width" which symbolizes between 4.5m and 12m in width. The decision for 4.5m being the upper/lower bound was based on the average width of from the roundabout characteristics table (Table 4.3). The Direction variable was reduced from being yes, partial, and no down to either yes or no, with the no response now encompassing all roundabouts that are not 100% uni-directional.

D.2.5. Cyclist behavioural questionnaire

The path diagram shows causal relations between variables and separates independent variables from dependent variables. An example of a path diagram that was used to create the Cyclist Behavioural Questionnaire (CBQ) (Useche et al., 2018) shows the independent variables (numbers within squares) and the dependent/latent variables (oval shaped) and can be found in Figure D.9. A more recent study from Belgium adapted the CBQ by removing certain independent variables (Unintentionally, hitting a parked vehicle; When I use the bicycle path (or bicycle-lane), I always use the indicated lane; I avoid circulating if I feel very tired or sick.) due to their low λ values ($\lambda < .30$) and validating the CBQ model for the Belgian population, to ensure that there were still significant correlations (Useche et al., 2021). This research will take the CBQ one step further, by taking the three latent variables shown in Figure D.9 and having them directly influence 1 latent variable: "cycling behaviours" as the focus on this research is on bicyclists comfort levels and perceptions of safety in specific traffic situation, that of a roundabout.

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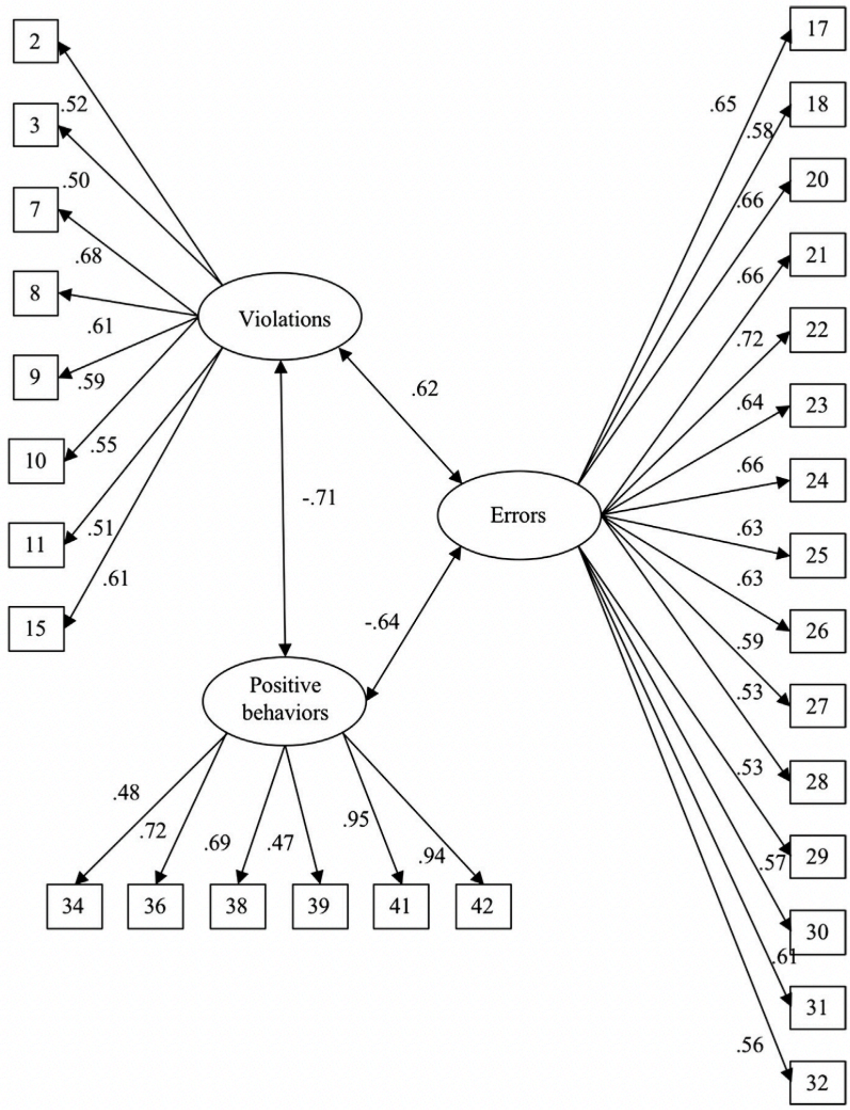


Fig. 1. Standardized parameter estimates. Notes: All estimates p < .001; the numbers within squares represent the original numbers of the items in the CBQ scale (as shown in Table 1).

Figure D.9: Path diagram showing risky and positive bicyclist behaviours: Standardized parameter estimates from the study by (Useche et al., 2018)

After review of the CBQ model, the questions were altered and consolidated in order to still understand respondents' underlying bicycling behaviours but focusing more on the traffic design angle and also understanding the type of bicyclist that a respondent is. As such, Table D.2 was modified to be better tailored to the Netherlands and the focus of this research, which is about roundabouts. The final Table that was used in the survey is Table 4.4.

Table D.2: Original CBQ, showing questions and scales of the indicators. Courtesy of Useche, 2018

Label	Question Formulation	Scale
	Violations latent variable group	
2	Cycling under the influence of alcohol and / or other drugs or hallucinogens.	1=Never - 5= Always
3	Going against the direction of traffic (wrong way).	1=Never - 5= Always
7	Zigzagging between vehicles when using a mixed lane.	1=Never - 5= Always
8	Handle potentially obstructive objects while riding a bicycle (food, packs, cigarettes...).	1=Never - 5= Always
9	Feeling that sometimes I'm going at a higher speed than I should be going at.	1=Never - 5= Always
10	Crossing what appears to be a clear crossing, even if the traffic light is red.	1=Never - 5= Always
11	Carry a passenger on your bicycle without it being adapted for such a purpose.	1=Never - 5= Always
15	Have a dispute in speed or ''race'' with another bicyclist or driver.	1=Never - 5= Always
	Errors latent variable group	
17	Unintentionally, crossing the street without looking properly, making another vehicle brake to avoid a crash.	1=Never - 5= Always
18	Colliding (or being close to it) with a pedestrian or another bicyclist while cycling distractedly.	1=Never - 5= Always
20	Brake suddenly and be close to causing an accident.	1=Never - 5= Always
21	Fail to notice the presence of pedestrians crossing when turning.	1=Never - 5= Always
22	Not braking on a ''Stop'' or ''Yield'' sign and being close to colliding with another vehicle or pedestrian.	1=Never - 5= Always
23	Braking very abruptly on a slippery surface.	1=Never - 5= Always
24	While you're distracted, you do not realize that a pedestrian intended to cross a crosswalk and so you do not stop to let him or her do so.	1=Never - 5= Always
25	Not realizing that a vehicle that was parked intends to leave and having to brake abruptly to avoid colliding with it.	1=Never - 5= Always
26	When you drive on the right, you do not realize that a passenger is getting out of a vehicle or bus and are close to hitting him or her.	1=Never - 5= Always
27	Trying to overtake a vehicle that had previously used its indicators to signal that it was going to turn, having to brake.	1=Never - 5= Always
28	Misjudging a turn and hitting something on the road or being close to losing balance (or falling).	1=Never - 5= Always
29	Unintentionally, hitting a parked vehicle.	1=Never - 5= Always
30	Failing to be aware of the road conditions and therefore falling over a bump or hole.	1=Never - 5= Always
31	Mistaking one traffic signal for another, and maneuvering according to the latter.	1=Never - 5= Always
32	Trying to brake but not being able to use the brakes properly due to poor hand positioning.	1=Never - 5= Always
	Positive Behaviours latent variable group	
34	I stop and look both sides before crossing a corner or intersection.	1=Never - 5= Always
36	I try to move at a prudent speed to avoid sudden mishaps or braking.	1=Never - 5= Always
38	I usually keep a safe distance from other bicyclists or vehicles.	1=Never - 5= Always
39	When I use the bicycle path (or bicycle-lane), I always use the indicated lane.	1=Never - 5= Always
41	I avoid circulating under adverse weather conditions.	1=Never - 5= Always
42	I avoid circulating if I feel very tired or sick.	1=Never - 5= Always

D.3. Survey construction assumptions and notes

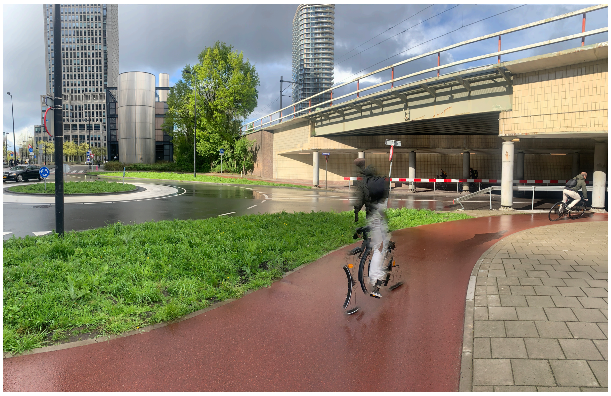
During this process, the 8 selected roundabouts (see Table 4.3) did not all perfectly match the attributes except for Delftlandplien (choice situation 8). The unmatched conditions for each selected location are shown below in Figure D.10.

Design	Separation from Vehicle Lane (m)	Bike Yielding Priority	Art/Ads in Center	Uni-Directional	Bike Volumes (15min)	Facility Style	4-Legged	Real world location		Unmatched Conditions
Choice situation	alt1.buffer	alt1.yield	alt1.art	alt1.direction	alt1.flow	alt1.shape	alt1.legs	Real world location	City	
1	2	1	1	1	0	0	0	Dierenselaan/Apeldoornselaan	Den Haag	Art/Ads in Center
2	5	1	0	0	0	0	1	Neherkade/Slachthuisstraat	Den Haag	Uni-Directional
3	5	0	1	0	0	1	0	Putsebocht tram stop,	Rott	Art/Ads in Center, Uni-Directional
4	2	0	0	1	0	1	1	Planbaan/Kernbaan	Zoetermeer	Bike Yielding Priority, Uni-Directional
5	5	0	0	1	1	0	0	Amstelplein	Amsterdam	Bike Yielding Priority, Uni-Directional
6	2	0	1	0	1	0	1	Gordelweg/Rodenrijsestraat	Rott	Bike Yielding Priority
7	2	1	0	0	1	1	0	Meerzichtlaan/Berglaan	Zoetermeer	Art/Ads in Center, Bike Volumes (15min);
8	5	1	1	1	1	1	1	Delftlandplien	Delft	All matched

Figure D.10: Choice situation table (created by Ngene), with columns showing the real-world locations that best matched the attributes along with any unmatched attributes

The images taken from Google Earth/Google Maps or AD (2022) for the satellite views and taken by the research team (for the bicyclist-level views) were edited using a photo editing software in order to remove, change, or add in features such as signage, art, advertisements, paint markings, and bicyclists. Even Delftlandplien was modified to add more advertisement/artwork and more motor vehicles so that all eight locations presented a motor vehicle about to conflict with a bicyclist at a crossing point. In addition to that, extra bicycles and vehicles were added in order to show varying ranges of bicycle volumes but a consistent heavy presence of vehicles in order to make it seem as if vehicle volumes are constant between all 8 choice situations. As mentioned in Section B.2, this was due to the experimental design process and use of the BASIC 1 plan. This meant that a question about roundabout familiarity (e.g. Have you used this roundabout before?) could not be asked. PNG images were found at the following websites: (Image, 2024; PNG, 2024). Figure D.11 shows an example of the original photograph, with the edited version on the left hand side.

(a) Final image used in choice situation 5



(b) Unedited, real-world picture of Amstelplein, Amsterdam. Note that due to 180 degree camera, moving objects sometimes became distorted

Figure D.11: Image editing process for Amstelplein (Roundabout #5)

At Delftlandplein, there was no updated Google Maps or Google Earth aerial image, so the researcher used the Bicycle Dutch website. This website is run by a Dutch bicycle blogger from Utrecht that had gotten access to a nearby apartment and took an isometric view of the roundabout from a high angle after the bicycle path was reconstructed in 2022.

D.4. Data issues and data scrubbing

This research was not setup in Qualtrics in a way that allowed for the direct interpretation of data, thus there were minor adjustments that were needed before the data could be properly analysed using probit model with R. The following list was the manual steps that were taken to prepare the data:

1. The education, income, gender, bicyclist skill level, and bicyclist crash history variables had to have the opt-out response option shifted to be coded as lowest on the ordinal scale (i.e. moved from being coded as 5 down to 0 or 1).

2. Bicyclist skill level is categorical and has 4 categories (1,2,3,4), but the data shows that no one choose category 1. The model was adjusted to not take it into account.

3. Education is categorical and it has categories of 2,3,4, and 5 (there is no 1). The model was adjusted to not take it into account.

4. Respondents sometimes wrote their age or gender in letters which meant a manual review of the raw data set was performed in order to convert these into responses that the R program could understand.

D.5. Ordered probit regression

Constructing the multivariate ordinal regression model posed many challenges. Due to the dataset being transposed as long data, there are panel effects that meant that either a random or fixed effect model had to be used. In addition, there are two ways of writing the formula for such models:

$$Y_{ij}^* = \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \lambda_{0ij} + \epsilon_i \tag{D.1}$$

$$Y_{ij}^* = \beta_1 X_1 + dZ_1 + \epsilon_1 + \beta_2 X_2 + \ldots + \beta_n X_n + dZ_n + \epsilon_n \tag{D.2}$$

where the top equation represents using an additional error term (ϵ_i) that varies between respondents and the bottom equation makes use of a dZ dummy for each of the eight roundabout locations, simulating all the choices made by one respondent. The decision was made to use the top equation as that would make for a smaller equation. Another decision had to be made regarding whether to use a random versus fixed effect. These formulas are shown below, with the top one being the random effect:

$$Y = \beta X + \lambda_0 + \epsilon_1 \quad (D.3)$$

$$Y = \beta X + \delta(ID) + \epsilon_0 \quad (D.4)$$

Note that ϵ_1 can be assumed to be an error term with a multivariate normal distribution whereas in the 2nd equation $\delta(ID)$ is simply a unique ID coefficient that is linked with each respondent. The decision was made to proceed with a random effects ordered probit model as one error term can be used for both the panel data effect and the multivariate component.

All categorical variables had to be transformed into factors for the models to read the data in those variables(Libraries, 2024) and the variables had different factor levels, ranging from 3 to 5. Initially it was thought to first perform an ordinal regression just for the CBQ latent variable which is based off of the 12 questions related to that topic and grouped into three topics: Errors, Positive Attitude, and Violations. This step proved challenging since either a composite score or an index had to be used to create the 'cycling behaviours' dependent variable. After this step, the results of that model and subsequent factor analysis would feed into the larger ordinal regression model for perceptions of safety and comfort. However, this proved to be difficult and time-consuming, and thus was abandoned. It would have resulted in a loss of data as this latent variable is not really categorical but all the indicator independent variables are, thus leading to a categorical outcome that would have had to be discretized in order for it to be placed into the larger ordinal regression model.

Another challenge that was surmounted was ensuring that the data was kept in the format that it could be correctly read, i.e. ordinal data needed to be converted to being read as ordinal in the model setup. In addition, the 'age' variable needed to be scaled since it is the only continuous variable in the dataset. Standard scaling was used, which is a method that transforms each feature to have a mean of 0 and a standard deviation of 1. This method is useful when comparing variables that have different units or very different distributions.

Another process that proved too difficult to accomplish was a factor analysis of the 'mode preference' and 'usage frequency' independent variables because certain usage frequencies were removed in the preliminary data scrubbing in order to remove people whom never use any of the possible bicycle options (e.g. If a person that has a special bicycle but not a normal bicycle, they were still counted.). Since the bicycle options counted for four of the eight different modes studied, this did alter the response rates and distribution. A factor analysis uses the assumption that the underlying data is continuous and normally distributed.

Performing a multivariate ordered probit model in R using the library 'mvprobit' proved impossible because that library can only handle dependent variables that have the same formula (independent variables). It kept giving an error message saying that "using different regressors for the dependent variables has yet to be implemented". This shouldn't of been an issue but during the model trials, the estimated correlations between the two dependent variables were giving erroneous values. In theory, using this library allows for correlation estimations of the error terms between the different equations, which tells you how the unobserved factors affecting 'Perception_of_Safety' are related to those affecting 'Comfort'. A possible approach could have been to use a generalized linear model function with a probit link and then analyzing the correlations of the error terms post estimation.

A cross-validation was performed by creating a correlation matrix and looking for any highly correlated predictors. There were none until going down to a threshold value of 0.50. No variables were removed at this stage. Currently the 'mvord' library does not directly support random effects (it only performs multivariate ordered probit models but with the option of probit, cloglog, and logit link functions), thus the plan at this stage was to use the 'mvord' library to perform separate model runs and then combine them later using the 'plm' library.

The decision was made to proceed with using a Bayesian style model with the 'brms' library as it can handle multivariate models with random effects. Unfortunately the 'rescor' parameter, which is crucial for calculating residual correlations is only possible in multivariate Gaussian or student models, which meant that a post-hoc correlation analysis had to be performed. This model worked but was slow and took 24 hours just to run a simple version of the model with very few variables being explored. Another model was used, based off of a model created by Hirk et al. (2020). This model proved to be easier to use but was limited due to the perfect multicollinearty created by the roundabout attribute variables (due to the experimental design process).

D.5.1. Model performance

In order to validate the ordered regression model, and ensure the correct variable type assignment the Maximum Likelihood (ML) estimation method will be used for the model parameters (e.g. β and Y). A ML estimation method assuming a discrete distribution was almost performed for the ordered regression model. The higher the ML value, the better the model fits the data. As the developed models are less complex than the true model, variables and thus subjective factors were not included. The ML calculation accounts for these lost factors. The ML estimation method uses derivatives to minimize the following fit function, where the discrepancy between the observed covariance matrix **S** and the covariance matrix implied by the model, Σ , is measured(Newsom, 2023a):

$$F_{ML} = \log|\Sigma(\theta)| + tr(\mathbf{S}\Sigma^{-1}(\theta)) - \log|\mathbf{S}| - (p+q) \tag{D.5}$$

D.5.2. Marginal probability effects

Due to the non-linear nature of Equation 4.1, the β coefficient values can't be directly interpreted as increases or decreases in the latent variables (Jafari Anarkooli et al., 2017). As such, the elasticities or marginal effects will be calculated to show the percentage of contribution that each independent variable has on each dependent variable (Hirk et al., 2020). Equation D.6 represents the marginal effects calculation for the perceptions of safety latent variable where β_p represents the explanatory variable p

$$ME_{kp|X_{jp}} = \frac{\partial P(Y_{ij} = k|X_{ij})}{\partial X_{jp}} = \left[f(\mu_{k-1} - X'_{ij}\beta) - f(\mu_k - X'_{ij}\beta)\right] \cdot \beta_p \tag{D.6}$$

and $f(.)$ is the density function. However marginal effects is more often used for continuous variables and as such, this research will use elasticities which are better suited for discrete data (with binary and categorical variables).

D.6. Ordinal SEM model

This Section describes another model family, called a Structural Equation Model (SEM) and this researches' attempt to run the data through a ordinal SEM model. The 1st part of this section describes the functions of a SEM and it's theoretical formula. The 2nd part of this section, goes over the step by step model implementation and associated model result and correlation matrix. The reason this model was not used in the final report was due to computational times.

D.6.1. Model overview and formulation

Structural Equation Models (SEM) models are family of models that look at the psychological behaviour behind people's travel choices(Molin, 2005). An SEM looks at the psychological motivation underlying the behaviour. It looks at personal factors (age, gender, and environmental concerns). This type of model can also be used if the assumption is that the built environment affects travel behaviour (street connectivity, street scale, land use, etc). Certain SEM models can handle categorical variables, such as age, gender, and other binary variables, which lead to non-normality issues unless properly addressed(Xing et al., 2018). There continues to this day, a long standing debate regarding whether or not to consider variables collected via Likert scales with five response options as continuous/normal variables, so long as the data meets three criteria: there is missing data; sample size if small (N < 50); and if there are more than five response options(Xing et al., 2018;Epskamp, 2020; Newsom, 2023d).

An ordinal SEM model application makes use of an intermediate latent continuous variable y_1^*. This method is a threshold model, with the assumption that underlying the ordinal categorical data response, there is a latent continuous variable (respondents are forced to choose one response that fits within the Likert scale given)(Muthén, 1984). The Weighted Least Squares Mean and Variance adjusted (WLSMV) estimation method used creates a matrix of polychoric correlations, which estimate the value of the association between two continuous, normally distributed variables if they had been converted to ordinal observed variables (Newsom, 2023d). This matrix is represented as **S**. The assumption is that y_1^* is normally distributed and thus allows y_1 to be an ordinal observed variable, allowing for the different thresholds to be noted (e.g. c = 1 = "Very unsafe"). In the estimation process, the polychoric correlations are used to create an asymptotic covariance matrix that serves as the weight matrix for the WLS estimation. The resulting path estimates represent the change in y^* on a standardized z scale for each unit change in the predictor(Newsom, 2023d). Equations D.7 and D.8 represent the theoretical equations of the model. These equations are split into a measurement model component (Equation D.7), where η is the set of latent variables; ϵ is a vector of indicator residuals; Λ is a matrix of factor loadings relating indicators to latent variables; and $\mathbf{v}$ is a vector of indicator intercepts. The link between the two equations is that the structural component of the model allows η latent variables to affect each others whilst in the measurement model, those latent variables make up a linear function with the indicator variables y (Jorgensen & Johnson, 2022). The structural model (Equation D.8) consists of $\mathbf{a}$ which is a vector of latent variable intercepts; ζ is a vector of latent variable residuals; and B is a matrix of linear regression slops relating the latent variables together.

$$y = \mathbf{v} + \Lambda\eta + \epsilon \tag{D.7}$$

$$\eta = \mathbf{a} + B\eta + \zeta \tag{D.8}$$

$$X = c \text{if} \tau_c < Y \leq \tau_{c+1} \tag{D.9}$$

In addition, equation D.9 denotes the threshold model that is appended to this SEM model in order to link the observed discrete response x with a normally distributed latent response variable, y (Jorgensen & Johnson, 2022), with C thresholds that form boundaries around the contiguous regions of a normal distribution. The example of this research is that there is a scale of 5 categories (e.g. 1=very unsafe, 2=unsafe, 3=neutral, 4=safe, 5=very safe) which means that there are $C = 4$ thresholds. This ordinal SEM model must be correctly specified in order to take into account the random effects associated across individuals but also correctly estimate a model given that each respondent sees the same eight roundabouts and ranks them based on their comfort and safety levels. A probit link function will be used to relate the latent variables to the observed ordinal responses from the indicator questions. The roundabout characteristics are included as covariates as they are predictors of the latent variables: perceptions of safety and comfort level. However this form of ordinal SEM models need multiple indicator variables for comfort and safety in order for the model to create polychoric correlations with the intermediate latent variables y_X^*. Due to lack of time allocated to this research, only 1 indicator variable per latent variable (safety and comfort) will be used and thus a Pearson product-moment correlation matrix will be used. More information regarding the modeling process can be found in Appendix D.

D.6.2. Ordinal SEM Model for this research

A path diagram is created in order to test the hypotheses raised in the beginning of Chapter 3, but modified to account for model simplification. Notably, the 12 responses related to the bicycling behaviours were averaged within the three categories: errors, violations, and positive attitudes, resulting in the removal of the latent bicycling behaviour variable. The graphical software, AMOS is used in order to draw a conceptual model, as shown in Figure D.12. The dependent variables are shown in rectangles whilst the latent variables are shown in ovals. Note that there are error terms for the questions directly related to the two latent variables that form the focus on this research. The mathematical formula for the Ordinal SEM model is:

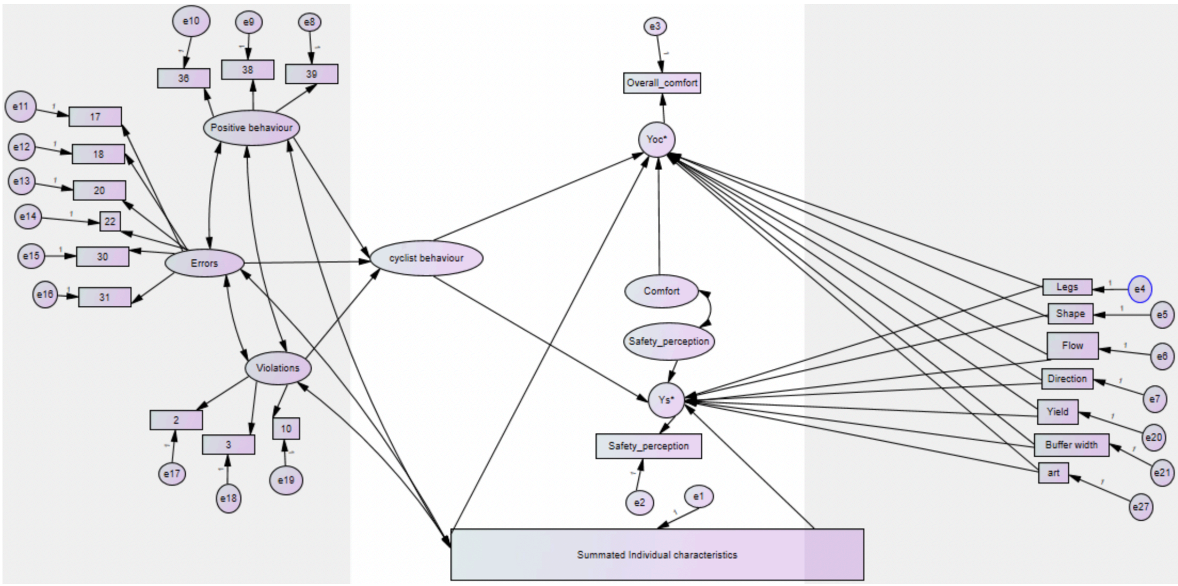


Figure D.12: SEM Path Diagram showing measured and latent variables. Please refer to Table 4.4 for the legend of the numbered measured variables that comprise the CBQ.

Measurement models

$$\begin{aligned} latent\_comfort = {} & indicator_1 + indicator_2 + indicator_3 \\ & + indicator_4 + indicator_5 + indicator_6 \\ & + indicator_7 + indicator_8 \end{aligned} \tag{D.10}$$

$$\begin{aligned} latent\_safety = {} & indicator_1 + indicator_2 + indicator_3 \\ & + indicator_4 + indicator_5 + indicator_6 \\ & + indicator_7 + indicator_8 \end{aligned} \tag{D.11}$$

Structural model

$$\begin{aligned} latent\_comfort = latent\_safety \quad = \\ & Separation\_from\_Vehicle\_Lane + bicycle\_Yielding\_Priority \\ & + Art\_Ads\_in\_Center + Uni\_Directional + bicycle\_Volumes + \\ & Facility\_Style + 4\_Legged + Walk_{freq} + Bike_{freq} + \\ & Ebike_{freq} + Cargobike_{freq} + Specialbike_{freq} + \\ & Scooter_{freq} + Car_{freq} + Public\_Transport_{freq} + \\ & Education + Income + Age + Skill\_level + Crash\_history + Gender \end{aligned} \tag{D.12}$$

D.6.3. Model performance

In order to test the goodness of fit, validate the model, and ensure the correct variable type assignment WLSMV may be used if there is enough data collected (minimum of 200 complete responses but on average 500 or more are recommended). The WLSMV method uses a pairwise deletion estimation, thus it may not work well if there is missing data (Newsom, 2023d). Equation D.13 shows the estimation formula with **S** being the observed covariance matrix and σ representing the factorized form of Σ, the covariance matrix implied by the model (Epskamp, 2020):

$$F_{WLS} = (\mathbf{s} - \sigma)^T \mathbf{W}^{-1} (\mathbf{s} - \sigma) \tag{D.13}$$

where the **W** is a weights matrix that allows the researcher to place a higher importance on certain differences versus others ($\mathbf{s} - \sigma$)(Muthén, 1984). The concern with categorical data is that the use of ML estimation, then there would be moderate to severe underestimation of the standard errors of the parameter estimates and one would have a spuriously inflated model χ^2 values(Xing et al., 2018). The ordinal SEM model will use WLSMV estimation method.

There are additional ways to test for model convergence, including the following:

- R-hat (Potential Scale Reduction Factor): Values close to 1 indicate good convergence. Values above 1.05 suggest problems with convergence.
- Bulk_ESS (Effective Sample Size for Bulk Tails): Indicates the effective number of independent samples for estimating means. Higher values are better.
- Tail_ESS (Effective Sample Size for Tails): Indicates the effective number of independent samples for estimating tail quantiles. Higher values are better.
- Trace Plots: Visual inspection of trace plots for each parameter to check if the chains have mixed well.
- Posterior Predictive Checks: Use the 'pp_check' function to compare the predicted values from your model to the observed data.
- A correlation matrix can be created to check how much one variable impacts another. If the coefficient value is closer to -1 or 1, then it can be considered a strong correlation. The hypothesis of this research is that there is a strong correlation between the two dependent variables.

Nested Tests
In order to use a likelihood ratio test with an Ordinal SEM model, a scaling correction factor must be used in order to have robust estimation using the WLSMV method(Newsom, 2023d). For the chi-square test, a second-order test can be used to approximate the chi-square distribution's mean and variance by using an estimated degrees of freedom (Newsom, 2023c). However it is only available in the Mplus software program which was not accessible for this research and thus not performed.

D.6.4. Ordinal SEM model run attempts and results

All categorical variables had to be transformed into factors for the models to read the data in those variables(Libraries, 2024) and the variables had different factor levels, ranging from 3 to 5. The amount of variables acquired during this research, meant that there was alot of model changes/edits that were needed before a functioning model could be run using R studio. Initially, the issue was that the library 'lavaan' doesn't allow for categorical variables to be computed directly if they are over two levels. Unfortunately that meant that all of the categorical variables (education, income, gender, self-ascribed bicycling skill level, and crash history) had to be modified to have dummy variables in order for that library to be able to read the variable. This would have resulted in a loss of data as one of the categories gets replaced with a dummy (it avoids multicollinearity).

The next issue arose due to the fact that the data is comprised of binary variables (the roundabout characteristics), categorical variables, the age variable being a continuous variable, and the rest are ordinal (mode and frequency questions, CBQ questions, and the roundabout indicator questions on perceptions of safety and comfort). Then due to having a panel data set, a multilevel SEM (also known as hierarchical SEM or latent growth modeling) had to be used so that the model knows to violate the independent observations assumption. A multi-level SEM was created, with level one being the within-individual variability and the level two being the between-individual variability. A column in the data set called 'ResponseID' was used to account for the panel structure. An issue arose with the 'lavaan' library as it is not currently able to support a mix of categorical variables and a multi-level SEM model (which is needed due to the panel dataset). Since Mplus software was not available for this research, another solution had to be undertaken.

An attempt was made to use IBM's AMOS program to look at the SEM model; however the program can't do a weighted squares estimation (it is only capable of maximum likelihood, unweighted least squares, generalized least squares, scale-free least squares, Bayesian estimation, and Browne's asymptotically distribution-free criterion)(Arbuckle, 2022) either. A Bayesian multi-level model was then used as it can handle the different variable types present. A cumulative logit formulation was chosen as the hypothesis is that it best fits the dataset (with a majority ordinal data). It required that the number of iterations was 4000 and that the other parameters were adjusted to overcome the following: divergent transitions, exceeded maximum treedepth, and low effective sample size (ESS). An effort was done to check for any priors and to further simplify the model by checking for multicollinearity and only keeping the strongest predictors but no priors were found from past literature. In total this model was run 12 times with different variable combinations and the average computational time was 12 hours per run.

The results of the Ordinal SEM model are shown below in the matrix of responses:

Table D.3: Comfort dependent variable ordinal SEM model results

			Comfort				
Parameter	**Estimate**	**Est.Error**	**l-95% CI**	**u-95% CI**	**Rhat**	**Bulk_ESS**	**Tail_ESS**
sd(Intercept)	73.86	9.59	57.40	94.83	1.00	9419	6433
Intercept[1]	-97.20	33.33	-166.85	-36.76	1.00	8183	6990
Intercept[2]	-66.38	29.58	-126.59	-10.39	1.00	8680	6447
Intercept[3]	-52.21	28.61	-109.89	2.20	1.00	8627	6418
Intercept[4]	-40.75	27.99	-96.55	12.89	1.00	9039	6364
Intercept[5]	-10.02	27.03	-61.96	43.31	1.00	9083	5979
Intercept[6]	7.42	27.03	-44.73	61.92	1.00	8966	6101
Intercept[7]	23.18	27.19	-28.97	78.44	1.00	9129	6030
Intercept[8]	37.66	27.36	-13.71	93.24	1.00	9091	5973
Intercept[9]	51.30	27.66	-0.59	107.23	1.00	9069	5940
Intercept[10]	67.11	28.01	15.47	124.68	1.00	8976	5988
Intercept[11]	81.82	28.50	29.08	141.15	1.00	8810	6059
Intercept[12]	93.31	28.86	40.33	154.20	1.00	8743	5984
Intercept[13]	102.72	29.14	49.72	164.35	1.00	8614	5917
Intercept[14]	112.74	29.66	59.31	175.31	1.00	8515	6107
Intercept[15]	122.98	30.27	69.11	186.89	1.00	8407	5894
Intercept[16]	132.06	30.76	77.00	197.45	1.00	8353	6009
Intercept[17]	142.06	31.34	86.08	209.20	1.00	8222	6130
Intercept[18]	155.15	32.23	98.06	225.17	1.00	8174	5914
Intercept[19]	172.48	33.48	113.52	245.12	1.00	7826	5689
Intercept[20]	185.46	34.42	124.86	259.44	1.00	7720	5613
Intercept[21]	198.86	35.58	136.41	275.16	1.00	7764	5400
Intercept[22]	205.48	36.05	143.08	282.97	1.00	7783	5513
Intercept[23]	218.07	37.16	154.16	297.48	1.00	7733	5701
Intercept[24]	229.90	38.24	163.92	313.56	1.00	7703	5675
Intercept[25]	259.36	41.98	187.06	350.03	1.00	7418	6243
Facility Style 1	-0.00	0.26	-0.51	0.50	1.00	9012	5410
Bicycle usage– 2 to 4 days per month	4.21	24.83	-44.26	53.97	1.00	8786	4912
Bicycle usage– 2 to 4 days per week	29.87	21.33	-11.33	71.73	1.00	8589	5064

Parameter	Estimate	Est.Error	l-95% CI	u-95% CI	Rhat	Bulk_ESS	Tail_ESS
Bicycle usage– 4 to 6 days per week	36.64	21.48	-4.27	80.72	1.00	7946	4868
Bicycle usage– everyday	72.50	22.43	31.18	119.53	1.00	7995	5658
Education–high school	17.83	21.14	-23.58	60.77	1.00	9102	5909
Education–bachelors degree	17.56	20.80	-22.70	59.36	1.00	9422	5794
Education–Masters degree	25.06	47.64	-66.27	119.99	1.00	10439	6216
Gender–Male	-2.84	11.68	-26.04	20.21	1.00	7470	5691
Gender–Female	69.30	107.43	-138.60	282.09	1.00	8976	6502
Gender–Non binary	34.03	76.52	-116.51	187.76	1.00	9324	5857
Recent crashes-Yes	58.59	18.14	25.01	96.65	1.00	8362	5309
Recent crashes-No	-135.80	119.76	-377.12	97.34	1.00	9679	6541
Violations	-5.51	9.49	-24.35	12.91	1.00	7982	5419
Errors	3.18	11.58	-19.33	25.87	1.00	9149	4922
Positive Behaviour	18.31	9.43	0.30	37.44	1.00	7517	4811

Table D.4: Safety dependent variable ordinal SEM model results

			Perception	of safety			
Parameter	**Estimate**	**Est.Error**	**l-95% CI**	**u-95% CI**	**Rhat**	**Bulk_ESS**	**Tail_ESS**
Intercept[1]	-120.14	32.57	-191.47	-63.82	1.00	8227	6564
Intercept[2]	-95.11	28.03	-154.80	-44.97	1.00	8076	5915
Intercept[3]	-73.85	25.47	-127.49	-26.22	1.00	7854	5710
Intercept[4]	-62.73	24.73	-114.50	-16.83	1.00	7826	5471
Intercept[5]	-50.40	23.95	-99.84	-4.99	1.00	7792	5454
Intercept[6]	-35.98	23.24	-83.39	8.56	1.00	7761	5681
Intercept[7]	-19.79	22.72	-64.85	24.93	1.00	7723	5800
Intercept[8]	0.23	22.48	-43.37	45.30	1.00	7743	5781
Intercept[9]	11.88	22.52	-31.04	58.03	1.00	7647	5736
Intercept[10]	25.38	22.69	-17.23	71.92	1.00	7625	5913
Intercept[11]	35.93	22.80	-6.79	83.42	1.00	7613	5803
Intercept[12]	48.27	23.00	5.95	96.37	1.00	7639	5966
Intercept[13]	56.98	23.14	14.21	105.67	1.00	7591	5785
Intercept[14]	69.17	23.72	25.75	119.59	1.00	7598	5719
Intercept[15]	80.76	24.34	36.69	132.56	1.00	7538	5719
Intercept[16]	93.02	25.01	48.34	146.60	1.00	7542	5836

Parameter	Estimate	Est.Error	l-95% CI	u-95% CI	Rhat	Bulk_ESS	Tail_ESS
Intercept[17]	105.31	25.73	59.33	160.69	1.00	7439	5912
Intercept[18]	126.22	27.22	78.14	185.34	1.00	7324	6017
Intercept[19]	135.57	27.86	86.80	196.14	1.00	7315	5978
Intercept[20]	149.57	28.89	99.02	213.36	1.00	7214	6030
Intercept[21]	168.22	30.68	114.73	236.04	1.00	7328	6171
Intercept[22]	176.96	31.48	122.60	246.59	1.00	7371	5927
Intercept[23]	192.48	33.32	135.13	265.00	1.00	7490	5899
Intercept[24]	208.17	35.42	147.31	286.92	1.00	7936	6218
Intercept[25]	233.27	40.25	164.98	322.15	1.00	8128	5893
Facility Style 1	0.00	0.25	-0.50	0.50	1.00	8955	5329
Bicycle usage– 2 to 4 days per month	3.08	21.43	-37.98	45.30	1.00	8244	5486
Bicycle usage– 2 to 4 days per week	17.84	17.98	-16.66	54.25	1.00	7285	5579
Bicycle usage– 4 to 6 days per week	18.53	17.68	-14.78	54.73	1.00	6654	5362
Bicycle usage– Everyday	37.58	18.10	3.31	74.38	1.00	7450	5532
Education–high school	14.94	17.72	-19.52	50.68	1.00	8949	5043
Education–bachelors degree	-4.64	16.80	-38.60	28.35	1.00	8205	5595
Education–Masters degree	0.61	39.46	-76.81	78.46	1.00	10920	6182
Gender-Male	1.51	10.05	-18.39	21.16	1.00	6735	5686
Gender-Female	96.01	89.06	-74.62	275.37	1.00	841	
Gender–Non binary	77.94	65.66	-49.63	208.69	1.00	10016	6093
Recent crashes-Yes	36.2	14.77	9.09	66.35	1.00	8109	5497
Recent crashes-No	-87.45	99.24	-284.67	101.2	1.00	9930	6472
Violations	-2.37	8.11	-18.72	13.74	1.00	7465	5594
Errors	-1.89	9.58	-20.79	16.94	1.00	7806	5302
Positive behaviour	5.54	7.64	-9.48	20.42	1.00	7181	5402

Table D.5: Bayesian Ordinal SEM model Correlation Matrix

									Safety	latent	variable									
	b_Intercept[1]	b_Intercept[2]	b_Intercept[3]	b_Intercept[4]	b_Intercept[5]	b_Intercept[6]	b_Intercept[7]	b_Intercept[8]	b_Intercept[9]	b_Intercept[10]	b_Intercept[11]	b_Intercept[12]	b_Intercept[13]	b_Intercept[14]	b_Intercept[15]	b_Intercept[16]	b_Intercept[17]	b_Intercept[18]	b_Intercept[19]	b_Intercept[20]
b_Intercept[1]	-0.0112	-0.0157	-0.0119	-0.0147	-0.0188	-0.0210	-0.0224	-0.0239	-0.0224	-0.0247	-0.0239	-0.0247	-0.0249	-0.0245	-0.0255	-0.0238	-0.0238	-0.0206	-0.0173	-0.0158
b_Intercept[2]	-0.0189	-0.0203	-0.0184	-0.0195	-0.0225	-0.0222	-0.0229	-0.0227	-0.0201	-0.0214	-0.0205	-0.0204	-0.0206	-0.0202	-0.0204	-0.0195	-0.0187	-0.0155	-0.0123	-0.0109
b_Intercept[3]	-0.0161	-0.0169	-0.0150	-0.0146	-0.0169	-0.0162	-0.0170	-0.0174	-0.0151	-0.0156	-0.0148	-0.0144	-0.0147	-0.0144	-0.0148	-0.0137	-0.0134	-0.0095	-0.0069	-0.0055
b_Intercept[4]	-0.0177	-0.0181	-0.0149	-0.0141	-0.0164	-0.0156	-0.0152	-0.0150	-0.0126	-0.0131	-0.0120	-0.0113	-0.0115	-0.0113	-0.0117	-0.0106	-0.0106	-0.0066	-0.0040	-0.0025
b_Intercept[5]	-0.0183	-0.0168	-0.0161	-0.0149	-0.0177	-0.0164	-0.0153	-0.0146	-0.0118	-0.0117	-0.0117	-0.0114	-0.0119	-0.0119	-0.0130	-0.0122	-0.0122	-0.0096	-0.0074	-0.0056
b_Intercept[6]	-0.0152	-0.0136	-0.0151	-0.0143	-0.0173	-0.0157	-0.0149	-0.0139	-0.0114	-0.0107	-0.0108	-0.0106	-0.0109	-0.0106	-0.0115	-0.0110	-0.0110	-0.0086	-0.0063	-0.0050
b_Intercept[7]	-0.0122	-0.0118	-0.0143	-0.0137	-0.0169	-0.0157	-0.0140	-0.0128	-0.0104	-0.0094	-0.0100	-0.0097	-0.0098	-0.0094	-0.0103	-0.0099	-0.0099	-0.0077	-0.0053	-0.0040
b_Intercept[8]	-0.0116	-0.0114	-0.0133	-0.0127	-0.0156	-0.0145	-0.0133	-0.0120	-0.0098	-0.0088	-0.0094	-0.0094	-0.0097	-0.0094	-0.0103	-0.0099	-0.0101	-0.0081	-0.0059	-0.0049
b_Intercept[9]	-0.0126	-0.0128	-0.0153	-0.0147	-0.0173	-0.0158	-0.0148	-0.0137	-0.0115	-0.0104	-0.0109	-0.0108	-0.0112	-0.0114	-0.0117	-0.0110	-0.0113	-0.0089	-0.0069	-0.0058
b_Intercept[10]	-0.0120	-0.0116	-0.0151	-0.0143	-0.0170	-0.0160	-0.0152	-0.0138	-0.0117	-0.0105	-0.0111	-0.0112	-0.0115	-0.0116	-0.0116	-0.0113	-0.0114	-0.0094	-0.0073	-0.0062
b_Intercept[11]	-0.0112	-0.0112	-0.0156	-0.0151	-0.0184	-0.0174	-0.0167	-0.0154	-0.0132	-0.0118	-0.0123	-0.0124	-0.0128	-0.0124	-0.0126	-0.0122	-0.0124	-0.0101	-0.0079	-0.0069
b_Intercept[12]	-0.0112	-0.0111	-0.0153	-0.0146	-0.0174	-0.0164	-0.0157	-0.0145	-0.0123	-0.0109	-0.0115	-0.0117	-0.0119	-0.0115	-0.0120	-0.0115	-0.0116	-0.0094	-0.0072	-0.0063
b_Intercept[13]	-0.0114	-0.0110	-0.0150	-0.0143	-0.0170	-0.0159	-0.0154	-0.0141	-0.0117	-0.0104	-0.0110	-0.0112	-0.0114	-0.0112	-0.0113	-0.0109	-0.0110	-0.0085	-0.0064	-0.0058
b_Intercept[14]	-0.0110	-0.0107	-0.0145	-0.0138	-0.0167	-0.0158	-0.0152	-0.0137	-0.0114	-0.0100	-0.0106	-0.0108	-0.0110	-0.0104	-0.0110	-0.0103	-0.0103	-0.0079	-0.0057	-0.0051
b_Intercept[15]	-0.0121	-0.0122	-0.0159	-0.0152	-0.0179	-0.0167	-0.0158	-0.0143	-0.0117	-0.0104	-0.0109	-0.0110	-0.0112	-0.0111	-0.0113	-0.0105	-0.0104	-0.0080	-0.0059	-0.0051
b_Intercept[16]	-0.0120	-0.0123	-0.0160	-0.0153	-0.0181	-0.0172	-0.0163	-0.0145	-0.0125	-0.0113	-0.0119	-0.0120	-0.0122	-0.0112	-0.0125	-0.0116	-0.0115	-0.0089	-0.0069	-0.0062
b_Intercept[17]	-0.0118	-0.0117	-0.0146	-0.0139	-0.0169	-0.0159	-0.0149	-0.0136	-0.0112	-0.0101	-0.0107	-0.0110	-0.0112	-0.0107	-0.0114	-0.0107	-0.0106	-0.0083	-0.0062	-0.0056
b_Intercept[18]	-0.0114	-0.0109	-0.0141	-0.0138	-0.0167	-0.0158	-0.0149	-0.0137	-0.0113	-0.0102	-0.0110	-0.0115	-0.0116	-0.0111	-0.0112	-0.0111	-0.0111	-0.0089	-0.0069	-0.0063
b_Intercept[19]	-0.0121	-0.0110	-0.0153	-0.0149	-0.0178	-0.0169	-0.0165	-0.0133	-0.0115	-0.0103	-0.0134	-0.0118	-0.0134	-0.0129	-0.0122	-0.0112	-0.0107	-0.0103	-0.0085	-0.0078
b_Intercept[20]	-0.0107	-0.0101	-0.0141	-0.0140	-0.0168	-0.0156	-0.0153	-0.0240	-0.0224	-0.0247	-0.0239	-0.0247	-0.0249	-0.0117	-0.0122	-0.0114	-0.0113	-0.0091	-0.0075	-0.0068
b_Intercept[21]	-0.0114	-0.0095	-0.0133	-0.0131	-0.0157	-0.0143	-0.0137	-0.0120	-0.0101	-0.0083	-0.0092	-0.0096	-0.0098	-0.0089	-0.0093	-0.0086	-0.0084	-0.0062	-0.0044	-0.0032
b_Intercept[22]	-0.0114	-0.0090	-0.0131	-0.0133	-0.0159	-0.0141	-0.0136	-0.0117	-0.0097	-0.0078	-0.0088	-0.0090	-0.0092	-0.0083	-0.0087	-0.0077	-0.0076	-0.0056	-0.0037	-0.0024
b_Intercept[23]	-0.0100	-0.0080	-0.0116	-0.0108	-0.0133	-0.0117	-0.0111	-0.0096	-0.0075	-0.0056	-0.0066	-0.0068	-0.0069	-0.0058	-0.0062	-0.0051	-0.0051	-0.0035	-0.0016	-0.0008
b_Intercept[24]	-0.0077	-0.0058	-0.0096	-0.0088	-0.0117	-0.0102	-0.0097	-0.0087	-0.0065	-0.0048	-0.0061	-0.0067	-0.0070	-0.0063	-0.0068	-0.0059	-0.0058	-0.0041	-0.0022	-0.0015
b_Intercept[25]	-0.0046	-0.0021	-0.0081	-0.0083	-0.0100	-0.0084	-0.0078	-0.0071	-0.0056	-0.0044	-0.0053	-0.0061	-0.0063	-0.0060	-0.0064	-0.0059	-0.0055	-0.0038	-0.0021	-0.0012
b_Facility Style 1	-0.0089	-0.0056	-0.0049	-0.0083	-0.0159	-0.0147	-0.0179	-0.0172	-0.0176	-0.0162	-0.0166	-0.0154	-0.0152	-0.0164	-0.0142	-0.0144	-0.0158	-0.0137	-0.0148	-0.0147
b_(bike)-2-4 days per month	-0.0072	-0.0105	-0.0169	-0.0161	-0.0133	-0.0150	-0.0140	-0.0083	-0.0090	-0.0074	-0.0077	-0.0073	-0.0072	-0.0088	-0.0088	-0.0096	-0.0095	-0.0087	-0.0083	-0.0080
b_(bike)-2-4 days per week	-0.0154	-0.0166	-0.0183	-0.0141	-0.0123	-0.0114	-0.0110	-0.0082	-0.0087	-0.0086	-0.0102	-0.0102	-0.0103	-0.0088	-0.0091	-0.0087	-0.0094	-0.0070	-0.0078	-0.0081
b_(bike)-4-6 days per week	-0.0211	-0.0205	-0.0218	-0.0186	-0.0164	-0.0156	-0.0165	-0.0152	-0.0167	-0.0176	-0.0184	-0.0187	-0.0178	-0.0181	-0.0191	-0.0192	-0.0183	-0.0175	-0.0173	-0.0164
b_(bike)-Everyday	-0.0145	-0.0162	-0.0212	-0.0183	-0.0155	-0.0136	-0.0121	-0.0106	-0.0103	-0.0103	-0.0107	-0.0120	-0.0127	-0.0133	-0.0140	-0.0139	-0.0143	-0.0122	-0.0115	-0.0119
b_Q33	0.0099	0.0043	0.0041	0.0024	-0.0027	-0.0014	-0.0011	-0.0001	0.0013	0.0009	0.0007	0.0007	0.0012	0.0006	-0.0003	-0.0014	-0.0017	0.0019	0.0048	0.0026
b_Q34	0.0089	0.0068	0.0042	0.0050	0.0000	0.0026	0.0054	0.0046	0.0060	0.0056	0.0051	0.0054	0.0057	0.0069	0.0060	0.0053	0.0053	0.0070	0.0083	0.0049
b_Q35	0.0047	0.0068	0.0076	0.0056	0.0004	0.0007	0.0018	0.0012	0.0026	0.0022	0.0014	-0.0005	-0.0014	-0.0011	-0.0024	-0.0033	-0.0037	-0.0025	-0.0016	-0.0065
b_Q62	0.0063	0.0086	0.0068	0.0058	0.0028	0.0033	0.0026	0.0026	0.0030	0.0039	0.0029	0.0017	0.0014	0.0009	0.0011	0.0014	0.0005	-0.0014	-0.0014	0.0009
b_Q63	0.0059	0.0020	-0.0074	-0.0081	-0.0139	-0.0158	-0.0147	-0.0189	-0.0175	-0.0191	-0.0195	-0.0193	-0.0190	-0.0184	-0.0186	-0.0190	-0.0188	-0.0195	-0.0211	-0.0239
b_Q65	-0.0092	-0.0087	-0.0050	-0.0014	-0.0050	-0.0063	-0.0077	-0.0101	-0.0141	-0.0131	-0.0132	-0.0152	-0.0156	-0.0171	-0.0185	-0.0200	-0.0222	-0.0235	-0.0228	-0.0240
b_Q332	-0.0165	-0.0106	-0.0117	-0.0123	-0.0121	-0.0136	-0.0134	-0.0128	-0.0106	-0.0081	-0.0075	-0.0066	-0.0073	-0.0059	-0.0053	-0.0037	-0.0030	-0.0026	-0.0016	0.0033
b_Q333	0.0093	0.0019	-0.0046	-0.0033	-0.0024	-0.0036	-0.0032	0.0009	0.0048	0.0048	0.0057	0.0079	0.0092	0.0095	0.0128	0.0136	0.0135	0.0144	0.0144	0.0174
b_Violations	0.0192	0.0185	0.0211	0.0243	0.0175	0.0126	0.0119	0.0119	0.0095	0.0096	0.0077	0.0054	0.0041	0.0005	-0.0001	-0.0014	-0.0024	-0.0098	-0.0099	-0.0066
b_Errors	-0.0192	-0.0159	-0.0099	-0.0107	-0.0019	0.0021	0.0025	0.0075	0.0080	0.0101	0.0114	0.0141	0.0154	0.0171	0.0182	0.0192	0.0201	0.0230	0.0243	0.0265
b_Positive behaviour	0.0043	0.0009	0.0048	0.0079	0.0108	0.0108	0.0101	0.0135	0.0141	0.0158	0.0154	0.0132	0.0116	0.0109	0.0102	0.0089	0.0078	0.0047	0.0057	0.0062

	b_Intercept[21]	b_Intercept[22]	b_Intercept[23]	b_Intercept[24]	b_Intercept[25]	b_Facility Style 1	b_Q2322	b_Q2323	b_Q2324	b_Q2325	b_Q33	b_Q34	b_Q35	b_Q62	b_Q63	b_Q65	b_Q332	b_Q333	b_Violations	b_Errors	b_Positive behaviour
b_Intercept[1]	-0.0167	-0.0145	-0.0151	-0.0210	-0.0143	-0.0089	-0.0072	-0.0154	-0.0211	-0.0145	0.0099	0.0089	0.0047	0.0063	0.0059	-0.0092	-0.0165	0.0093	0.0016	-0.0063	0.0172
b_Intercept[2]	-0.0108	-0.0095	-0.0091	-0.0136	-0.0086	-0.0056	-0.0105	-0.0166	-0.0205	-0.0162	0.0043	0.0068	0.0068	0.0086	0.0020	-0.0087	-0.0106	0.0019	-0.0016	-0.0099	0.0226
b_Intercept[3]	-0.0062	-0.0049	-0.0046	-0.0090	-0.0045	-0.0049	-0.0169	-0.0183	-0.0218	-0.0212	0.0041	0.0042	0.0076	0.0068	-0.0074	-0.0050	-0.0117	-0.0046	-0.0016	-0.0101	0.0219
b_Intercept[4]	-0.0022	-0.0009	-0.0010	-0.0055	-0.0011	-0.0083	-0.0161	-0.0141	-0.0186	-0.0183	0.0024	0.0050	0.0056	0.0058	-0.0081	-0.0014	-0.0123	-0.0033	0.0006	-0.0129	0.0210
b_Intercept[5]	-0.0064	-0.0054	-0.0054	-0.0087	-0.0068	-0.0147	-0.0133	-0.0123	-0.0165	-0.0155	-0.0027	-0.0013	0.0004	0.0028	-0.0139	-0.0047	-0.0152	-0.0086	-0.0010	-0.0069	0.0145
b_Intercept[6]	-0.0060	-0.0053	-0.0045	-0.0064	-0.0039	-0.0179	-0.0150	-0.0114	-0.0161	-0.0136	-0.0014	0.0026	0.0007	0.0033	-0.0158	-0.0063	-0.0136	-0.0110	0.0002	-0.0063	0.0135
b_Intercept[7]	-0.0046	-0.0047	-0.0037	-0.0051	-0.0046	-0.0190	-0.0140	-0.0110	-0.0165	-0.0121	-0.0011	0.0054	0.0018	-0.0001	-0.0147	-0.0077	-0.0125	-0.0087	-0.0020	-0.0064	0.0129
b_Intercept[8]	-0.0060	-0.0063	-0.0057	-0.0071	-0.0059	-0.0239	-0.0120	-0.0133	-0.0217	-0.0183	-0.0025	0.0028	0.0028	0.0005	-0.0193	-0.0125	-0.0145	-0.0097	-0.0027	-0.0067	0.0095
b_Intercept[9]	-0.0068	-0.0071	-0.0066	-0.0075	-0.0073	-0.0224	-0.0201	-0.0214	-0.0218	-0.0205	-0.0060	0.0060	0.0026	0.0039	-0.0191	-0.0198	-0.0116	0.0048	-0.0013	-0.0071	0.0088
b_Intercept[10]	-0.0072	-0.0077	-0.0072	-0.0072	-0.0078	-0.0247	-0.0205	-0.0214	-0.0218	-0.0141	0.0009	0.0022	0.0010	0.0040	-0.0171	-0.0131	-0.0104	-0.0143	0.0005	-0.0072	0.0066
b_Intercept[11]	-0.0082	-0.0087	-0.0082	-0.0081	-0.0078	-0.0239	-0.0205	-0.0214	-0.0184	-0.0140	-0.0014	0.0054	0.0025	-0.0075	-0.0191	-0.0188	-0.0115	0.0098	0.0011	-0.0075	0.0052
b_Intercept[12]	-0.0080	-0.0088	-0.0086	-0.0080	-0.0079	-0.0247	-0.0204	-0.0204	-0.0184	-0.0128	-0.0018	0.0060	0.0012	-0.0071	-0.0193	-0.0193	-0.0112	0.0077	0.0019	-0.0064	0.0054
b_Intercept[13]	-0.0078	-0.0088	-0.0086	-0.0079	-0.0083	-0.0249	-0.0206	-0.0206	-0.0178	-0.0133	-0.0015	0.0056	0.0026	-0.0086	-0.0190	-0.0195	-0.0114	0.0092	0.0016	-0.0069	0.0042
b_Intercept[14]	-0.0071	-0.0082	-0.0080	-0.0067	-0.0073	-0.0245	-0.0202	-0.0202	-0.0181	-0.0132	0.0006	0.0069	-0.0011	0.0014	-0.0184	-0.0222	-0.0067	0.0095	0.0024	-0.0061	0.0045
b_Intercept[15]	-0.0072	-0.0082	-0.0083	-0.0069	-0.0069	-0.0255	-0.0204	-0.0207	-0.0191	-0.0128	0.0045	0.0060	-0.0024	0.0011	-0.0179	-0.0252	-0.0004	0.0179	0.0032	-0.0062	0.0041
b_Intercept[16]	-0.0085	-0.0094	-0.0093	-0.0078	-0.0079	-0.0238	-0.0195	-0.0198	-0.0200	-0.0174	0.0036	0.0053	-0.0065	0.0020	-0.0200	-0.0249	0.0011	0.0200	0.0033	-0.0070	0.0032
b_Intercept[17]	-0.0079	-0.0087	-0.0090	-0.0073	-0.0072	-0.0238	-0.0187	-0.0187	-0.0222	-0.0222	0.0060	0.0072	-0.0027	0.0020	-0.0173	-0.0229	0.0033	0.0189	0.0035	-0.0070	0.0024
b_Intercept[18]	-0.0088	-0.0097	-0.0099	-0.0084	-0.0082	-0.0206	-0.0155	-0.0154	-0.0235	-0.0209	0.0055	0.0086	-0.0034	0.0053	-0.0199	-0.0204	-0.0026	0.0172	0.0042	-0.0060	0.0015
b_Intercept[19]	-0.0103	-0.0113	-0.0113	-0.0096	-0.0098	-0.0173	-0.0123	-0.0123	-0.0237	-0.0233	0.0021	0.0060	-0.0084	0.0046	-0.0179	-0.0239	0.0026	0.0241	0.0038	-0.0075	0.0004
b_Intercept[20]	-0.0095	-0.0106	-0.0106	-0.0086	-0.0080	-0.0158	-0.0109	-0.0121	-0.0233	-0.0222	-0.0004	0.0068	-0.0031	0.0009	-0.0204	-0.0200	0.0040	0.0200	0.0043	-0.0073	0.0021
b_Intercept[21]	-0.0057	-0.0066	-0.0069	-0.0043	-0.0039	-0.0108	-0.0108	-0.0122	-0.0223	-0.0182	-0.0171	-0.0073	0.0013	-0.0160	0.0007	-0.0063	0.0048	0.0135	0.0069	-0.0081	0.0020
b_Intercept[22]	-0.0051	-0.0060	- -0.0064	-0.0038	-0.0034	-0.0086	-0.0090	-0.0107	-0.0212	-0.0186	-0.0158	-0.0098	-0.0027	-0.0118	0.0012	-0.0047	0.0039	0.0088	0.0067	-0.0084	0.0007
b_Intercept[23]	-0.0035	-0.0045	-0.0053	-0.0030	-0.0026	-0.0074	-0.0116	-0.0124	-0.0226	-0.0197	-0.0125	-0.0077	-0.0056	-0.0156	0.0010	-0.0074	0.0017	0.0020	0.0065	-0.0067	0.0008
b_Intercept[24]	-0.0044	-0.0054	-0.0057	-0.0028	-0.0030	-0.0084	-0.0117	-0.0122	-0.0213	-0.0171	-0.0182	-0.0061	-0.0055	-0.0155	0.0033	-0.0066	0.0031	0.0020	0.0031	-0.0063	0.0001
b_Intercept[25]	-0.0036	-0.0048	-0.0041	-0.0026	-0.0037	-0.0103	-0.0116	-0.0117	-0.0212	-0.0176	-0.0090	-0.0060	-0.0056	-0.0133	-0.0070	-0.0058	0.0045	0.0026	0.0025	-0.0094	-0.0006
b_Facility Style 1	-0.0157	-0.0145	-0.0099	-0.0106	-0.0110	0.0026	0.0130	0.0079	-0.0059	-0.0049	0.0117	0.0101	-0.0099	0.0063	0.0009	0.0053	-0.0039	0.0210	-0.0075	-0.0169	-0.0077
b_Q2322	-0.0070	-0.0068	-0.0045	-0.0113	-0.0113	0.0066	0.0077	0.0082	-0.0049	-0.0100	-0.0060	-0.0179	0.0012	0.0122	-0.0070	-0.0102	0.0044	-0.0008	-0.0086	-0.0060	0.0057
b_Q2323	-0.0107	-0.0110	-0.0120	-0.0136	-0.0162	-0.0092	0.0079	0.0063	0.0048	0.0010	-0.0154	-0.0186	0.0022	0.0131	-0.0069	-0.0047	0.0055	0.0179	-0.0030	0.0038	-0.0135
b_Q2324	-0.0182	-0.0210	-0.0232	-0.0233	-0.0237	0.0021	0.0162	0.0224	0.0186	0.0140	-0.0070	-0.0140	-0.0070	0.0211	0.0013	0.0029	0.0012	0.0034	0.0021	-0.0043	-0.0072
b_Q2325	-0.0153	-0.0174	-0.0183	-0.0170	-0.0176	-0.0098	0.0159	0.0188	0.0134	0.0158	-0.0075	-0.0050	-0.0030	0.0094	-0.0116	-0.0110	0.0046	0.0055	-0.0029	0.0075	-0.0132
b_Q33	0.0045	0.0051	0.0077	0.0039	0.0004	-0.0173	-0.0108	-0.0199	-0.0289	-0.0245	0.0117	0.0257	0.0116	-0.0173	-0.0158	-0.0098	-0.0073	0.0051	-0.0081	-0.0202	-0.0019
b_Q34	0.0068	0.0068	0.0069	0.0060	0.0048	-0.0082	-0.0152	-0.0259	-0.0256	-0.0178	0.0257	0.0302	0.0093	-0.0153	-0.0180	-0.0098	-0.0075	0.0128	-0.0112	-0.0122	-0.0061
b_Q35	-0.0062	-0.0071	-0.0048	-0.0034	-0.0084	0.0113	-0.0015	0.0005	0.0000	0.0023	-0.0086	-0.0061	-0.0160	0.0023	-0.0174	0.0012	0.0013	0.0148	0.0017	0.0113	-0.0160
b_Q62	0.0009	0.0020	0.0013	-0.0011	0.0023	0.0144	-0.0108	-0.0150	-0.0108	-0.0156	-0.0173	-0.0226	-0.0090	-0.0063	-0.0069	0.0010	0.0023	-0.0008	-0.0017	0.0125	0.0080
b_Q63	-0.0207	-0.0198	-0.0173	-0.0199	-0.0179	-0.0012	-0.0150	-0.0198	-0.0180	-0.0199	0.0030	0.0093	0.0012	-0.0069	-0.0120	-0.0150	0.0112	0.0127	0.0124	0.0194	-0.0120
b_Q65	-0.0252	-0.0249	-0.0229	-0.0204	-0.0239	0.0053	-0.0102	-0.0047	-0.0035	-0.0133	-0.0098	-0.0075	-0.0150	-0.0063	-0.0150	-0.0004	-0.0011	0.0241	0.0177	-0.0163	-0.0150
b_Q332	-0.0004	-0.0011	-0.0021	0.0018	0.0026	-0.0044	-0.0028	-0.0026	-0.0052	-0.0070	-0.0075	-0.0084	0.0012	0.0023	0.0112	0.0237	0.0182	0.0048	0.0169	0.0002	0.0237
b_Q333	0.0179	0.0200	0.0189	0.0172	0.0241	0.0148	-0.0152	-0.0075	-0.0106	-0.0097	0.0051	0.0128	0.0054	-0.0008	0.0127	0.0241	0.0179	0.0148	-0.0197	0.0104	0.0148
b_Violations	-0.0055	-0.0053	-0.0080	-0.0070	-0.0095	-0.0075	-0.0086	-0.0048	0.0021	-0.0029	-0.0081	-0.0112	-0.0067	0.0022	0.0124	0.0177	-0.0017	0.0005	0.0097	0.0005	0.0130
b_Errors	0.0261	0.0241	0.0223	0.0234	0.0235	-0.0169	-0.0060	0.0038	-0.0043	0.0075	-0.0202	-0.0122	0.0113	0.0125	0.0194	-0.0163	0.0002	0.0104	-0.0087	-0.0082	0.0112
b_Positive behaviour	0.0075	0.0077	0.0044	0.0059	0.0026	-0.0077	0.0177	-0.0135	-0.0072	-0.0132	-0.0019	-0.0061	-0.0160	0.0080	-0.0120	-0.0150	0.0237	0.0148	-0.0047	-0.0018	0.0038

The correlation matrix, shows the comparison of the two latent variables and their respective intercepts and independent variables. On the Y axis are the variables for the Comfort latent variable. The highest correlation between the two dependent variables was 0.0265, for CBQ errors group variable of the Comfort latent variable and the CBQ Positive behaviour group of the Safety dependent variable. Both these values is not close to 1 or -1, so it is shows that there is only weak correlations between the two dependent variables. This contradicts this researches hypothesis, past research, and the results of the ordered probit model stated in Section 6.4.

E

R psuedo code

E.1. Model program

This research used the program R Studio and the programming language R in order to run the random effects ordered probit model. The libraries **mvord** and **mvordflex** were used since they were developed in 2020 and 2024 respectively for the purpose of fitting multivariate ordinal regression models (Hirk et al., 2020; Vana-Gür, 2024a; Vana-Gür, 2024b). The more recent library, **mvordflex**, can even make use of multiple repeated measurements, thus looking at longitudinal data sets. The data set that was collected for this research was cross-sectional but it was in a panel format since each respondent gave their perception of safety and comfort for eight different roundabout locations. For the pseudo code, please see the Sections below.

E.2. Multicollinearity check

Import Packages

```
# Import necessary libraries
Load libraries: dplyr, caret, corrplot, polycor, vcd, ggplot2
```

Load Data

```
# Load the data
Set data_path to the CSV file location
Read CSV file into safety_comfort_full
```

Inspect Data

```
# Inspect the structure and summary of the data
Display the structure of safety_comfort_full
Display the summary of safety_comfort_full
```

Data Pre-processing

```
# Convert Q5 to numeric
Convert Q5 to numeric
# Optional: Normalize Q5 using z-score (if needed)
# Create Age_Category by categorizing Q5 into age groups
Convert Age_Category to a factor
# Drop the original Q5 variable
Drop Q5
```

Create Variables

```
# Create the Comfort and Perception_of_Safety variables
Compute Comfort as the average of specified indicators
Compute Perception_of_Safety as the average of specified indicators

# Create the CBQ variables
Compute Violations as the average of specified indicators (scaled)
Compute Errors as the average of specified indicators (scaled)
Compute Positive_behaviour as the average of specified indicators (scaled)
```

Rename Variables

```
# Rename independent variables for graph plotting
Rename various variables for clarity
```

Convert Data Types

```
# Convert ordinal and categorical data to factors
Convert ordinal variables to ordered factors
Convert socio-demographic variables to factors

# Adjust specific categorical variables
Adjust categories for Q32 and Q3
```

Compute Correlations

```
# Function to compute correlations between mixed types of variables
Define function compute_mixed_correlations
  Initialize correlation matrix
  Loop through variable pairs
    Compute correlation based on variable types (numeric, ordered, factor)
  Return correlation matrix

# Prepare data for correlation analysis
Select relevant variables for analysis

# Compute the mixed correlations
Call compute_mixed_correlations on the subset of data

# Print the mixed correlation matrix
Print the correlation matrix

# Plot the mixed correlation matrix
Create a correlation plot using corrplot with specified parameters
```

E.3. Random effects ordered probit model

Import Packages

```
# Import necessary libraries
Load libraries: mvord, readr, dplyr, tidyr, writexl, ggplot2, patchwork
```

Load Data

```
# Load the data
Set data_path to the CSV file location
Read CSV file into safety_comfort_full
```

Adjust Categories

```
# Adjust the categories for Q32 and Q23_6
Convert Q32 to a factor with levels 0, 2, 3
Convert Q23_6 to a factor with levels 1, 2
```

Create Age Category

```
# Create an Age categorical variable
Categorize Q5 into age groups
```

Create CBQ Variables

```
# Create CBQ variables by averaging the indicators
Compute Violations as the average of specified indicators (scaled)
Compute Errors as the average of specified indicators (scaled)
Compute Positive_behaviour as the average of specified indicators (scaled)
```

Ensure Factors

```
# Ensure binary variables are factors
Convert binary_vars to factors

# Ensure categorical variables are factors
Convert categorical_vars to factors

# Convert ResponseId to a factor
Convert ResponseId to a factor

# Make sure Comfort and Safety are ordered factors
Convert Comfort to an ordered factor
Convert Safety to an ordered factor
```

Rename Variables

```
# Rename independent variables for graph plotting
Rename various variables for clarity
```

Fit the Model

```
# Fit the multivariate ordinal regression model with random effects
Define formula for MMO2
Specify data as safety_comfort_full
Set error structure to cor_general
Set link function to mvprobit
Control the solver with max iterations and trace options
Fit the model using mvord function
```

Model Results

```
# Output the model summary and other metrics
Compute AIC
Compute BIC
Compute log likelihood
Display summary of the fit
Display head of error structure
Display structure of the fit
```

Marginal Effects

```
# Create a new dataset for marginal effects calculation
Create new_data by expanding the grid of independent variable levels
Sample a subset of new_data for memory efficiency
Predict probabilities for each level of Comfort and Safety
Combine predicted probabilities with new_data
Summarize and format marginal effects
Write marginal effects to an Excel file
Display the average marginal effects
```

Confidence Intervals

```
# Extract coefficients and standard errors
Create coef_summary with estimates and standard errors

# Calculate confidence intervals and odds ratios
Compute CI_Lower and CI_Upper
Compute Odds_Ratio, OR_CI_Lower, and OR_CI_Upper
Write coefficients and odds ratios to an Excel file
```

Graphing Results

```
# Filter and combine data for plotting
Filter comfort and safety variables
Add type labels for Comfort and Safety
Combine the data for plotting

# Create and display the combined plot
Generate plot with standardized regression coefficients and error bars
Save the combined plot
```

E.4. Fixed effects ordered probit model

Import Packages

```
# Import necessary libraries
Load libraries: mvord, readr, dplyr, tidyr, mvordflex
```

Load Data

```
# Load the data
Set data_path to the CSV file location
Read CSV file into safety_comfort_full
```

Adjust Categories

```
# Adjust the categories for Q32 and Q23_6
Convert Q32 to a factor with levels 0, 2, 3
Convert Q23_6 to a factor with levels 1, 2
```

Create Age Category

```
# Create an Age categorical variable
Categorize Q5 into age groups
```

Create CBQ Variables

```
# Create CBQ variables by averaging the indicators
Compute Violations as the average of specified indicators (scaled)
Compute Errors as the average of specified indicators (scaled)
Compute Positive_behaviour as the average of specified indicators (scaled)
```

Ensure Factors

```
# Ensure binary variables are factors
Convert binary_vars to factors

# Ensure categorical variables are factors
Convert categorical_vars to factors

# Convert ResponseId to a factor
Convert ResponseId to a factor

# Make sure Comfort and Safety are ordered factors
Convert Comfort to an ordered factor
Convert Safety to an ordered factor
```

Convert Data Format

```
# Convert data format for latent variable response
Create df_MMO3 by binding rows with Comfort and Safety responses
Create respondent_id_roundabout by combining ResponseId and Roundabout_
    ↪ Number
```

Fit the Model

```
# Fit the multivariate ordinal regression model with fixed effects
Define formula for MMO
Specify data as df_MMO3
Set error structure to cor_general
Set link function to mvprobit
Control the solver with max iterations and trace options
Fit the model using mvord function
```

Summary and Predictions

```
# Output the model summary
Display summary of the fit

# Get model coefficients
Display coefficients of the fit

# Check error structure
Display head of error structure

# Set print options for large output
Set max.print option to a large value

# Generate marginal predictions
Compute marginal predictions with type ”prob”
Display head of marginal predictions
```

Bibliography

AD. (2022). *Verbouwing delflandplein minder succesvol dan gehoopt: 'fietsers zijn eigenwijs'*. Retrieved April 12, 2024, from https://www.ad.nl/delft/verbouwing-delflandplein-minder-succesvol-dan-gehoopt-fietsers-zijn-eigenwijs~aefcb7e74/

Akgün, N., Dissanayake, D., Thorpe, N., & Bell, M. C. (2018). Cyclist casualty severity at roundabouts – to what extent do the geometric characteristics of roundabouts play a part? *Journal of Safety Research*, *67*, 83–91.

Aldreda, R., & Goodman, A. (2018). Predictors of the frequency and subjective experience of cycling near misses: Findings from the first two years of the uk near miss project. *Accident Analysis and Prevention*, *110*, 161–170.

Arbuckle, J. L. (2022). *Ibm® spss® amostm 29 user's guide*. IBM.

ARUP. (2022). Design recommendations for bicycle roundabouts–expert session.

Bahmankhah, B., Fernandes, P., & Coelho, M. C. (2019). Cycling at intersections: A multi-objective assessment for traffic, emissions and safety. *Transport*, *34*, 225–236.

Bösehans, G., & Massola, G. M. (2018). Commuter cyclists' risk perceptions and behaviour in the city of são paulo. *Transportation Research Part F*, *58*, 414–430.

Bruno, M. (2022). Cycling innovations: The challenges of supporting people who cycle in a transition to sustianable mobility.

Cantisani, G., Durastanti, C., & Moretti, L. (2021). Cyclists at roundabouts: Risk analysis and rational criteria for choosing safer layouts. *Infrastructures*, *6*.

Chaurand, N., & Delhomme, P. (2013). Cyclists and drivers in road interactions: A comparison of perceived crash risk. *Accident Analysis & Prevention*, *50*, 1176–1184.

Chen, F., Song, M., & Ma, X. (2019). Investigation on the injury severity of drivers in rear-end collisions between cars using a random parameters bivariate ordered probit model. *Internation Journal of Environmental Research and Public Health*.

Choice-Metrics. (2024). *Ngene features*. Retrieved May 16, 2024, from https://www.choice-metrics.com/features.html

CROW, F. (2019a). *Hernieuwde aandacht voor de veiligheid van fietsers op rotondes*. Retrieved November 21, 2023, from https://fietsberaad.nl/Kennisbank/Hernieuwde-aandacht-voor-de-veiligheid-van-fietser?URLReferrer=searchtext%3drotonde%26sort%3d0%26page%3d3%26aliaspath%3d%252fKennisbank

CROW, F. (2019b). *Verkenning verbetering verkeersveiligheid fietsers op rotondes*. Retrieved November 21, 2023, from https://fietsberaad.nl/Kennisbank/Verkenning-verbetering-verkeersveiligheid-fietsers?URLReferrer=searchtext%3drotonde%26sort%3d0%26page%3d3%26aliaspath%3d%252fKennisbank

CROW, F. (2021). *Tilburg past voorrangssituatie op 23 rotondes aan*. Retrieved November 21, 2023, from https://fietsberaad.nl/Kennisbank/Tilburg-past-voorrangssituatie-op-23-rotondes-aan?URLReferrer=searchtext%3drotonde%26sort%3d0%26page%3d2%26aliaspath%3d%252fKennisbank

CROW, F. (2023). *Gedragscampagne wijst fietsers de weg op delflandplein*. Retrieved November 21, 2023, from https://fietsberaad.nl/Kennisbank/Gedragscampagne-wijst-fietsers-de-weg-op-Delflandp?URLReferrer=searchtext%3drotonde%26sort%3d0%26aliaspath%3d%252fKennisbank

CROW, F. (2024a). *Bolle bestrating tegen hinderlijk geparkeerde fietsen*. Retrieved February 29, 2024, from https://www.fietsberaad.nl/Kennisbank/Bolle-bestrating-tegen-hinderlijk-geparkeerde-fiet?URLReferrer=searchtext%3drotondes%26sort%3d0%26aliaspath%3d%252fKennisbank

CROW, F. (2024b). *Inrichtingsaanbevelingen voor fietsrotondes (fietsberaadnotitie)*. Retrieved February 29, 2024, from https://www.fietsberaad.nl/Kennisbank/Inrichtingsaanbevelingen-voor-fietsrotondes

CROW, F. (2024c). *Retrospective - knowledge café bicycle-friendly intersections 1: Kick-off meeting*. Retrieved March 13, 2024, from https://www.fietsberaad.nl/Kennisbank/Terugblik-Kenniscafe-Fietsvriendelijke-kruispunten?URLReferrer=searchtext%3drotondes%26sort%3d0%26aliaspath%3d%252fKennisbank

CROW–Kennisbank. (2014a). 3.6 afwikkeling fietsers and voetgangers. *CROW*.

CROW–Kennisbank. (2014b). 4.1 achtergronden–rotonde. *CROW*.

CROW–Kennisbank. (2014c). 6 rotonde. *CROW*.

CROW–Kennisbank. (2020). Overzicht crow kennisproducten op het gebied van verkeer en vervoer (2018-2020). *CROW*.

Dabbour, E., & Easa, S. M. (2008). Evaluation of safety and operational impacts of bicycle bypass lanes at modern roundabouts. *Canadian Journal of Civil Engineering*, *35*, 1025–1032.

Daniels, S., Nuyts, E., & Wets, G. (2008). The effects of roundabouts on traffic safety for bicyclists: An observational study. *Accident Analysis and Prevention*, 518–526.

de Hartog, J. J., Boogaard, H., Nijland, H., & Hoek, G. (2010). Do the health benefits of cycling outweigh the risks? *Environmental Health Perspectives*, *118*, 1109–1116.

de Waard, D., Prey, A., Mohr, A. K., & Westerhuis, F. (2020). Differences in cycling performance of dutch and non-dutch students in the netherlands. *Transportation Research Part F: Traffic Psychology and Behaviour*, *68*, 285–292.

Distefano, N., Leonardi, S., & Consoli, F. (2019). Drivers' preferences for road roundabouts: A study based on stated preference survey in italy. *KSCE Journal of Civil Engineering*, *23*, 4864–4874.

Dozza, M., & Werneke, J. (2014). Introducing naturalistic cycling data: What factors influence bicyclists' safety in the real world? *Transportation Research Part F*, 83–91.

Duivenvoorden, K. (2021). The effects of intersection design and road users' behaviour on the interaction between cyclists and car drivers.

Epskamp, S. (2020). *Sem 1 - lecture 4-1: Ordered categorical data*. Retrieved May 10, 2024, from https://www.youtube.com/watch?v=NmF1blf2zDI

Fernández-Heredia, Á., Monzón, A., & Jara-Díaz, S. (2014). Understanding cyclists' perceptions, keys for a successful bicycle promotion. *Transportation Research Part A*, 1–11.

Friel, D., Wachholz, S., Werner, T., Zimmerman, L., Schwedes, O. S., & Stark, R. (2023). Cyclists' perceived safety on intersections and roundabouts – a qualitative bicycle simulator study. *Journal of Safety Research*.

González-Gómez, K., & Castro, M. (2020). Analysis of sight distances at urban intersections from a vulnerable users' approach: A case study. *Transportation Research Procedia*, *45*, 226–233.

Haag, M. R. D. (2024). *Ontwerpbegroting 2024 en meerjarenbegroting 2025-2027*. Retrieved July 29, 2024, from https://raad.albrandswaard.nl/Documenten/bijlage-5-Ontwerpbegroting-MRDH-2024.pdf

Han, L. (2023). Perceived risk of interaction with e-bikes.

Harkey, D. L., & Carter, D. L. (2006). Observational analysis of pedestrian, bicyclist, and motorist behaviors at roundabouts in the united states. *Transportation Research Record*, *1982*, 155–165.

Hirk, R., Hornik, K., & Vana, L. (2020). Mvord: An r package for fitting multivariate ordinal regression models. *Journal of Statistical Software*, *93*, 1–41.

Image, P. (2024). *Png images and cliparts for web design*. Retrieved April 12, 2024, from https://pngimg.com/

Jafari Anarkooli, A., Mehdi Hosseinpour, M., & Kardar, A. (2017). Investigation of factors affecting the injury severity of single-vehicle rollover crashes: A random-effects generalized ordered probit model. *Accident Analysis Prevention*, *106*, 399–410.

Jensen, S. (2012). Pedestrian and bicycle level of service at intersections, roundabouts and other crossings. *Transportation Research Record*, 0-19.

Jensen, S. (2013). Safety effects of converting intersections to roundabouts. *Transportation Research Record*, *2389*, 22–29.

Jensen, S. U. (2017). Safe roundabouts for cyclists. *Accident Analysis and Prevention*, *105*, 30–37.

John Parkin, J., Wardman, M., & Page, M. (2007). Models of perceived cycling risk and route acceptability. *Accident Analysis and Prevention*, *39*, 364–371.

Jorgensen, T. D., & Johnson, A. R. (2022). How to derive expected values of structural equation model parameters when treating discrete data as continuous. *Structural Equation Modeling*, *29*, 639–650.

Kazemzadeh, K., Afghari, A. P., & Cherry, C. R. (2024). For whom is sharing really scaring? capturing unobserved heterogeneity in perceived comfort when cycling in shared spaces. *Transportation Research Part F: Psychology and Behaviour*, *103*, 306–318.

Kelly, P., Kahlmeier, S., Götschi, T., Orsini, N., Richards, J., Roberts, N., Scarborough, P., & Foster, C. (2014). Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose response relationship. *International Journal of Behavioral Nutrition and Physical Activity*, *11*, 132.

Kim, J. S., & Ratchford, B. (2013). A bayesian multivariate probit for ordinal data with semiparametric random-effects. *Computational Statistics Data Analysis*, *64*, 192–208.

Kummeneje, A.-M., Ryeng, E. O., & Rundmo, T. (2019). Seasonal variation in risk perception and travel behaviour among cyclists in a norwegian urban area. *Accident Analysis and Prevention*, *124*, 40–49.

Lawton, B. J., Webb, P. J., Wall, G. T., & Davies, D. G. (2003). Cyclists at ’continental’ style roundabouts: Report on four trial sites. *ARRB*.

Lee, J., Abdel-Aty, M., Cai, Q., & Wang, L. (2018). Effects of emergency medical services times on traffic injury severity: A random effects ordered probit approach. *Traffic Injury Prevention*, *19*, 577–581.

Libraries, M. U. (2024). *What is the difference between factors, factor levels, and treatments?* Retrieved May 1, 2024, from https://libanswers.lib.miamioh.edu/stats-faq/faq/336908

Macioszek, E., Sierpiński, G., & Czapkowski, L. (2010). Problems and issues with running the cycle traffic through the roundabouts. *International Conference on Transport Systems Telematics*, 107–114.

Marín Puchades, V., Fassina, F., Fraboni, F., De Angelis, M., Prati, G., de Waard, D., & Pietrantoni, L. (2018). The role of perceived competence and risk perception in cycling near misses. *Transportation Research Part F*, *105*, 167–177.

Meuleners, L., Fraser, M., & Roberts, P. (2023). Improving cycling safety through infrastructure design: A bicycle simulator study. *Transportation Research Interdisciplinary Perspectives*, *18*.

Meuleners, L. B., Stevenson, M., Fraser, M., Oxley, J., Rose, G., & Johnson, M. (2019). Safer cycling and the urban road environment: A case control study. *Accident Analysis and Prevention*, *129*, 342–349.

Molin, E. (2005). A causal analysis of hydrogen acceptance. *Transportation Research Records*, *1941*, 115–121.

Møller, M., & Hels, T. (2008). Cyclists’ perception of risk in roundabouts. *Accident Analysis and Prevention*, *40*, 1055–1062.

Muthén, B. (1984). A general structural equation model with dichotomous, ordered categorical, and continous latent variable indicators. *Psychometrika*, 115–132.

news, A.-.-.-e. A. (2019). *Voorrangsregels haarlemmermeercircuit ’totaal gestoord’*. Retrieved April 5, 2024, from https://www.at5.nl/artikelen/191069/dfcd

News, D. (2022). Roundabouts are a safety hazard for cyclist, new data suggests. *Society*, *35*, 1.

Newsom, J. (2023a). *Alternative estimation methods*. Retrieved April 20, 2024, from https://web.pdx.edu/~newsomj/semclass/ho_estimation.pdf

Newsom, J. (2023b). *Example with categorical indicators*. Retrieved April 20, 2024, from https://web.pdx.edu/~newsomj/semclass/

Newsom, J. (2023c). *Examples of chi-square difference tests with nonnormal and categorical variables*. Retrieved April 20, 2024, from https://web.pdx.edu/~newsomj/semclass/ho_difftests.pdf

Newsom, J. (2023d). *Sem with categorical variables*. Retrieved April 20, 2024, from https://web.pdx.edu/~newsomj/semclass/ho_categorical.pdf

Pieters, N. (2019). Morality in the preference for advanced driver assistance systems.

PNG, C. (2024). *Png images without backgrounds*. Retrieved April 12, 2024, from https://www.cleanpng.com/

Poudel, N., & Singleton, P. A. (2021). Bicycle safety at roundabouts: A systematic literature review. *Transport Reviews*.

Poudel, N., & Singleton, P. A. (2022). Preferences for roundabout attributes among us bicyclists: A discrete choice experiment. *Transportation Research Part A*, *155*, 316–329.

Poudel, N., & Singleton, P. A. (2023). Bicycling comfort at roundabouts: Effects of design and situational factors. *Transportation Research Part F: Traffic Psychology and Behaviour*, *94*, 227–242.

Pulvirenti, G., DeCeunynck, T., Daniels, S., Distefano, N., & Leonardi, S. (2021). Safety of bicyclists in roundabouts with mixed traffic: Video analyses of behavioural and surrogate safety indicators. *Transportation Research Part F*, *76*, 72–91.

Richard Mantona, R., Rau, H., Fahy, F., Sheahan, J., & Clifford, E. (2016). Using mental mapping to unpack perceived cycling risk. *Accident Analysis and Prevention*, 138–149.

Rijkswaterstaat. (2024). *Documenten richtlijnen autosnelwegen*. Retrieved April 7, 2024, from https://www.rijkswaterstaat.nl/zakelijk/werken-aan-infrastructuur/bouwrichtlijnen-infrastructuur/autosnelwegen

Sakshaug, L., Laureshyn, A., Svensson, Å., & Hydén, C. (2010). Cyclists in roundabouts—different design solutions. *Accident Analysis and Prevention*, *42*, 1338–1351.

Sanders, R. (2015). Perceived traffic risk for cyclists: The impact of near miss and collision experiences. *Accident Analaysis and Prevention*, 26–34.

Schepers, P., Twisk, D., Fishman, E., Fyhri, A., & Jensen, A. (2017). The dutch road to a high level of cycling safety. *Safety Science*, 264–273.

Schepers, P., & den Brinker, B. (2011). What do cyclists need to see to avoid single-bicycle crashes? *Ergonomics*, *54*, 315–327.

Se, C., Champahom, T., Jomnonkwao, S., Chaimuang, P., & Ratanavaraha, V. (2021). Empirical comparison of the effects of urban and rural crashes on motorcyclist injury severities: A correlated random parameters ordered probit approach with heterogeneity in means. *Accident Analysis and Prevention*, *161*.

services, V. H. (2023). *Question scales part 1: Should i use an even or odd number of response options?* Retrieved April 20, 2024, from https://veritaengage.com/odd-or-even-number-of-response-options/

Shen, J., Wang, T., Zheng, C., & Yu, M. (2020). Determinants of bicyclist injury severity resulting from crashes at roundabouts, crossroads, and t-junctions. *Journal of Advanced Transportation*, *2020*.

Silvano, A., Ma, X., & Koutsopoulos, H. (2014). A hierarchical modelling framework for vehicle□bicycle interactions at roundabouts. *International Cycling Safety Conference*.

Statistics, L. (2018). *Ordinal regression using spss statistics*. Retrieved May 10, 2024, from https://statistics.laerd.com/spss-tutorials/ordinal-regression-using-spss-statistics.php

Sungjun, L., Seongmin, P., Juneyoung, P., & Junhan, C. (2022). Severity analysis for children-related crashes in school zones using random effects ordered probit models. *Journal of Korean Society of Transportation*, 599–611.

Tan, T., Haque, S., Lee-Archer, L., Mason, T., Parthiban, J., & Beer, T. (2019). Bicycle-friendly roundabouts: A case-study. *Journal of Road Safety*, *30*, 67–70.

Thomas, L., Ryus, P., Semler, C., Thirsk, N. J., Krizek, K., & Zegeer, C. (2016). Delivering safe, comfortable, and connected pedestrian and bicycle networks: A review of international practices. *Pedestrian and Cyclist Safety: U.S. Trends and Initiatives and International Practices*, 45–117.

Useche, S. A., Alonso, F., Montoro, L., & Esteban, C. (2019). Explaining self-reported traffic crashes of cyclists: An empirical study based on age and road risky behaviors. *Safety Science*, *113*, 105–114.

Useche, S. A., Montoro, L., Tomas, J. M., & Cendales, B. (2018). Validation of the cycling behavior questionnaire: A tool for measuring cyclists' road behaviors. *Transportation Research Part F*, *58*, 1021–1030.

Useche, S. A., Philippot, P., Ampe, T., Llamazares, J., & Geus, B. d. (2021). "pédaler en toute sécurité": The cycling behavior questionnaire (cbq) in belgium – a validation study. *Transportation Research Part F*, *80*, 260–274.

van der Leeden, E. (2012). A comparison between the pleintje, priority intersection roundabout.

Vana-Gür, L. (2024a). Multivariate ordinal regression for multiple repeated measurements.

Vana-Gür, L. (2024b). *Multivariate ordinal regression for multiple repeated measurements*. Retrieved June 10, 2024, from https://repositum.tuwien.at/bitstream/20.500.12708/197326/1/Vana%20Guer-2024-Multivariate%20ordinal%20regression%20for%20multiple%20repeated%20meas...-vor.pdf

van Bentem, L. (2022). The impact of infrastructure design on cycling safety.

van Infrastructuur en Waterstaat, M., van JenV, M., IPO, & VNG. (2018). Veilig van deur tot deur. het strategisch plan verkeersveiligheid 2030: Een gezamenlijke visie op aanpak verkeersveiligheiddsbeleid [safe from door to door. strategic plan road safety 2030: A shared vision on road safety policy]. *Rijkswaterstraat*.

Vos, J., Haneen Farah, H., & Marjan Hagenzieker, M. (2021). How do dutch drivers perceive horizontal curves on freeway interchanges and which cues influence their speed choice? *IATSS Research*, *45*, 258–266.

Wang, K., & Akar, G. (2018). Street intersection characteristics and their impacts on perceived bicycling safety. *Transportation Research Record*, *2672*, 41–54.

Washington, S., Karlaftis, M. G., Mannering, F., & Anastasopoulos, P. (2020). *Statistical and econometric methods for transportation data analysis*. Chapman; Hall/CRC.

Wegman, F., & Schepers, P. (2024). Safe system approach for cyclists in the netherlands: Towards zero fatalities and serious injuries? *Accident Analysis and Prevention*, *195*, 30–37.

Werner, B., & Birgit, S. (1990). Capacity and safety of roundabouts in west germany. *Conference of the Australian Road Research Board*, 275–281.

Xiao, D., Yuan, Q., Kang, S., & Xu, X. (2021). Insights on crash injury severity control from novice and experienced drivers: A bivariate random-effects probit analysis. *Discrete Dynamics in Nature and Society*, 0–13.

Xing, C., Johnson, P., Sullivan, M., & Kite, B. (2018). *Structural equation modeling for ordinal data*. Retrieved April 15, 2024, from https://pj.freefaculty.org/guides/crmda_workshops/sem/sem-ordinal/presentation/ordinalSEM.pdf

Xing, C., Johnson, P., Sullivan, M., & Kite, B. (2019). *Structural equation modeling for ordinal data*. Retrieved April 15, 2024, from https://pj.freefaculty.org/guides/crmda_workshops/sem/sem-3/sem-3-3-sem_ordinal/sem-3-3-sem_ordinal.pdf

Zeuwts, L. H., Iliano, E., Smith, M., Deconinck, F., & Lenoir, M. (2021). Mental fatigue delays visual search behaviour in young cyclists when negotiating complex traffic situations: A study in virtual reality. *Accident Analysis and Prevention*, *161*.

Zhang, B., & Ma, Z. (2015). *Revolutionise roundabout design on bicycle routes*. Australian Institute of Traffic Planning; Management (AITPM) National Conference.

Zheng, Z., Liu, Z., Liu, C., & Shiwakoti, N. (2014). Understanding public response to a congestion charge: A random-effects ordered logit approach. *Transportation Research Part A*, *70*, 117–134.