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Riding the circle: Cyclists' perceived safety and comfort in urban roundabouts☆

Ian Trout [a,1], Maria Salomons [b,2], Amir Pooyan Afghari [c,3], Haneen Farah [*,b,4]

[a] 2 Wilton Place, Dublin, D02 V2R9, Dublin, Ireland
[b] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, Delft, 2628, CN, the Netherlands
[c] Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, Delft, 2628, BX, the Netherlands

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ABSTRACT

Perceived safety and comfort influence cycling mode choice and behaviour. While roundabouts are associated with a decreased severity of motor vehicle crashes, recent crash data in the Netherlands suggests that this is not the case for bicycle crashes, with 12% of all bicycle crashes between 2014 and 2021 occurring at roundabouts. Previous studies have mainly focused on intersection type and bicycle facilities, and overlooked how different design elements of dedicated bicycle facilities on roundabouts affect cyclists' perceived safety. Furthermore, previous studies did not investigate the relationship between perceived safety and comfort.

To address these gaps, this study aims to better understand the factors contributing to cyclists' perceived safety and comfort at roundabouts. A total of 239 complete responses from cyclists to a stated preference survey were collected. A bivariate random effect ordered probit model was used to simultaneously model cyclist's perceived safety and comfort as a function of behavioural factors and infrastructural design elements.

The results revealed that roundabouts where cars must yield to cyclists and with fewer vehicular entrance points were perceived by cyclists as safer and more comfortable. Also, cyclists' place of residence (in or outside the Netherlands), their likelihood to commit traffic violations, their recent crash history, and the type of bicycle they use, significantly affect their perceived safety.

To improve cyclists' perceived safety and comfort in urban environments, it is recommended to ensure bicycle yielding priority, design dedicated bicycle facilities on roundabouts and maintain uniformity in bicycle infrastructure design.

1. Introduction

Roundabouts have existed for over a century, and it is known that they improve safety, for motor vehicle traffic (Distefano et al.,

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* Corresponding author.
E-mail address: H.Farah@tudelft.nl (H. Farah).
[1] **ORCID:** 0000-0003-4992-5752.
[2] **ORCID:** 0000-0001-6545-1759.
[3] **ORCID:** 0000-0003-1158-880×.
[4] **ORCID:** 0000-0002-2919-0253.

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2019). As a result, many countries have built roundabouts, but recent studies have noted that more attention must be given to vulnerable road users, such as cyclists and pedestrians, as crash records show that this road users' group represents almost 70% of total fatalities in urban areas (EU Commission, 2024), and the safety benefits for motorists may not necessarily translate to these more vulnerable road users (Brilon and STUWE, 1990). A recent Dutch crash data analysis also points to this trend, with 12% of all bicycle crashes occurring at roundabouts (Wegman and Schepers, 2024). Roundabouts with bi-directional bicycle facilities and bicycle yielding priority (i.e. vehicles must yield to bicycles), can be particularly challenging because cyclists may cross vehicular lanes in both directions. Several studies have indicated that bi-directional bicycle tracks are less safe than uni-directional bicycle tracks (CROW, 2016; Davidse et al., 2014; Schepers, 2013). Perceived safety also plays an important role, as studies have shown that cyclists engage in significant detours to avoid traffic infrastructure perceived as unsafe (Gössling and McRae, 2022). Perceived safety is defined as how safe road users feel while cycling, and it depends on various factors, including physical infrastructure, traffic volumes, and a person's own condition, e.g., stress levels, and past experiences (Prati et al., 2019). Identifying bicycle infrastructure characteristics and cyclists' behavioural factors that influence both objective and perceived cycling safety at roundabouts can inform roundabout design guidelines (de Waard et al., 2020; Shen et al., 2020; Wegman and Schepers, 2024). This paper focuses on perceived cycling safety as it is sometimes misaligned with objective safety outcomes (Costa et al., 2025). Therefore, having insights regarding objective safety might not inform about the status of perceived safety. If designers know how cyclists perceive a certain roundabout, they can adjust their designs accordingly to enhance perceived safety (Tan et al., 2019).

Perceived comfort is another factor that might affect the use of cycling as a chosen transport mode (Ahmed et al., 2023; Ahmed et al., 2024). In transport science, the concept of comfort in cycling extends beyond physical ease to encompass the rider's overall experience of the cycling environment. Comfort is influenced by infrastructure design, pavement quality, gradients, intersection treatments, and the presence of dedicated cycling facilities (i.e., separation from motor vehicles). Some cyclists ride more frequently (greater exposure) and therefore are more comfortable being next to motor vehicles with no physical separation (Poudel and Singleton, 2022). Perceived comfort of cycling can also be how comfortable it is compared to other modes of transport, such as offering spontaneity, seating, or protection from the weather (Fernández-Heredia et al., 2014).

A comfortable cycling environment reduces stressors such as sudden stops, rough surfaces, or conflicts with motorized traffic, thereby lowering the physical and cognitive effort required to ride. Research on cycling behaviour consistently shows that environments designed for comfort, characterized by smooth, continuous, and predictable routes, encourage higher levels of cycling uptake and sustain long-term ridership (see for example, the findings on public preferences towards bicycle sharing systems (Abolhassani et al., 2019), or on how shared spaces affect comfort in meeting and passing events (Kazemzadeh et al., 2024). This research defines a cyclist's comfort level as overall level of ease as one cycle around a roundabout, and this can vary significantly between people.

While perceived safety and comfort are distinct (the former is related to the sense of risk i.e. the likelihood and consequence of an undesired event such as a crash, whereas the latter is the overall experience of cycling), they may still be correlated because they are both measuring the same psychological construct: coping capacity of cyclists when riding through roundabouts. Therefore, there may be shared underlying causes behind perceived safety and comfort. In addition, comfort can be influenced by perceived safety, which often has a greater impact on cycling decisions than actual crash statistics. Riders may avoid otherwise shorter routes if they feel unsafe due to narrow lanes, proximity to high-speed traffic, or poor lighting, even when official data show relatively low crash rates. Conversely, comfortable infrastructure, such as protected bike lanes, wide shoulders, and traffic-calmed streets, can enhance feelings of safety by reducing exposure to conflict points and unpredictable vehicle interactions. For example, a simulation study of different intersection designs showed that continuous cycling infrastructure and physical separation significantly improve perceived safety, and that “comfort” is one of the key factors influencing cyclists' perceptions (Friel et al., 2023). In addition, research from the Netherlands shows that high crowding on bike paths negatively affects both route preference and perceived safety, especially amongst older cyclists and women, indicating how comfort (e.g. amount of space, path width) contributes to perceived safety (Uijtdewilligen et al., 2024).

Previous studies investigating perceived safety of cyclists at roundabouts have mainly focused on intersection/roundabout configurations and types of bicycle facilities and have overlooked how the different design elements of a dedicated bicycle facility on roundabouts can affect perceived safety. Furthermore, they have not looked at the relationship between perceived safety and comfort and have mostly analysed these two variables separately. As such, this research aims to: (1) determine what behavioural factors and infrastructural design elements influence a cyclist's perceived safety and comfort at urban roundabouts; (2) to understand the relationship between perceived safety and perceived comfort.

The scientific contributions of this research are the investigation of cyclists' perceived safety and comfort simultaneously, as a function of roundabout attributes and socio-demographic independent variables, and the novel employment and use of a bivariate random effects ordered probit model to do so. The practical contribution of this research is to provide recommendations to policy makers on how to improve cycling safety and comfort at urban roundabouts.

The remainder of this paper is organized as follows. Section 2 presents a review of previous research that focused on roundabout features and design guidelines, followed by a brief background on cyclists' behavioural and perceived safety models. Section 3 describes the conceptual framework and model attributes used in this study. The study area, characteristics of the data, the respondents, and the methodology for modelling perceived safety and comfort of cyclists at roundabouts are explained in Section 4. The estimation results and the interpretation of parameter estimates are then presented in Section 5. Section 6 presents the main findings and discussion, followed by Section 7 with the study limitations, and finally Section 8 with the conclusions and recommendations for further research.

2. Literature review

The following sub-sections present the literature regarding the impact of roundabout design features on perceived and objective safety, then reviews cyclists' behaviours, compliance with traffic rules and the relationship with perceived safety, and finally a summary of the research and knowledge gaps.

2.1. Impact of roundabout design features on perceived and objective safety

One can note that roundabouts come in many forms, with variations in 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 other characteristics that heavily influence how motor vehicles travel through roundabouts and whether they yield or not to cyclists (Poudel and Singleton, 2022). 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 Fig. 1a and b), (Jensen, 2017; Møller and Hels, 2008; Poudel and Singleton, 2022; Sakshaug et al., 2010).

However there have been few studies that have focused solely on urban roundabouts with a separate bicycle facility, enabling a more in depth focus on studying the impact of design factors, such as number of legs or bi-directional bicycle paths at roundabouts (which allow bicycles to have a more direct path of travel), on safety and cyclists' compliance. In existing design guidelines, there is ambiguity regarding dimensioning of bicycle facilities, where there is simply an acknowledgement that bi-directional bicycle facilities at roundabouts require additional consideration and "extra attention from the designer" (CROW, 2014). Scientific research can inform and provide input to update the design guidelines on how bi-directional cycle paths at roundabouts influence cyclists' use of a roundabout with such a facility. The study by Pulvirenti et al. (2021) did this but from the behavioural standpoint of motorists. One Swedish study found that 38% of cyclists travel in a clockwise direction, against the vehicular circulation direction (Sakshaug et al., 2010), thus proving that there is a behavioural desire from cyclists to follow the shortest path. This study did not analyse the impact that this design feature has on perceived safety of cyclists.

Another design feature is yielding priority, which can vary from country to country. Even though Dutch design guidelines recommend providing cyclists with yielding priority at all urban roundabouts (CROW, 2014), there are many locations in the country where exceptions can be found. Findings from the Netherlands and Denmark indicate that such locations are unsafe (CROW, 2019; Jensen, 2017). This ambiguity and differences in design feature applications can lead to lower perceived safety and comfort ratings and deserve further research.

The above examples of how roundabout features affect safety underscores the critical influence of roundabout design on the safety and the interaction between cyclists and motorists. There are many different design characteristics to consider when building a roundabout, and designers may select design solutions based on their expertise and local knowledge of the traffic network. However, encountering two roundabouts in the vicinity of each other which vary greatly in their design characteristics, such as inscribed circle diameter, yielding priority, bicycle facility, etc., can cause confusion to motorists and cyclists. The variance in findings across different studies emphasizes the need for a more in-depth investigation of the various design characteristics that affect the interactions between

(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. Note that there are five legs at this roundabout.

Fig. 1. Aerial photos of two types of bicycle paths at roundabouts, with one being circular and one being a polygon shape. Images courtesy of Google Earth. (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. Note that there are five legs at this roundabout. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cyclists and motorists and have implications for cyclists' safety. The centre 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. The CROW design guidelines do not mention consideration of perceived safety of cyclists when deviating from the design guidelines, even though perceived safety of cyclists is gaining more and more attention of cities and should be taken into consideration (Sanders, 2015; Wang and Gulsah., 2018).

The next section reviews previous studies that investigate how cyclists' perceptions of safety and comfort are influenced by their personal and behavioural factors.

2.2. Impact of cyclists' personal and behavioural factors on safety and comfort perceptions

Safety, comfort, and the existence of proper facilities are key to improving road users' perceptions of cycling (Fernández-Heredia et al., 2014). When road users think that a roundabout is unsafe, they often demand that the local government implements design changes, even when that location has a good objective safety record (Duivenvoorden, 2021). Cyclists do not necessarily perceive a certain location as unsafe because of its poor objective safety record, rather, their perception is shaped by their personal experiences of unsafety at that location (Friel et al., 2023; Sanders, 2015). A recent focus of research on understanding cyclists' risky behaviour, (Useche et al., 2021), led to the development of the cyclist behavioural questionnaire (CBQ) which has been verified in Belgium, the United States of America, and Spain. Subsequent research has validated the CBQ in the five continents and has shown that its outcomes have measurable relationships to infrastructural characteristics such as city size (Useche et al., 2022). The CBQ aims to provide a measurement of risky and positive cyclists' behaviours (Useche et al., 2018). That same study found a strong positive correlation between a cyclist's compliance with traffic laws and positive cycling behaviours. Building upon this, the study by Baumanis et al. (2024) on dedicated bicycle traffic signals in the USA, found that if perceived safety and comfort are high, then compliance will be high as well. Kummeneje et al. (2019) found a significant positive correlation between a persons' attitude towards traffic rules and their compliance with these rules. Guo et al. (2018) found that factors related to cyclists' demographics, bike type, road design, bike and traffic volume, and average vehicle speed affect cyclists' red-light running behaviour. Møller and Hels (2008) found that novice, inexperienced or male cyclists were found to not comply with traffic rules unless clear regulations for road users (e.g. indication of having a yielding priority) is present. Studies have shown that if cyclists underestimate the risks of cycling, they are more likely to be involved in a crash and to suffer severe injuries as a result (Dong et al., 2023). If cyclists overestimate perceived risk, they may become mentally fatigued, which leads to mistakes and potentially crashes (Chaurand and Delhomme, 2013). This becomes a self-balancing feedback loop: the occurrence of bicycle crashes raises a cyclist's subjective risk perception; this leads to decreased risky behaviour, and potentially fewer crashes (Useche et al., 2019). Integrating cyclists' behaviours and socio demographic characteristics with roundabout infrastructure design has not been studied before and it is the missing link in the design of roundabouts that properly cater for cyclists' needs and perceived comfort and safety.

Cyclists' past experiences, such as past involvement in crashes, can influence their behaviour. Many studies found that cyclists who have experienced a conflict or a crash, have a higher perception of risk (Marín Puchades et al., 2018; Poudel and Singleton, 2022; Sanders, 2015; Singleton and Poudel, 2023). Poudel and Singleton (2022) concluded that respondents' preferences between two different roundabouts with various configurations (e.g. sharrows or dedicated cycling facility) are motivated by their perceived safety and comfort of these roundabout configurations. However, the authors did not utilize the CBQ to understand the underlying heterogeneity in cyclists' preferences.

Cyclists' perceived safety and comfort are both important since if road users feel safe, they may be inclined to feel more comfortable, and vice-versa. Due to the increasing preference to separate cyclists from motorized vehicles and pedestrians, the issue now is to determine what specific design features of a roundabout with separate cycling facilities affect their perceived safety and comfort.

From the methodological standpoint, 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 (Chen et al., 2019; Jensen, 2017; Lee et al., 2018; Schepers et al., 2017; Shen et al., 2020; Xiao et al., 2021). Recent perceived safety models use either a structural equation (SEM) type model (Distefano et al., 2019; Fernández-Heredia et al., 2014; Kummeneje et al., 2019; Singleton and Poudel, 2023), or a form of regression analysis (Aldred and Goodman, 2018; Møller and Hels, 2008; Sanders, 2015; Wang and Gulsah., 2018) to see if there are significant correlations between variables and the indicator variable of perception of comfort or safety. Amongst the studies that used regression analysis, three studies used a form of logit or probit regression (ordered probit (Singleton and Poudel, 2023), cumulative logit (Jensen, 2017), and non-linear least squares (Parkin et al., 2007)). No study was found to have performed a multivariate ordered probit regression on cyclists perceived safety and comfort levels. This is a research gap, as cyclist heterogeneity means that cyclists do not view perceived safety the same as comfort, and might mean that certain design features that would be statistically significant in a perceived safety model may become un-significant in a model considering both variables, safety and comfort.

2.3. Research gaps and research question

There are many design features and design guidelines regarding roundabouts with separate bicycle facilities that sometimes conflict and can lead to a reduction in objective and perceived safety. The link between perceived safety and comfort is ambiguous, as many studies focus on only one or the other (Jensen, 2017; Poudel and Singleton, 2022; Sanders, 2015).

Few advanced discrete choice models have been dedicated to studying the impact of urban roundabout characteristics with a dedicated bicycle facility on safety. With the recent development of the CBQ, a study making use of CBQ factors, individual factors, and roundabout cycle facility design features would be a novel approach to analyse cyclists' perceived safety and comfort. For these reasons, it was decided to use an ordered probit model to evaluate cyclists' perceptions of safety and comfort at urban roundabouts in the Netherlands with various bicycle facility features. This paper can inform design guidelines regarding factors that contribute to cyclists' perceived safety and comfort. This research will reach this goal by answering the following main research question:

What factors contribute to cyclists' perceived safety and comfort at roundabouts?

3. Conceptual framework

Based on the literature review discussed in the previous section, and the main research question defined above, several hypotheses were put forward pertaining to cyclists' perceived safety and comfort. These hypotheses can subsequently be placed into a conceptual model and be used to generate attributes and their respective levels. These hypotheses are structured in four parts as follows:

Correlation between perceived safety and comfort:

1. A cyclist's perceptions of safety and comfort are highly correlated.

Impact of roundabout design characteristics on perceived safety:

2. Yielding priority for cyclists leads to higher perceived safety by cyclists.
3. A buffer distance of four to five meters between motorized traffic and cyclists increases perceived safety at roundabouts.
4. Bi-directional bicycle paths do not decrease cyclists' perceived safety.

Impact of traffic on perceived safety:

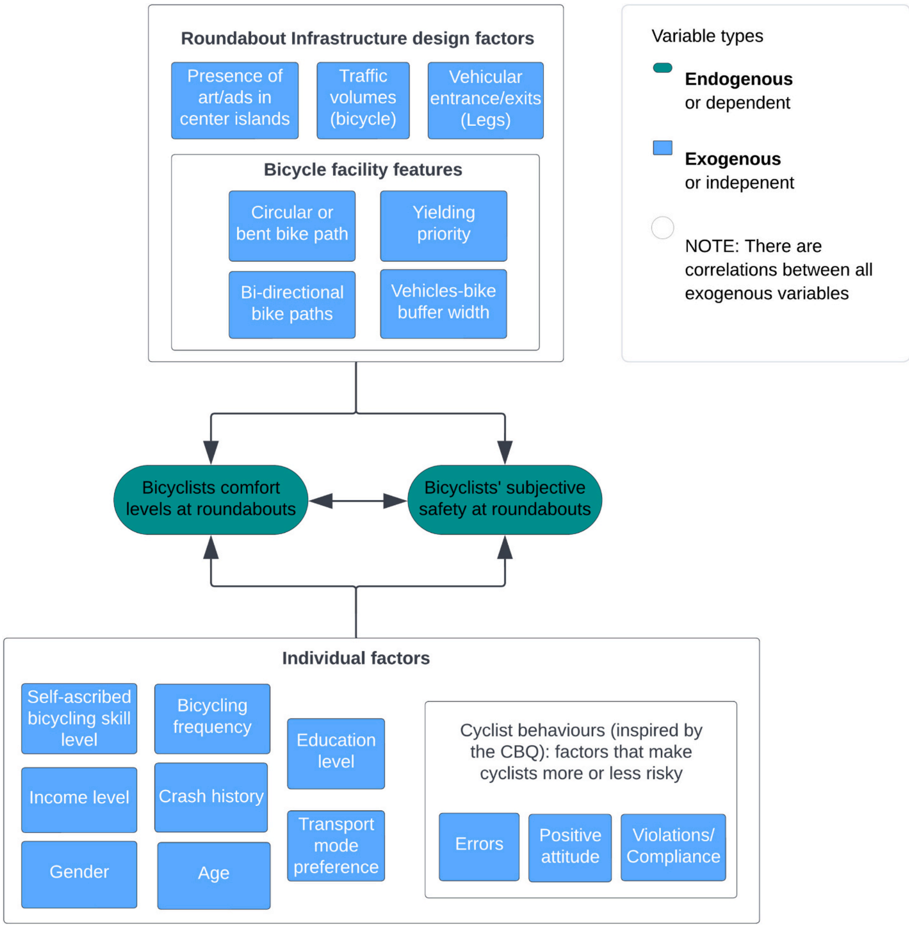


Fig. 2. Conceptual model of this research. Model created via Lucid.

5. Higher bicycle volumes lead to lower perceived safety by cyclists.

Impact of cyclists' characteristics on perceived safety:

6. Cyclists who have recently experienced a crash or "near miss" at a roundabout, will have lower perceived safety at a roundabout, regardless of the design features.
7. Less experienced cyclists have a lower perceived safety at roundabouts.
8. Females and elderly cyclists have a lower perceived safety level compared to male and younger cyclists.

Building on the literature review, main research question and the research hypotheses, Fig. 2 illustrates the conceptual framework that guided this study. The two dependent variables of perceived safety and comfort are represented in green, whilst the measured independent variables are in blue, with the roundabout design features on the top and the individual cyclist attributes on the bottom. As there are no studies looking at the correlation between perceived safety and comfort for cyclists, this research is setting a precedent by looking at both variables within one dataset.

The individual factors included the CBQ with factors related to errors, positive attitude, and violations/compliance. These relate to how a cyclist behaves when riding a bicycle and consisted of 12 questions as described in section 4.2. The other individual factors are all ordinal in nature and help to characterize the respondents. In the roundabout infrastructure design factors group, there is a subgroup that pertains specifically to bicycle facility features such as buffer width, the shape of the bike path, or it's unique characteristics such as the presence of yielding priority for cyclists. In addition, there are three general roundabout variables that describe physical characteristics that are not related to the bike path. These include the number of vehicular entrances/exits, bicycle traffic volume, and presence of art/ads in centre islands. The connection type of the entering roads (radial vs. tangential) was not included in the model, since in the Dutch context all roundabout connections are designed to be as radial as possible, meaning that tangential connections were not present in the dataset. 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.

4. Methodology

The first part of this research included 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 cycling design guidelines and what designers and government officials are currently concerned about regarding roundabout safety. Field observations were performed in Spring 2024 during the weekday rush hour periods (between 4:00 and 6:30 p.m.) to get the busiest traffic volumes, which may add stress for cyclists and increase the probability of crashes (Møller and Hels, 2008). Scooters (i.e. light mopeds) were counted and considered part of the bicycle volumes, as well as any other micromobility vehicle 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 cyclist behaviour and compliance with local traffic regulations. After the expert insights and field observations were analysed to garnish information for the survey, this research chose various levels or categories for each independent variable, as shown in Table 1.

The socio-demographic questions are shown in Table 1 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.

The second part of this research presents the quantitative analysis of the survey data regarding cyclists' perceptions using two methods: first, a descriptive analysis of the survey results followed by an ordered probit model. The ordered probit model is explained in further detail in subsection 4.4.

This division of the research was done to refine the number of roundabout design features to provide the maximum utility to the results for practitioners and policy makers, whilst still adhering to the limitations imposed by the ordered probit model.

4.1. Selection of roundabouts

Determination of the roundabout locations started by considering only Dutch cities with a population over 300,000 (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 more than 50 roundabouts in Delft, The Hague, Pijnacker, Zoetermeer, Rotterdam, and Amsterdam in order to find roundabouts that had similar design features. It was important to use locations that resembled each other with only one or two characteristics differing in order to control the number of roundabout independent variables when constructing the survey. The real-world location characteristics used in the survey are shown in Table 2.

4.2. Survey development

This research employed a fractional factorial experiment design to examine multiple binary attributes while maintaining attribute balance, thereby reducing multicollinearity that could compromise model fit. Certain roundabouts with yielding priority, art/ads present in the centre island, and uni-directional cycle track attributes were modified to preserve attribute balancing so that all

Table 1
Model attributes and levels/categories of the indicators.

Label	Variable	Explanation	Categories
Roadway geometric characteristics			
Buffer	Buffer width between vehicles and bicycles	This space is critical for clear separation of modes and allows for reaction time for yielding behaviour.	0-5.7 m 5.7-11.9 m
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 (buffer width) is $\leq$ 10 m.	No Yes
Art	Presence of art in the centre island	The centre island features can help warn 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. Adds complexity but allows for better accessibility and route choice.	No/hybrid Yes
Flow	Bicycle volumes	This criterion relates to bicycles volumes during peak hours on roundabout.	Below 480 Above 480
Shape	Bicycle path shape	Separated bicycle facilities come in two different shapes: circular (mimicking the vehicular lane) and polygon.	Circular/hybrid Polygon
Legs	Vehicular entrance points	This criterion is whether the roundabout has 4 entrance/exit points for vehicles which can reduce or add complexity.	No Yes
Socio-demographic questions			
Mode	Most common mode of transportation	What is your primary transport mode to commute to your work/ study place?	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 educations 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; Male; Non-Binary; 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?	€1000; €1001-4000; + €4000; Prefer not to say
Skill	Self-ascribed cycling skill level	What would you qualify your level of expertise in cycling?	Inexperienced, Competent; Highly skilled; Prefer not to say
Risky	Risky behaviour as a cyclist	Based on 12 general cyclist behavioural questions within three categories (Violations, Errors, Positive Attitude), this variable determines how risky you are as a cyclist.	See Table 3

Table 2
Selected roundabout's location and characteristics.

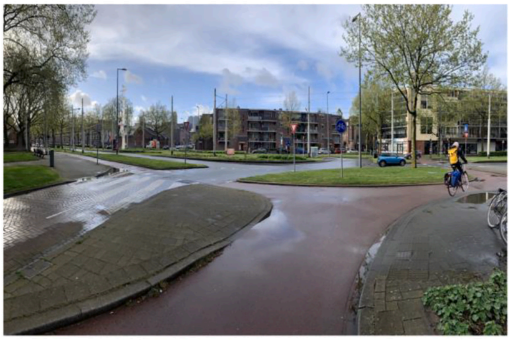
No.	Location	City	Art/ads in centre	Bicycle yielding priority	Uni-directional	4-legged	Separation from motorized traffic (m.)	15 min bicycle volumes (PM Peak)	Facility style
1	Dierenselaan/ Apeldoornselaan	Den Haag	x	√	√	x	3.8	80	Circular
2	Neherkade/ Slachthuisstraat	Den Haag	x	√	√*	√	5.1†	90	Circular
3	Putsebocht tram stop	Rotterdam	x	x	√	x	11.4	83	Polygon
4	Planbaan/Kernbaan	Zoetermeer	x	√	√‡	√	4.5	13	Polygon
5	Amstelplien	Amsterdam	x	√	√§	x	5.8	559	Circular
6	Gordelweg/ Rodenijsestraat	Rotterdam	√	√	√#	√	5.0	193	Circular
7	Meersichtlaan/ Berglaan	Zoetermeer	√	√	x	x	4.8	39	Polygon
8	Delftlandplien	Delft	√	√	√	√	9.6	341	Polygon

* No crossing possible on the north side.
† This roundabout includes aprons to facilitate the passage of heavy vehicles.
‡ The Southern side is bi-directional.
§ except the west side and no crossing possible on the east side.
\# The northern side is bi-directional.

participants saw an equal number of attribute levels. Eight different roundabouts were included in the survey. Participants were asked to rank how comfortable or safe they felt from the standpoint of a cyclist going through each roundabout. They were asked to refrain from comparing roundabouts. The order in which each participant would see these roundabouts was randomized. Some photos of the eight roundabouts were slightly modified using a photo editing software to showcase particular characteristics of each roundabout as

(a) Cyclist view of entering the roundabout located at Dierenselaan/Apeldoornselaan in The Hague. Note the two-way cycle path was added to the image.

(b) Cyclist view of exiting the roundabout located at Neherkade/Slachthuisstraat in The Hague.



(c) Cyclist view of entering the roundabout located at Putsebocht tram stop in Rotterdam.

(d) Cyclist view of circulating in the roundabout located at Planbaan/Kernbaan in Zoetermeer.

(e) Cyclist view entering the roundabout at Amstelplien, Amsterdam. Note that the yielding priority was modified in the image.

(f) Exiting and circulating at the roundabout located at Gordelweg/Rodenijsestraat in Rotterdam. Note the cyclists and yielding priority was modified in the image.

(g) Cyclist view circulating and exiting the roundabout at Meersichtlaan/Berglaan in Zoetermeer. Note that a number of cyclists were added to this image.

(h) Cyclist view circulating and entering the roundabout at Delftlandplien in Delft. Note that the centre art installation was added to this image.

(caption on next page)

Fig. 3. Pictures from the survey showing each roundabout. (a) Cyclist view of entering the roundabout located at Dierenselaan/Apeldoornselaan in The Hague. Note the two-way cycle path was added to the image. (b) Cyclist view of exiting the roundabout located at Neherkade/Slachthuisstraat in The Hague. (c) Cyclist view of entering the roundabout located at Putsebocht tram stop in Rotterdam. (d) Cyclist view of circulating in the roundabout located at Planbaan/Kernbaan in Zoetermeer. (e) Cyclist view entering the roundabout at Amstelplien, Amsterdam. Note that the yielding priority was modified in the image. (f) Exiting and circulating at the roundabout located at Gordelweg/Rodenijsestraat in Rotterdam. Note the cyclists and yielding priority was modified in the image. (g) Cyclist view circulating and exiting the roundabout at Meersichtlaan/Berglaan in Zoetermeer. Note that a number of cyclists were added to this image. (h) Cyclist view circulating and entering the roundabout at Delftlandplien in Delft. Note that the centre art installation was added to this image.

described in the sub-titles of Fig. 3. During this process, it was decided to show four photos of each location, with one being an aerial satellite view and the others being a cyclist eye level. This was done to give participants a full overview of the entire roundabout and see various scenarios, under similar PM peak hour traffic conditions, which would help nonlocal participants get familiar with the roundabout in question and its unique characteristics. External factors such as traffic volumes and weather were controlled to the extent possible so that the images used in the survey do not vary.

The conceptual framework makes use of a group of “cyclist behaviour” variables, measured from 12 independent variables modified from the studies by Useche et al. (2018) and Useche et al. (2021) that used 42 independent variables (only 29 were significant), called the CBQ. Some of the original 42 questions did not apply as many Dutch cyclists perform actions such as allowing a rider on their bicycle rack or carrying cumbersome objects such as beer crates, plywood, and more. In essence, if cyclists take more risk under various typical situations encountered whilst cycling, they are likely to have a higher tolerance for what is considered as an unsafe situation. Since this research is focused on design elements and different types of cyclists, the questions presented in Table 3 reflect only the questions that had the strongest correlations to the variables found in the Useche et al. (2018) and Useche et al. (2021) studies.

During the model run stage, an ordinal factorial analysis of these 12 questions was discarded, as this would have required a more complex modelling approach that would also cost long running time to be estimated. Instead, an averaging of each respondents' responses for each category (Violations, Errors, Positive Attitude) was performed instead. This was done to simplify the overall model and run times, while maintaining detailed information about these three aspects of the CBQ.

4.3. Survey procedure and participant selection

Participants first answered the socio-demographic questions in the survey, followed by the twelve CBQ questions, and then they were shown the four images (from various perspectives) of each of the eight urban Dutch roundabouts chosen (in total 32 images), followed by a short prompt explaining the roundabout attributes present, and then two Likert scale questions for the indicators of perceived safety and comfort.[5] As an even-numbered Likert scale leads to a “forced choice” situation (*Ordinal Regression using SPSS Statistics*, 2018), this research chose a 5-point Likert scale, thus allowing respondents to express a neutral opinion. The final question in the stated preference survey allowed participants to freely express their thoughts and concerns regarding traffic safety at roundabouts.

Research ethic approval from the human research ethics committee of TU Delft was received prior to the survey distribution. 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 employees, cyclists who use the selected roundabouts, and the general public via social media channels. In addition, by directly handing out the QR code link to random cyclists after they had ridden through a roundabout, a more even distribution of the Dutch population was achieved, which reduced bias in the results. All survey participants were introduced to the study via a preamble and consent form stating that they are to respond to the questions from the point of view of a cyclist. Roundabout locations and questions were randomized to avoid effects related to the order of the stimuli and questions. The average duration per participant to complete the survey was 9.7 min and a total of 239 complete responses were received.

4.4. Model choice

The two dependent variables in this study (Fig. 2) are constructed from responses to the following two questions:

“Overall, how safe do you feel this roundabout is as a cyclist?”

“Overall, how comfortable would you feel cycling through this roundabout?”

Since the responses are ordered and in Likert scale (For perceived comfort: very uncomfortable, uncomfortable, neutral, comfortable, and very comfortable, and, for perceived safety: very unsafe, unsafe, neutral, safe and very safe), ordered discrete outcome models must be used for their quantification, and since perceived safety and perceived comfort are assumed to be correlated, a bivariate[6] random effects ordered probit model was chosen as the modelling technique in this study. The random effects specification

[5] The link to the survey: https://tudelft.fra1.qualtrics.com/jfe/form/SV_0ddVflDJFAe99Xw.

[6] Bivariate models are typically used for dependent variables that are less correlated whereas perceived safety and comfort are highly correlated in our study. However, bivariate modelling is still beneficial in our case due to the following reasons:(1) To guide the interpretation of the results: even though perceived safety and comfort are highly correlated, their associations with the predictors may differ in size or direction.(2) To validate measurement consistency: if both perceived safety and comfort are supposed to measure related constructs (i.e. they are two psychological constructs measuring coping capacity of cyclists when riding through roundabouts), a strong correlation supports their validity and a bivariate analysis confirms that the relationship is statistically significant, not just assumed.

Table 3
Cyclist behavioural questionnaire (CBQ), showing the questions and scales of the indicators.

CBQ Label	Question Formulation	Scale
Violations/Compliance		
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		
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 cyclist 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 manoeuvring according to the latter	1 = Never - 5 = Always
Positive Attitude		
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 cyclists 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

was used to handle the panel nature of the data via the incorporation of an additional error term that only changes between respondents (but is fixed across the observations for the same respondents), thus preventing overfitting of the model (Anarkooli et al., 2017; Lee et al., 2022).

Let Y_{1ij} and Y_{2ij} represent the two dependent variables, perceived safety and comfort, for individual i at roundabout j and let s ($s = 1, 2, 3, 4, or\ 5$) represent ordinal categories of these dependent variables (e.g. s = 1: very unsafe, s = 2: unsafe, s = 3: neutral, s = 4: safe, and s = 5: very safe). The generic formula for the bivariate random effects ordered probit model can be written as:

$$\begin{cases} Y^*_{1ij} = \beta_1 X_{1ij} + \lambda_{1ij} + \epsilon_{1i} \\ Y^*_{2ij} = \beta_2 X_{2ij} + \lambda_{2ij} + \epsilon_{2i} \end{cases} \tag{1}$$

where,

$$\epsilon_{1i} \sim \mathrm{N}\left(0, \nu_1^2\right) \tag{2}$$

$$\epsilon_{2i} \sim \mathrm{N}\left(0, \nu_2^2\right) \tag{3}$$

$$\left(\lambda_{1ij}, \lambda_{2ij}\right) \sim \mathrm{MVN}(0, \Sigma) \tag{4}$$

In the above formulation, Y^*_{1ij} and Y^*_{2ij} are continuous latent variables assumed to underlie the observed ordinal categories of Y_{1ij} and Y_{2ij} for the ith individual and the jth roundabout. X_{1ij} and X_{2ij} are independent variables; β_1 and β_2 are estimable parameters; and λ_{1ij} and λ_{2ij} are the error terms of the model assumed to follow a bivariate normal distribution (MVN stands for Multivariate Normal Distribution) with mean 0 and variance-covariance matrix Σ to capture the correlation between perceived safety and comfort:

$$\Sigma = \begin{bmatrix} \sigma 11 & \sigma 12 \\ \sigma 21 & \sigma 22 \end{bmatrix} \tag{5}$$

ϵ_{1i} and ϵ_{2i} are the random effects of the model and are assumed to follow univariate normal distributions with mean 0 and variances ν_1^2 and ν_2^2, (respectively)

Eq. (1) shows the latent variables underlying the actual observed data whereas what is gathered in the survey are those observed ordinal data. The observed values (s = 1, 2, 3, 4, or 5) are presented via indicator variables, but these latent variables have cut-off points that are estimated (Lee et al., 2018) via the following equation:

$$Y_{ij} = s \ if \ \mu_{s-1} < Y^*_{ij} \leq \mu_s \tag{6}$$

where μ_s are thresholds or cut-off points which are used to analyse the propensity of individuals to shift between adjacent categories in their comfort or perceived safety ratings (Chen et al., 2019). These cut-off values and thresholds are needed as they represent the point at which a respondent will change their dependent variable response. In other words, Y_{ij} is observed to be in category s when the latent variable falls in the interval between μ_s and μ_{s-1} (Zheng et al., 2014). Maximum Likelihood (ML) estimation method was used to estimate the model parameters (β, μ, ν and σ). In order to test the goodness of fit, the Akaike Information Criterion (AIC) or Bayesian Information Criterion (BIC) are used as they correctly penalize every additional independent variable that is added to the model (Washington et al., 2020).

4.4.1. Elasticities

Due to the nonlinear nature of Eq. (1), the β coefficient values can't be directly interpreted as increases or decreases in the dependent variables (Anarkooli et al., 2017). As such, the elasticities will be calculated to show the percentage of contribution that each independent variable has to each dependent variable (Hirk et al., 2020). Eq. (7) represents the elasticity calculation where i is the individual at the jth roundabout location and where β_p represents the explanatory variable p:

$$Elasticity_{sp|X_{jp}} = \frac{X_{jp}}{P(Y_{ij} = s|X_{ij})} \times \left[f\left(\mu_{s-1} - X'_{ij}\beta\right) - f\left(\mu_s - X'_{ij}\beta\right) \right] \times \beta_p \quad (7)$$

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

5. Results

In total, 260 respondents completed the survey. Out of those, 239 rode a bicycle (any type) and therefore, the responses from these participants were used to estimate the model. The average survey respondent age was 40 years old, with a standard deviation of 13.6 years old. More than half (52.5%) of the respondents were male which is representative of the cycling population. Seventy-five percent of the respondents reported residing in the Netherlands. Most respondents (85%) reported that they did not have a bicycle crash within the last three months. Each respondent had to rate their perceived safety and comfort for cycling through all eight roundabouts. In total, 1912 perception ratings were collected. Most (78.1%) answers to the dependent variables' questions (safety and comfort) are in the range from 3 (neutral) till 5 (very comfortable or very safe). Most respondents replied that they walk or use a normal bicycle daily or 4 to 6 days per week (60% and 56% respectively).

5.1. Ordered probit model results

The estimated coefficients of the impact of roundabout characteristics and sociodemographic and behavioural characteristics on perceived safety and comfort ratings, according to the random effect ordered probit model, are presented in Table 4. It is important to note that the age variable was transformed into a binary variable, with ages grouped into individuals over 40 years old and individuals under the age of 40, which was the reference category.

Table 4
Results of the bivariate random effects ordered probit model.

	Comfort			Perceived safety		
Variable	Estimate	SE	z-value	Estimate	SE	z-value
Thresholds						
Comfort: very uncomfortable-uncomfortable	1.239	0.056	22.13	–	–	–
Comfort: uncomfortable-neutral	1.792	0.092	19.517	–	–	–
Comfort: neutral-comfortable	1.896	0.061	31.16	–	–	–
Comfort: comfortable-very comfortable	2.909	0.069	42.32	–	–	–
Safety: very unsafe-unsafe	–	–	–	1.079	0.062	17.49
Safety: unsafe-neutral				1.955	0.098	19.961
Safety: neutral-safe	–	–	–	1.970	0.069	28.54
Safety: safe-very safe	–	–	–	3.419	0.081	41.99
Coefficients:						
Roundabout design and traffic characteristics						
Bike Volumes: Yes	−0.122	0.050	−2.464	−0.143	0.050	−2.852
Bike Yielding Priority: Yes	0.560	0.050	11.167	0.529	0.051	10.386
Bi-Directional: Yes	−0.035	0.035	−1.000	–	–	–
Buffer width: Large	0.008	0.049	0.168	−0.036	0.049	−0.727
Art/Ads in Centre: Yes	−0.044	0.035	−1.256	–	–	–
Four legs-entrance points: Yes	−0.146	0.049	−2.933	−0.122	0.050	−2.439
Socio-demographic & behavioural characteristics						
Respondent residence: NL	0.416	0.059	6.981	0.486	0.060	8.049
Age Category: 40+	−0.018	0.051	−0.341	−0.181	0.053	−3.439
Gender: Male	0.017	0.052	0.322	−0.026	0.053	−0.492
Bicycle crash history: Recent	−0.382	0.085	−4.514	−0.311	0.085	−3.681
Violations: Most of the time	0.268	0.112	2.401	0.335	0.109	3.074
Errors: Most of the time	−0.536	0.259	−2.067	–	–	–
Positive behaviour: Most of the time	0.079	0.036	2.180	–	–	–
Normal bicycle Freq: Everyday	0.293	0.065	4.539	0.138	0.064	2.163
E-bicycle Freq: Everyday	0.349	0.116	3.021	0.339	0.113	2.991
Cargo bicycle Freq: Sometimes	−0.095	0.168	−0.566	−0.693	0.208	−3.330
Cargo bicycle Freq: Everyday	0.970	0.848	1.144	1.209	0.389	3.102
Error Structure:						
Covariance comfort & perceived safety	0.809	0.009	86.01			
Measures of statistical fit:						
LL0 (log-likelihood of the null model)	−4498.261					
LL (log-likelihood at convergence)	−4315.395					
McFadden's Rho Square	0.041					
Akaike information criterion (AIC)	8710.415					
Bayesian information criterion (BIC)	8931.607					

The estimated 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 dependent variable, the thresholds very uncomfortable-uncomfortable and very unsafe-unsafe were reference thresholds in the model. All the other threshold estimates were statistically significant at the 99% confidence level. In addition, the intercepts for both variables and the correlation estimates of the random terms for the two variables are also statistically significant at the 99% confidence level. There was a statistically significant high positive covariance of 0.809 between the perceived safety and perceived comfort 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 association.

Yielding priority had a positive parameter that was significant at 99% confidence level. This means that if there is yielding priority for bicycles (i.e. drivers have to yield to cyclists), respondents' perceptions of safety and comfort, as cyclists, increase. On the contrary, the parameter of higher bicycle volumes showed a negative sign, indicating that respondents' perceived safety and comfort levels decrease when bicycle volumes on roundabouts are higher. This was supported by the survey answers which noted that increased bicycle congestion reduces riding comfort, especially when turning. The parameter of CBQ violations variable was marginally significant for comfort but statistically significant for perceived safety; this is intuitive as violations have been shown to be well associated with perceived safety (Friel et al., 2023). The model results found that Dutch respondents perceived higher safety and comfort levels, when compared with respondents who currently do not live in the Netherlands. The parameter of age was negative, which is according to expectations: older cyclists often perceive lower safety and comfort ratings in general, so it would also apply at roundabouts (Kazemzadeh et al., 2024; Shen et al., 2020; Singleton and Poudel, 2023; Wegman and Schepers, 2024). An older population has greater sensitivity to roundabout characteristics whilst controlling for certain design features such as yielding priority, compared with a younger population. The parameter of bicycle crash history was negative and statistically significant, which is intuitive and aligns with past studies showing that individuals who have experienced a recent crash report lower perceived 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. As people cycle more, they have higher perceived safety and comfort levels. The results of the model follow the conceptual model shown in Fig. 2 with exception of four independent variables that were dropped due to a low explanatory value (bike path shape, self-ascribed cycling skill level, income, and education).

5.2. *Elasticities*

Due to the nonlinear nature of random effects ordered probit equations (Eq. 1), one cannot directly measure the impact of variables on safety and comfort from beta coefficients (estimate values). As such, elasticities are calculated for every level of each 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 (Anarkooli et al., 2017). The calculated elasticities show the percentage of contribution that each independent variable has on each dependent variable (Hirk et al., 2020). In essence, it is the change in probability that a person falls 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 dependent variables. Tables 5 and 6 show the elasticities from the ordered probit model for each category of each dependent variable.

According to the elasticities, the presence of yielding priority for bicycles (e.g. vehicles have to yield to bicycles) increases the

Table 5
Elasticities of variables – Comfort.

Variable	Very uncomfortable	Uncomfortable	Neutral	Comfortable	Very comfortable
Roundabout design and traffic characteristics					
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 cycle track: 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 Centre	0.320	0.220	−0.010	−0.322	−0.250
Four legs-entrance point	0.390	0.240	0.010	−0.420	−0.108
Socio-demographic & behavioural characteristics					
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 frequency: Everyday	−0.286	−0.119	0.038	0.204	0.308
***E*-bicycle frequency: Everyday**	−0.119	−0.284	−0.096	0.429	0.198
Cargo bicycle frequency: Sometimes	0.237	0.169	0.056	−0.295	−0.167
Cargo bicycle frequency: Everyday	−0.036	−0.429	−0.033	0.444	0.299

Bold indicates an independent variable that is statistically significant at least at the 90% confidence level.

Table 6
Elasticities of variables – perceived safety.

Variable	Very unsafe	Unsafe	Neutral	Safe	Very safe
Roundabout design & traffic characteristics					
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 cycle track: Yes	–	–	–	–	–
Buffer width	0.350	0.230	−0.040	−0.422	−0.298
Art/Ads in Centre	–	–	–	–	–
Four legs-entrance points	0.390	0.260	−0.040	−0.422	−0.298
Socio-demographic & behavioural characteristics					
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	–	–	–	–	–
Positive behaviour: Most of the time	–	–	–	–	–
Normal bicycle frequency: Everyday	−0.359	−0.186	−0.249	0.456	0.228
***E*-bicycle frequency: Everyday**	−0.306	−0.149	0.068	0.265	0.487
Cargo bicycle frequency: Sometimes	0.117	0.059	−0.368	−0.088	−0.159
Cargo bicycle frequency: Everyday	−0.358	−0.296	−0.049	0.198	0.269

Bold indicates an independent variable that is statistically significant at least at the 90% confidence level.
"—" indicates that the independent variable was removed from the model (refer to Table 4) and therefore no elasticity was calculated.

probability of a cyclist feeling comfortable by 20%, whereas the lack of yielding priority increases the probability of a cyclist feeling very uncomfortable by 18%. The probability of a cyclist feeling very comfortable is only 9.8%, which means that there may still be hesitancy and doubts about yielding priority being fully effective or safe.

In terms of perceived safety at roundabouts, the importance of cyclists having yielding priority is the same as if a cyclist were to sometimes ride a cargo bicycle (0.158 safe versus −0.159 very safe respectively). The elasticities of the final model show that the more frequently people ride bicycles or cargo bicycles, the higher the probability that they 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. 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 cycle, the more confidence and perceived control they may have, which leads to higher perceived safety and comfort levels (Marín Puchades et al., 2018; Sanders, 2015).

6. Main findings and discussion

In this section the main findings from this study, stemming from the integrations of findings from the surveys (including the open questions), expert insights, and filed observations, are presented and discussed.

6.1. Deviations from design guidelines

The expert insights revealed that deviations from design guidelines occur due to politics, geometrical constraints, private land boundaries, trees, water management or, in rare cases, funding challenges. The general design framework in the Netherlands, which should be followed for all roadway projects, details how deviations should be clearly documented (Rijkswaterstaat, 2024). However, there is no official review board since Dutch 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 centre of the roundabout means that 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 design guidelines.

Roundabouts four, five, and six presented in the survey (modified roundabouts based on Planbaan/Kernbaan, Amstelplein, and Gordelweg/Rodenrijsestraat, respectively from Table 2), purposely did not follow CROW design guidelines as they did not provide yielding priority to cyclists. At these locations there was a noticeable drop in the percentage of respondents who answered favourably, i.e., neutral to high ratings of perceived safety and perceived comfort. The average neutral-positive ratings were lower at these roundabouts for both perceived comfort (65.2% versus 80.4%) and perceived safety (74.0% versus 86.1%) compared with roundabouts that give cyclists priority.

A design change that gives yielding priority to vehicles increases the probability of a cyclist feeling very uncomfortable by 18%. Deviating from design guidelines does negatively impact a cyclist's perceived safety; which is in line with past studies that looked at yielding behaviours (Lawton et al., 2004; Zhang and Ma, 2015), and also a cyclist's comfort level.

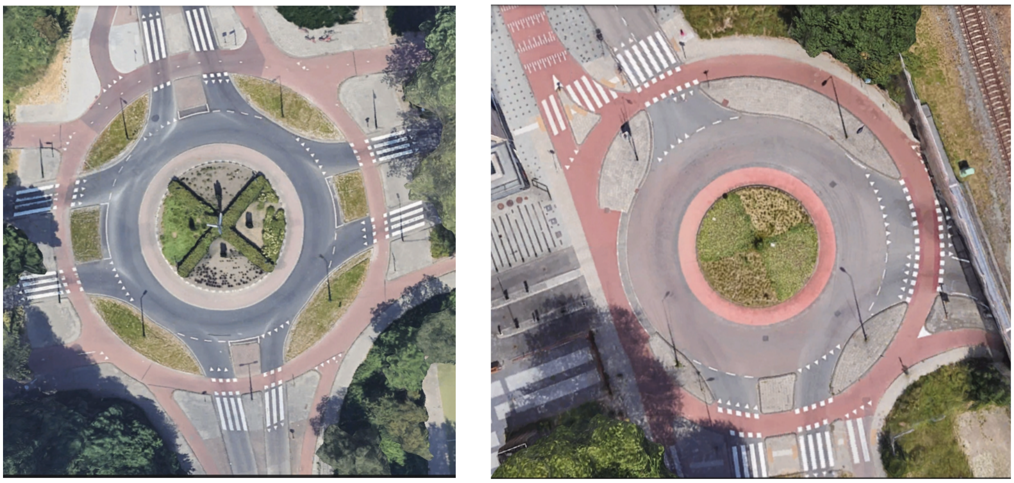
6.2. Impact of roundabout bicycle infrastructure design and behavioural factors on cyclists' perceived safety and comfort

The findings of the random effects ordered probit model regarding the number of legs at a roundabout and yielding priority are in line with past studies that found that limiting the number of legs at a roundabout and providing bicycles with yielding priority increase perceived safety (ARUP, 2022; Distefano et al., 2019). The model results for yielding priority align with respondents' answers to the open-ended question, stating that Dutch drivers almost always yield to cyclists, 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 respondents noting that it's much more difficult for a cyclist 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 (CROW, 2019; Jensen, 2017). Field observations support that yielding priority should be given to cyclists, as there were many illegal bicycle crossings observed at Putsebocht tram stop (Fig. 1b), where cyclists must yield to all other traffic.

Regarding the bicycle volumes variable, the findings are consistent with past studies: once the bicycle volume is higher than a certain threshold, the existing capacity of the cycle tracks can no longer accommodate it, leading to cyclists feeling less safe or comfortable (Reggiani et al., 2022). More bicycle traffic means more conflicts at bicycle crossing points and other critical decision areas such as entering or exiting a roundabout (Dabbour and Easa, 2008; Pulvirenti et al., 2021). Due to the binary nature of the variables included in this study and other variables, it is impossible to pinpoint at what bicycle volume threshold a shift in perception occurs.

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 compared to roundabouts with lower bicycle volumes. This is intuitive since a strong attractor, such as a grocery store or a geographic barrier, generates more turning movements which causes friction amongst cyclists and between cyclists and other modes. This would cause lower perceived safety levels 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) did not show a visible relationship between the location of the grocery store and bicycle movements. An explanation for this could be the additional perceived risk associated with fast moving trams or other public transport, causing cyclists to proceed more slowly and cautiously. Some roundabouts, such as at Gordelweg/Rodenrijsestraat, Rotterdam (Fig. 4a) or Amstelplein, Amsterdam (Fig. 4b) were observed to have significant bicycle volumes only on one side due to natural barriers (e.g., train tracks, highway bridges, canals).

Overall, this Section answers the question which types of bicycle infrastructure design and behavioural factors affect cyclists' perceived safety and comfort. In addition, this study also evaluated 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. However, from the results of this study it is possible to conclude that there is a positive significant correlation between cyclists' traffic law violations,



(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.

Fig. 4. Roundabouts that have strong directionality due to geographic barriers. Images courtesy of Google Earth. (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.

measured using the Violations group of the CBQ independent variable, and perceived safety and comfort they experience at roundabouts. This aligns with the theory of planned behaviour, that found that the more perceived control one has, the less risk and more comfort they perceive (Ajzen, 1991). This conclusion must however be taken with caution as other factors, such as risk tolerance, societal norms, stress, and perceived control likely influence a person's violation behaviour and comfort.

6.3. Cyclist population groups

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 (Schepers et al., 2017). The gender independent variable was statistically insignificant. According to the model results, non-Dutch people feel less comfortable or safe at roundabouts. 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 cycling near conflict points such as an urban roundabout.

A person's history and familiarity with cycling were found to significantly affect perceived safety and comfort. The cargo bicycle independent variable was found to be statistically significant in the model for the perceived safety variable but not for the comfort variable. Since the error structure between the two 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 usage frequency on perception of comfort.

What is noteworthy from the ordered probit model is that the sign of the coefficient for cargo bicycle usage 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. Cyclists 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 cyclist feeling comfortable by 30%. The finding about the sign of the cargo bicycle usage variable, along with the CBQ questions, align with past studies which concluded that the more people cycle, the more confidence and perceived control they may have, which leads to higher perceived safety and comfort levels (Marín Puchades et al., 2018; Sanders, 2015).

Another notable finding of this study, in terms of perceived comfort towards roundabouts, was that 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 (Table 5). This insight means that designers and policy makers should think further about transportation mode frequency of use as an important consideration when analysing and designing urban roundabouts. For example, larger radii curves could improve perceived comfort for users of e-bicycles.

An interesting finding of this paper was that even though perceived safety and comfort were found to be highly correlated, their associations with the predictor variables, notably the errors and positive behavioural variables from the CBQ, and age, were not equal. The finding that Age is not statistically significant in perceived comfort, but it is in perceived safety, is remarkable. Errors and Positive behaviour attributes were statistically significant for comfort but not for safety, which could potentially relate to how an individual perceives their attentiveness or lack thereof as a trade-off for additional comfort (e.g. 'following all traffic rules in order to have a more pleasant cycling experience', or 'having a more laissez-faire attitude towards how close I follow another cyclist but I do it since it's comfortable for me since I do it all the time').

This research found that if a cyclist had a recent crash, the model showed that those cyclists would have lower perceived comfort, which is intuitive and aligns with risk homeostasis or perceived risk theory (Marín Puchades et al., 2018; Poudel and Singleton, 2022; Sanders, 2015; Singleton and Poudel, 2023). It also relates to the cognitive load of a cyclist where more complex functions, such as roundabouts would be naturally perceived less comfortable or safe than a non-junction separated cycle track. Another interesting finding was that participants residing in the Netherlands had a higher perceived comfort level, which could be theorized is due to their familiarity with roundabouts with cycle tracks, a general awareness of cycling and cycling needs and desires, and also the Dutch culture surrounding cycling and their attitudes towards traffic rules and rule compliance (de Waard et al., 2020; Schepers et al., 2017; Wegman and Schepers, 2024).

Even though this study used a dataset from the Netherlands and makes references to the Dutch design guidelines, the methodology of this study can be generalized, as this study did include non-Dutch residents, CBQ factors, and roundabout design guidelines are similar between countries. A review of Irish and US design guidelines showed a 95% comparison rate to the Dutch guidelines.

7. Study limitations

A strength of this research was the collection of participant data via both physical and non-physical means (e.g. handing out flyers to cyclists and via online forums) which allowed the researchers to reach a section of the population that might not have been reached otherwise. A limitation, on the other hand, is that although the sample used in this study is not small, it may still be not completely representative of all cyclists' population in the Netherlands. In terms of the recruitment, the apparent overrepresentation of Dutch participants and respondents reached via the TU Delft networks, for example, might limit the generalizability of the findings. Even within the Netherlands, regional differences in cycling culture, infrastructure, and policy, such as the contrasts between urban centres like Amsterdam, Rotterdam, or Utrecht and smaller towns or rural areas, could shape respondents' perceptions in distinct ways. Without adequately addressing these factors, it is difficult to determine how broadly the results can be applied beyond the surveyed population, even though other variables such as bicycle frequency use are generalisable to anywhere in the world. Making use of the

CBQ (or part of it), which has been tested for its applicability in many different countries (Useche et al., 2022), Cross-culturally approaching the cycling behaviour questionnaire (CBQ: Evidence from 19 countries), allows this research to also be transferable to other countries, even ones that don't necessarily have the same roundabout characteristics.

This research was limited by resources and time, which meant that a large model with many variables would not be feasible. Therefore, it was decided to use survey photos instead of doing an intercept survey based on real world conditions. Several previous studies have used this research method and could relate their findings to other studies that collected real world data (Poudel and Singleton, 2022; Singleton and Poudel, 2023; Wang and Gulsah., 2018). This research was limited by resources and time, which meant that a large model with many variables would not be feasible. Therefore, it was decided to use survey photos instead of doing an intercept survey based on real world conditions. Several previous studies have used this research method and could relate their findings to other studies that collected real world data. Using images of existing roundabouts may be more effective, as cyclists are likely to relate to them through frequent real-world experience, unlike computer-generated images, which may appear less realistic. Møller and Hels (2008)'s study did perform an intercept survey and their results showed that clear regulation and cyclist priority were preferred, and that traffic volumes and presence or absence of a cycle facility being important factors for subjective safety. These results align with the results of this research. Therefore, although respondents' perceived safety and comfort based on images of roundabouts might not hold the same level of realism as an intercept survey, the results of our study align well with findings from previous studies giving confidence in the results.

While modifying photographs (e.g., altering yielding priority or cycle track direction) can be a useful tool for testing specific scenarios, such adjustments may inadvertently compromise validity if the photo editing is not with a good quality. In our study even though image manipulations were necessary to have similar characteristics, the quality of the photo editing was such that it was still very realistic (even to the point it might confuse those familiar with the location), and the locations still adhered to the CROW design guidelines. However, greater transparency in acknowledging and addressing this issue, and validation of the realism via follow-up interviews with the respondents would increase the reliability of the study's results and conclusions.

Other limitations included the binary nature of the roundabout variables which meant that more detailed thresholds for bicycle volumes and buffer width could not be explored and the low number of data responses for certain transportation mode frequencies (car/motorcycle, scooter, and public transport). Both limitations meant that the model could not capture the detail and the number of variables initially hoped.

Performing field data collection and survey preparation in mid-April, when thunderstorms and fluctuating weather patterns are common, made it difficult to control for weather conditions. The aim was for the final survey images to represent a cloudy and partially wet day; however, some images ultimately appeared less wet than intended. Pavement wetness could affect cyclists' perceived safety and comfort 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 cyclists' perceptions. 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 perceived safety perceptions. Research that specifically interviews participants regarding compliance at specific roundabout design features could have overcome the shortcomings in the experimental design of this research.

The initial desire of this research was to compare objective safety with subjective safety, however in looking at the Dutch crash statistics from the 2013 to 2023 period, several challenges emerged, many of which are prevalent in other countries as well: Underreporting of crash data, most likely due to 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 (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-year 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.

Moreover, there are 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.

8. Conclusions and recommendations

This research investigated how bicycle infrastructure design at urban roundabouts affects cyclists' perceived safety and comfort by performing a stated choice experiment and analysing the data via a bivariate random effect ordered probit model. The underlying aim of this study was to provide conclusive support for design features that make cyclists feel comfortable and safe navigating roundabouts. The model results led to the following hypotheses confirmation:

1. A cyclist's perceptions of safety and comfort are highly correlated.
2. Yielding priority for cyclists leads to higher perceived safety by cyclists.
5. Higher bicycle volumes lead to lower perceived safety by cyclists.
6. Cyclists who have recently experienced a crash or “near miss” at a roundabout, will have lower perceived safety at a roundabout, regardless of the design features.
8. Elderly cyclists have a lower perceived safety level compared younger cyclists.

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

This conclusion answers the main research question: *What factors contribute to cyclists' perceived safety and comfort at roundabouts?*

It was found that people who: are older, or have had a recent bicycle crash, or committed errors while cycling (part of the CBQ error group), or sometimes ride a cargo bicycle, or do not reside in the Netherlands have lower perceived comfort at roundabouts. Regarding infrastructure, cyclists had lower perceived 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 cyclists and to maintain uniformity in design of urban roundabouts. In addition, future designs should follow national design guidelines, and work towards limiting bicycle congestion and minimizing the number of vehicular legs entering or exiting roundabouts. It is important also to consider objective safety data and outcomes as motorist behaviour is heavily influenced by design standards but also congestion, driver frustration, impatience, and even driver ignorance to traffic laws.

Certain factors were found to be statistically insignificant. These include buffer width (hypothesis #3), bi-directional bicycle paths (hypothesis #4), bicycle path shape, a cyclist's level of cycling skill level (hypothesis #7), and cyclist's income. All these variables, except income, were binary variables. Making them ordinal or changing the definition of these binary categories could affect the results. 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. By using this research's methodology and approach, in consideration of some of the research limitations and lessons learned from this study, future road designers will be able to create roundabouts that are safe and comfortable for cyclists of all ages and abilities.

Declaration of generative AI use in writing

The authors declare that no generative AI was used in this work.

CRediT authorship contribution statement

Ian Trout: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Salomons:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Amir Pooyan Afghari:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Haneen Farah:** Writing – review & editing, Supervision, Conceptualization, Methodology.

Ethics statement

The methods for data collection in the present study have been approved by the TU Delft Human Research Ethics Committee (Decision: 19 March 2024).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The anonymized dataset and analysis code used for the research can be found at https://github.com/eotrout/thesis_data.

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Ian Trout received his master's degree at Delft University of Technology in 2024. His research interests cover traffic safety, urban planning, and, recently, cycling infrastructure design and behavioural factors. Since 2024, he works as a senior engineer at Arup, leading a team of designers that are working on building out Dublin, Ireland's protected cycling network.

Maria Salomons received her Ph.D. in Applied Physics at Delft University of Technology. Her research interests lie in the fields of traffic management and control, road infrastructure design, and human factors related to these fields. She has been affiliated with the Department of Transport and Planning since 2003, currently serving as a lecturer who supervises students conducting research on a broad range of transport-related topics.

Amir Pooyan Afghari received his Ph.D. in Road Safety from the University of Queensland. His research interest is at the intersection of transport engineering, social science and data science: understanding human behaviour and its impact on road safety using observational data, statistical and econometric methods and machine learning algorithms.

Haneen Farah received her Ph.D. in Transportation Engineering from the Technion- Israel Institute of Technology. She is an Associate Professor in the Department of Transport and Planning and a co-director of the Traffic and Transportation Safety Lab. Her research interests lie in the fields of road infrastructure design, road user behaviour, and traffic safety. In her research she combines her expertise in transportation engineering, with her curiosity in the fields of human factors and econometrics. Before joining TU Delft, she was a postdoctoral researcher at KTH - Royal Institute of Technology, Stockholm, Sweden.