

# The role of linear green infrastructure in perceived cycling safety: insights from Berlin

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## Abstract

**Purpose** – This study aims to investigate how different attributes of cycling infrastructure, with a particular focus on linear green infrastructure (LGI), influence cyclists' perceptions of safety.

**Design/methodology/approach** – An online survey was conducted with 25,334 residents of Berlin, who rated a series of hypothetical urban cycling scenarios characterised by key attributes, including the presence of LGI. A hybrid mixed logit (HMXL) model was used to analyse the data, integrating both observed and latent psychological factors.

**Findings** – The results highlight that LGI plays a critical role in improving cyclists' perceptions of safety, particularly for vulnerable social groups (i.e. women, older cyclists, those traveling with children) who are more risk-averse. LGI is also particularly effective in mixed-traffic environments. While infrastructure width and the absence of commercial activity also influence safety perceptions, this study further suggests that well-designed cycling infrastructure, incorporating LGI, can increase the safety perceptions of more reluctant cyclists to ride in unfavourable weather conditions.

**Practical implications** – This study highlights the importance of investing in LGI, especially in areas with limited cycling infrastructure. In these contexts, the presence of LGI significantly enhances the perceived safety of cyclists, particularly for vulnerable social groups. Prioritising LGI in less-developed urban areas can have a large impact on increasing cycling adoption and improving safety perceptions.

**Originality/value** – This study contributes to the literature by examining the specific role of LGI in enhancing cycling safety perceptions by estimating a HMXL model, a novel methodological approach that deepens the understanding of the psychological and infrastructural factors influencing cycling behaviour.

**Keywords** Cycling, Safety perception, Cycling infrastructure, Hybrid mixed logit model, Linear green infrastructure

**Paper type** Research paper

## 1. Introduction

Promoting cycling as a daily mode of transport requires not only the provision of infrastructure, but also attention to its design quality. A growing body of research has shown that cyclists' perception of safety is a key factor influencing their willingness to cycle, particularly for more risk-averse groups such as women, older adults and less experienced riders (Garrard, 2021; Graystone *et al.*, 2022; Van Cauwenberg *et al.*, 2018). While objective safety measures (e.g. accident or injury rates) remain important, subjective safety – how safe people feel while cycling – can have an even stronger effect on cycling behaviour



(Gössling and McRae, 2022; Lizana *et al.*, 2021; Piras *et al.*, 2021). Much of the existing literature has focused on well-known infrastructure features that improve perceived safety, such as physical separation from motor traffic, lane width and intersection design (Handy *et al.*, 2014; Hull and O'Holleran, 2014; Nello-Deakin, 2020). However, the role of linear green infrastructure (LGI) – trees, hedges, and other vegetation placed alongside cycling routes – has received considerably less attention. While some studies suggest that greenery may enhance the cycling experience by reducing stress and increasing comfort (Hardinghaus and Papantoniou, 2020; Rossetti *et al.*, 2019), its potential to improve perceived safety remains underexplored, particularly in empirical studies using stated preference and behavioural data.

In this study, we address this gap by examining how different infrastructure elements – including LGI – affect cyclists' safety perceptions. We apply a hybrid mixed logit model, which integrates both observable design attributes and latent psychological factors, to analyse data from a large-scale online survey conducted in Berlin between December 2019 and February 2020. Respondents evaluated street images based on how safe they would feel cycling in each scenario. Our work builds on the Berlin data set previously examined in studies by Gössling and McRae (2022), von Stülpnagel and Binnig (2022) and von Stülpnagel and Rintelen (2024), but introduces two key innovations. First, we explicitly investigate the role of LGI – an aspect not considered in earlier analyses of this data set. Second, we use a more advanced econometric framework that allows us to capture both individual attitudes and infrastructure preferences simultaneously. We believe that this focus is particularly relevant for policy and planning, especially in urban contexts where physical space and financial resources are constrained. Green infrastructure may offer a flexible, cost-effective way to enhance cyclists' comfort and perceived safety, even where full physical separation is not feasible.

The paper is structured as follows: Section 2 reviews the relevant literature on infrastructure design and perceived safety. Section 3 outlines the data and survey method, while Section 4 presents the modelling approach. Section 5 discusses the results, and Section 6 concludes with practical implications and future research directions.

## 2. Background

### 2.1 Previous research works on the same data set

The data set used in our analysis has previously been analysed in research conducted by Gössling and McRae (2022), von Stülpnagel and Binnig (2022) and von Stülpnagel and Rintelen (2024), each using different analytical approaches. The analysis by Gössling and McRae (2022) provided a descriptive summary of the survey results and sparked the debate on the data. Among the key findings, the study identified several factors that increase perceived safety for cyclists, drivers and pedestrians. A key element is the clear separation of cycling infrastructure from the road and pavement, which should be reinforced visually and physically by grass strips or other barriers. In addition, where cycle lanes are on the road, a coloured surface improves safety perceptions by making the lane more recognisable to both cyclists and drivers. Finally, the study found that cars parked at the side of the road have a negative impact on perceived safety compared to scenarios without them. This is mainly due to the risk of collision and the potential danger of car doors opening unexpectedly, which is a concern for both cyclists and drivers.

The study by von Stülpnagel and Binnig (2022) analysed the perceived safety of cyclists in a specific urban context: a cycle lane on a main road. They estimated a generalised linear model. Among the main findings, the analysis showed that the presence of a dedicated cycle lane positively influences cyclists' perceptions of safety. This research confirms the

importance of designing cycling infrastructure that is clearly and physically separated from traffic. The study also looked at the influence of road markings and found that a solid line was perceived as significantly safer than a dashed or double line.

Von Stülpnagel and Rintelen (2024) investigated the perceived safety of cyclists, pedestrians and drivers in different mixed traffic scenarios using generalised mixed models. Their findings were consistent with previous research and confirmed the importance of protected, visible and wider cycling infrastructure in improving the perceived safety of not only cyclists, but also drivers and pedestrians in shared spaces. However, their study also highlighted the benefits of cycle boulevards – dedicated cycling infrastructure commonly found in the Netherlands, where motor vehicle access is restricted to local residents. In addition, in shared spaces between cyclists and pedestrians, the presence of cafés and other commercial activities was found to reduce perceived safety for both groups. In contrast, in mixed traffic scenarios involving cyclists and drivers, lower vehicle speeds and reduced traffic volumes contributed to increased perceived safety.

Our research builds on these previous studies by conducting a more focused analysis of cyclists' perceived safety, excluding drivers and pedestrians. Unlike previous research, we specifically examine two different urban cycling scenarios: a cycle path on a pavement and a cycle lane on a main road. In addition, we extend the scope of the analysis by examining key design elements of cycling infrastructure, with a particular focus on the role of LGI (e.g. hedges and flower boxes). This focus introduces a degree of novelty to our study. Finally, we extend previous research by investigating the influence of psycho-attitudinal factors to understand how and to what extent these factors influence cyclists' perceived safety.

### 2.2 Cycling infrastructure width

Studies such as Gössling and McRae (2022), Hull and O'Holleran (2014) and Li *et al.* (2012) have confirmed that the width of cycling infrastructure is a fundamental aspect in improving cyclists' perceptions of safety and comfort. On the one hand, a wider cycling infrastructure offers greater comfort by providing more space, facilitating smoother manoeuvring and helping to prevent collisions between cyclists (Schepers, *et al.*, 2023). Indeed, Boele-Vos *et al.* (2017) showed that narrow cycle lanes are a major cause of accidents in the Netherlands. They also highlighted another source of risk, namely, collisions with separation elements such as kerbs or bollards. Another study, by Vansteenkiste *et al.* (2013), investigated the visual behaviour of 12 adult cyclists riding on cycle lanes of different widths (10, 25 and 40 cm) over a distance of 15 m at different speeds. They found that cyclists tended to ride faster on wider lanes because they did not have to concentrate as much to maintain their position. This made the experience less stressful and more comfortable. On the other hand, a wider lane allows cyclists of different skill levels to coexist, reducing the risk of dangerous situations. Zamanov (2010) analysed 15 two-way cycling infrastructure of different widths in Vienna (Austria) and showed that cyclists maintained greater distances from each other as lane width increased. In addition, wider lanes allow cyclists to maintain an adequate distance from pedestrians and vehicles, especially in mixed traffic situation where there are no separating elements (von Stülpnagel and Rintelen, 2024). Similar findings were reported in contexts beyond Europe. For example, Zhao (2014) analysed cycling behaviour in Beijing and found that wider and better-marked lanes significantly increased cyclists' confidence, particularly in high-traffic conditions. Similarly, in Bogotá, wider segregated cycling lanes were positively associated with perceived safety and frequency of use (Rosas-Satizábal and Rodríguez-Valencia, 2019).

### 2.3 Separation and coloured surfaces

Many studies have highlighted the importance of providing adequate spatial and physical separation between cyclists and other road users, especially in shared traffic situations (Furth, 2021). For example, adequate spatial separation at the sides of cycling infrastructure can protect against certain hazards, such as sudden opening of car doors or dangerous parking manoeuvres, and prevent space invasion by pedestrians (Fees and LaPlante, 2015). Boundary lines further improve visibility, clearly delineate lane boundaries and positively influence cyclist behaviour. By precisely defining the cycling surface, these lines help prevent cyclists from leaving the cycling infrastructure or accidentally skidding (Westerhuis *et al.*, 2019). In support of this perspective, Van Houten and Seiderman (2005) found that cyclists maintained a greater distance from parked cars in the presence of edge lines, while Schepers and den Brinker (2011) emphasised the importance of drawing both edge and centre lines to reduce the risk of accidents, as they regulate cyclists' behaviour while cycling.

In addition, physical separation elements such as bollards, raised kerbs and planters are often used when cycle lanes are located on roads (Pucher *et al.*, 2010). In Latin American cities such as Santiago and Mexico City, physically protected lanes with planters or parked cars are increasingly used to shield cyclists from traffic (Oviedo *et al.*, 2020), a strategy that has shown promising results in terms of perceived safety. In South-East Asia, recent studies (e.g. Maohao *et al.*, 2021) suggest that marked separation and surface differentiation in Singapore's dense urban network also play a key role in increasing comfort and trust in cycling infrastructure. A study by Lin and Lou (2022) in Toronto showed that the construction of protected cycle lanes significantly reduced cyclist crashes, with the positive effects extending to adjacent streets. In addition, the stated preference study by Hardingham and Papanitiou (2020) found that protected cycle lanes with bollards increased the likelihood of cycling.

Finally, another important aspect is the surface colour, either on the entire lane or at critical points (Auteliano and Felice, 2021). This practice is common in European cities such as Paris and Copenhagen. In the USA, however, some cities have begun to colour cycle lanes to highlight potentially dangerous sections, especially near intersections (Pucher *et al.*, 2010). The colours are intended to provide visibility and contrast with the adjacent surface, with blue, red and green being commonly used. Karlsen and Fyhri (2020), in a survey conducted in four major cities in Norway, found that people who were used to coloured cycle lanes perceived red as the safest solution, while those who were not used to it preferred green, in both cases over blue. However, the cost of surface painting remains an obstacle that may discourage administrations (Auteliano and Felice, 2021).

### 2.4 Linear green infrastructure

The presence of LGI along cycling infrastructure is positively correlated with bicycle use (Botes and Zanni, 2021; Nawrath *et al.*, 2019; Ricchetti *et al.*, 2024). In addition, the study of its impact on the perception of safety is an emerging topic that opens new interesting research perspectives. For example, Lusk *et al.* (2020) found that among 836 people surveyed, the combination of trees and shrubs between bike lanes and between roads or parked cars was the most preferred, followed by trees alone. Indeed, the literature is aligned in confirming that LGI acts as an effective barrier, separating spaces shared by cyclists and pedestrians, reducing the risk of collisions (Furth, 2021; Lin and Lou, 2022) and increasing safety from vehicular traffic (Mertens *et al.*, 2017). However, the literature highlights the need for regular maintenance of this type of infrastructure to prevent negative safety impacts that may discourage cycling (Evans-Cowley and Akar, 2014; Xie and Spinney, 2018; Nawrath *et al.*, 2019). While most empirical studies on LGI are based in Europe, emerging evidence from

other regions supports its relevance globally. For instance, in Columbus, OH, [Park and Akar \(2019\)](#) found that roadside greenery not only reduced perceived traffic stress but also encouraged greater route continuity among cyclists. Similarly, in Rio de Janeiro, Brazil, [Ferraz et al. \(2025\)](#) found that cyclists perceive LGI as strategic to provide crucial benefits while using cycle lanes, such as heat reduction and shade creation.

### 2.5 Surrounding environment

For the effectiveness of cycling infrastructure, the quality of the surrounding environment is as important as its design. Implementing speed limits and reducing traffic volumes are among the most effective measures to improve cyclists' perceptions of safety, as highlighted by [Caulfield et al. \(2012\)](#) in a stated preference study conducted in Dublin (Ireland). The study by [Ghekiere et al. \(2015\)](#), which analysed the preferences of parents and children, confirmed that speed limits and reduced traffic volumes have a significant impact on cycling. In addition, a research by [Mertens et al. \(2017\)](#) involving 1,950 middle-aged adults highlighted that when physical separation of cycle lanes from motorised traffic is not possible, reducing traffic speed from 50 to 30 km/h is an effective measure to encourage cycling. Similarly, [Sener et al. \(2009\)](#) in Austin, TX, found that cyclists preferred continuous cycling infrastructure with fewer stop signs and intersections, lower traffic volumes and speeds, and traffic lights.

### 2.6 Psychological and attitudinal latent factors

The study of personal perceptions, psychological and attitudinal latent factors is fundamental to the analysis of cycling mobility. They are crucial for understanding safety perceptions ([Barberan et al., 2017](#); [Christ et al., 2023](#)). [Piras et al. \(2021\)](#) estimated a hybrid choice model based on a survey of 2,128 people in 2016, highlighting that positive perceptions of cycling infrastructure encourage its provision, while perceptions of the positive benefits of cycling and perceptions of cycling comfort are positively associated with the propensity to cycle more. Similarly, the study by [Sottile et al. \(2019\)](#) showed that the availability of cycling infrastructure and facilities, as well as positive perceptions of cycling as a mode of transport, increased the propensity to cycle. Finally, [Muñoz et al. \(2016\)](#) explored perceptions of bad weather. They found that as precipitation increased, people in general were more likely to choose not to cycle, while snowfall was only a significant deterrent for less experienced cyclists. Therefore, to gain a broader understanding of cycling, it is essential to explore the psychological factors that may influence bicycle use, design preferences and people's decision-making processes.

## 3. Methodology and data analysis

### 3.1 Research area

Berlin, the capital and largest city of Germany, is a dynamic and cosmopolitan urban centre with a population of approximately 3.8 million and a population density of 4,220 inhabitants per square kilometre. The city is relatively flat and has a polycentric urban structure, administratively divided into 12 districts since 2001 ([Meng et al., 2014](#)). Its diverse population and urban morphology provide a relevant context for studying active mobility policies and infrastructure use. Cycling infrastructure development in Berlin began gaining significant traction in 2004, with the city's Senate adopting its first dedicated cycling strategy. This plan aimed to increase the modal share of cycling from 10% to 15% by 2010. However, progress was slowed due to the 2008 global financial crisis, which constrained public investment and delayed infrastructure expansion. The limited provision of safe cycling routes contributed to growing dissatisfaction among cyclists and, in 2016, sparked a

popular initiative demanding structural improvements and legislative action. This culminated in the 2018 adoption of Germany's first bicycle law as part of Berlin's broader mobility strategy (Werschmöller *et al.*, 2024).

This law promoted the development of a city-wide cycling network with a planned total length of 2,400 km and a minimum infrastructure width of 2.5 m. Investment in cycling infrastructure increased significantly, rising from under €5m in 2016 to over €30m in 2020. However, implementation targets have often fallen short. Between 2017 and 2020, fewer than 100 km of new cycle lanes were built. By 2024, only 23.3 km of new lanes had been completed, far below the target of 60 km. The rollout has also varied widely across districts, with central areas such as Mitte constructing over 3 km of new infrastructure, while some peripheral districts (e.g. Lichtenberg) built none at all. Despite these challenges, Berlin remains an important case study due to its ongoing transformation and efforts to improve cycling conditions in a complex and densely populated urban setting.

### 3.2 The questionnaire

The main aim of the survey was to explore the respondents' perceived safety by rating different hypothetical urban cycling scenarios. The survey, called "Straßencheck", was designed as an online questionnaire published on the website of the Berlin daily newspaper *Tagesspiegel*. Users were directed to the survey through a special article and an advertising banner, while a front page article in the newspaper helped to launch and spread the initiative. The survey was launched in December 2019, and data collection is still ongoing.

The survey was originally conceived and commissioned by the research and advocacy organisation [FixMyBerlin \(2025\)](#) GmbH, a project funded by the Federal Ministry for Digital and Transport and the Berlin Senate within the CityLAB Berlin initiative, in collaboration with the *Tagesspiegel* editorial team. The purpose of the initiative was to collect large-scale, user-generated insights into perceived safety across different cycling infrastructure designs in Berlin, to inform both public debate and policymaking around urban mobility. The scenarios presented in the questionnaire were based on real Berlin locations, with digitally modified elements (e.g. bike lanes, greenery, barriers) to allow comparative assessment. The design of the questionnaire was supervised by experts in mobility planning and behavioural research ([FixMyBerlin, 2025](#)).

The questionnaire consists of three main sections. The first section aims to collect opinions and personal experiences related to traffic in Berlin. The second section focuses on collecting information on the socio-economic characteristics of the participants, such as age, gender and place of residence. This part of the survey also includes questions on transport habits, looking at the availability and frequency of use of different modes of transport. With regard to the frequency of cycling, respondents are divided into "non-regular cyclists" and "regular cyclists". For non-regular cyclists, a specific multiple-choice question is asked about the reasons for not using the bicycle more often. Seven deterrents are listed: 1. lack of ability; 2. lack of safe infrastructure; 3. too long distances; 4. influence of others; 5. physical fatigue; 6. lack of a personal bicycle; 7. inability to take children on bike. There is also a space for further comments. For regular cyclists, they were asked to rate, on a five-point Likert scale, four items that could motivate or discourage them to cycle: 1. the perception of insecurity when cycling in Berlin traffic; 2. the perception that cycling is not a fast and flexible mode of transport; 3. the perception that cycling is an unpleasant mode of transport; 4. the perception that bad weather is an obstacle to cycling.

Finally, in the third section, participants are asked to rate 3D images of hypothetical urban cycling scenarios using a three-point Likert scale (1 = not safe; 3 = very safe). The question was "You cycle: do you feel safe here? (Sie fahren Fahrrad: Fühlen Sie sich hier sicher?)".

The scenarios are of three types: 1. Cycle lanes on main roads, hereafter referred to as MS; 2. Cycle path on pavement, hereafter as CP; 3. Cycle lanes on side roads (see [Plate 1](#) as an example). The full survey included about 1,900 images resulting from the combination of the different attributes and attribute levels ([Tables 1 and 2](#)).

In contrast to the research by [von Stülpnagel and Rintelen \(2024\)](#), where only some of the attributes were selected [1], our study included all of them. In addition, we chose to analyse only two of the three scenarios included in the questionnaire: CP and MS<sup>2</sup>. This choice was motivated by the fact that only these scenarios have a specific attribute related to LGI which is the main focus of our research. In the CP scenario, the cycle path can be bordered by hedges, while in the MS scenario planters can act as a separation between cycle lanes and the road. Respondents were divided into three different categories according to their frequency of use of motorised transport, cycling and walking. Their assigned category determined the visual perspective of the images they rated. After an initial evaluation of ten images for cyclists, participants could choose to continue rating further images from the same perspective or to switch to a different perspective (e.g. cyclist to driver). The exercise allowed participants to rate as many images as they wished.

### 3.3 Sampling strategy and sociodemographic characteristics of the sample

The data we analysed, which is available online in JSON format, covers the period from December 2019 to February 2020. The images to be evaluated could be viewed from three



**Plate 1.** Example of two images from the MS (on the left) and CP (on the right) scenarios  
Source: <https://radwege-check.de>

**Table 1.** Attributes and attributes' levels of the CP scenario

Attribute	Levels
Area to the left of the cycle path	Moving traffic   Stationary car parking   Hedge
Width of separation on the left of the cycle path	-   Narrow separation left (0.25 m)   Wide separation left (0.75 m)
Type of separation on the left of the cycle path	-   Grass strips   Raised pavement
Type of structural separation	-   Bollard
Width of the cycle path	Narrow (2.00 m)   Wide (3.50 m)
Width of separation on the right of the cycle path	-   Narrow separation left (0.25 m)   Wide separation left (0.75 m)
Type of separation on the right of the cycle path	-   Grass strips   Raised pavement
Area to the right of the cycle path	Hedge   Footpath (pavement and frontage)
Pavement width	Narrow (2.50 m)   Wide (5.00 m)
Commercial use on the pavement	-   Yes

**Source(s):** Authors' own work

**Table 2.** Attributes and attributes' levels of the MS scenario

Attribute	Levels
Type of traffic lane	Motor vehicle lane   Tram lane   One-way lane   Bus lane
Traffic volume	-   High   Normal
Traffic speed	-   30 km/h   50 km/h
Width of the cycle lane	-   Narrow   Wide
Position of the cycle lane	-   Between the traffic lane and the parking area or roadside Between parked vehicles and the roadside
Surface of the cycle lane	-   Asphalt   Asphalt coloured   Asphalt coloured hatching
Width of separation on the left of the cycle lane	-   Narrow separation (0.25 m)   Wide separation (0.75 m)
Marking of the left side of the cycle lane	Double line   Solid line   Zebra striped area   Dashed line
Physical separation on the left of the cycle lane	-   Planter box   High bollards   Low bollards
Width of separation on the right of the cycle lane	-   Narrow separation (0.25 m)   Wide separation (0.75 m)
Marking of the right side of the cycle lane	Double line   Solid line   Zebra striped area   Dashed line
Parking	-   Parallel parking

Source(s): Authors' own work

different perspectives, depending on the frequency of use of bicycle, motorised vehicles or the frequency of walking. This hence made it possible to divide the respondents into three categories: cyclist, pedestrian and driver. However, unlike the analysis by [von Stülpnagel and Rintelen \(2024\)](#), which included all three perspectives, our study focuses exclusively on cyclist-related data. This approach is intentional because we are interested in understanding if and how LGI affects cyclists' perceived safety while cycling. After a process of data quality check to exclude inconsistent data, the final sample used for the analysis consists of a total of 30,269 individuals and a total of 398,358 observations, representing 84% of the raw data. The distribution of the sample characteristics is fairly homogeneous across both scenarios (see [Tables 3 and 4](#)).

In terms of gender, the analysis revealed that men are over-represented compared to women. This shows a discrepancy compared to the actual distribution in the city (49% male) ([von Stülpnagel and Rintelen, 2024](#)). For what concerns the age distribution of the sample, the majority is between 25 and 64 years old in both scenarios. However, the age distribution does not align with the official 2023 statistics for Berlin population. Both the youngest and the oldest segments of society are underrepresented in our sample. In addition, a small proportion of our respondents reported having children under the age of 12. The sample is also biased towards people who own a bicycle and who cycle regularly (from once a week to almost daily). As noted by [von Stülpnagel and Rintelen \(2024\)](#), the demographics of the sample do not fully represent the Berlin population. However, the large sample size increases the reliability of the analysis, which is more reflective of regular cyclists than the broader Berlin population.

For those who reported rarely or never cycling, three main barriers were identified. The most common barrier is distance, followed by lack of safe cycling infrastructure and lack of a personal bicycle. In addition, in terms of psycho-attitudinal factors reported by regular cyclists, the majority in both scenarios reported not feeling safe when cycling in traffic, feeling faster and more flexible when cycling, and enjoying cycling. Finally, a significant proportion of the sample reported that they would not cycle in bad weather (see [Table 5](#)).

#### 4. Modelling framework

We analysed the data by estimating a hybrid mixed logit (HMXL) model, which combines the flexibility of the mixed logit framework with structural equation modelling (SEM) to account for psycho-attitudinal factors – intangible and unobservable elements that influence

**Table 3.** Summary statistics of the sample (CP scenario)

Socio-economic characteristics	N	%
Total sample:	15,311	
Total observations	241,315	
<i>Gender</i>		
Male	9,980	65
Female	5,331	35
<i>Age</i>		
Under 18 years old	69	0.4
From 18 to 24	776	5
From 25 to 29	1,388	9
From 30 to 39	4,560	30
From 40 to 49	3,351	22
From 50 to 64	3,964	26
From 65 to 74	1,034	7
Above 74 years old	169	1
<i>Having children under 12 years old</i>		
Yes	3,773	25
No	11,538	75
<i>Having a bicycle of property</i>		
Yes	13,443	88
No	1,868	12
<i>Being a regular cyclist</i>		
Yes	9,273	61
No	6,038	39
<i>Long bike trip (&gt;30 min)</i>		
Yes	1,838	12
No	13,473	88
<i>Living in the Mitte district</i>		
Yes	1,341	9
Other districts	13,970	91
<b>Source(s):</b> Authors' own work		

human behaviour and decision-making processes (Abou-Zeid and Ben-Akiva, 2024; De Dios Ortúzar and Willumsen, 2024; Giansoldati *et al.*, 2020). The term “mixed” refers to the inclusion of random parameters, meaning that some coefficients are not fixed, but instead vary according to a specified probability distribution. This approach allows for capturing unobserved heterogeneity across individuals.

We estimated a hybrid mixed logit model for each of the two scenarios under investigation, representing different types of cycling infrastructure: a cycle path on the pavement and a cycle lane on a main road. The safety rating was used as the ordinal dependent variable, with various attributes and socio-economic characteristics as predictors. In addition, we included a latent variable. These factors were included in both models.

The SEM has two components. The *measurement equation* that describes how the latent variable can be measured by indicators. We modelled it as a binary logit model:

**Table 4.** Summary statistics of the sample (MS scenario)

Socio-economic characteristics	N	%
Total sample	14,958	
Total observations	157,043	
<i>Gender</i>		
Male	9,770	65
Female	5,188	35
<i>Age</i>		
Under 18 years old	68	0.4
From 18 to 24	759	4
From 25 to 29	1,348	9
From 30 to 39	4,472	30
From 40 to 49	3,275	23
From 50 to 64	3,868	26
From 65 to 74	1,005	7
Above 74 years old	163	1
<i>Having children under 12 years old</i>		
Yes	3,699	25
No	11,259	75
<i>Having a bicycle of property</i>		
Yes	13,143	13143
No	1,815	1815
<i>Being a regular cyclist</i>		
Yes	9,066	61
No	5,892	39
<i>Long bike trip (&gt;30 min)</i>		
Yes	1,799	12
No	13,159	88
<i>Living in the Mitte district</i>		
Yes	1,296	9
Other districts	13,662	91

**Source(s):** Authors' own work

$$I_{rq} = \begin{cases} 1 & \text{if } I^*_{rq} > \tau_r \\ 0 & \text{if } I^*_{rq} \leq \tau_r \end{cases} \quad (1)$$

$$I^*_q = \gamma LV_q + \zeta_q \quad (2)$$

where  $I^*_q$  represents the value of the latent variable underlying the observed indicator  $I_{rq}$ , determined by the latent variable  $LV_q$ , while  $\tau_r$  is a parameter to be estimated which determines the cutoff between the two possible values of the indicator (0 and 1).  $\gamma$  is a parameter that captures the strength of the relationship between the latent variable  $LV_q$  and the observed indicator. Finally,  $\zeta_q$  is the error term, which accounts for the unobserved factors that influence the indicator but are not explained by the latent variable.

**Table 5.** Distribution of responses of the latent variable indicator in the CP and MS scenarios, respectively, included in our econometric models

Likert scale response options	N	%
<i>Bad weather effect when cycling</i>		
<i>Reply to the following question “I don’t ride my bike in bad weather”</i>		
0 = strongly disagree	3,088	33
1 = somewhat disagree	2,060	22
2 = partly agree	1,853	20
3 = somewhat agree	1,293	14
4 = agree	979	11
<i>Bad weather effect when cycling</i>		
<i>Reply to the following question “I don’t ride my bike in bad weather”</i>		
0 = strongly disagree	3,021	33
1 = somewhat disagree	2,019	22
2 = partly agree	1,811	20
3 = somewhat agree	1,258	14
4 = agree	957	11
<b>Source(s):</b> Authors’ own work		

The second component is the structural [equation \(3\)](#) which defines the causal relationship between the latent variable ( $LV_q$ ) (i.e. Weather Sensitivity) and the observed explanatory variables, such as the individuals’ socio-economic characteristics ( $SE_q$ ). Therefore, for each individual  $q$ , we get:

$$LV_q = \kappa + \alpha SE_q + \varepsilon_q \tag{3}$$

where  $LV_q$  is the vector of the latent variable,  $\kappa$  is the intercept term,  $\alpha$  is the vector of coefficients associated with the socio-economic characteristics ( $SE_q$ ). Finally,  $\varepsilon_q$  represents the error term, assumed to have a mean of zero, which captures random variation and unobserved factors not explained by the socio-economic variables.

The last component of the model is the *ordered logit* (OL). [Equation \(4\)](#) represents the utility function:

$$U_{iq} = \beta'_{qk} X_{qki} + \alpha'_q SE_q + \lambda' LV_q + \delta D_{Mitte,q} + \varepsilon_{iq} \tag{4}$$

where  $X_{qki}$  refers to the attributes of the images to be rated,  $SE_q$  detects respondents’ socio-economic characteristics and  $LV_q$  is the latent variables.  $D_{Mitte,q}$  is binary variable that takes the value 1 if the individual lives in Mitte, and 0 otherwise whilst  $\delta$  detects the random parameter that captures the individual effect of residing in Mitte.  $\varepsilon_{iq}$  is the error term. In this framework, the concept of “utility” refers to the (latent) level of satisfaction or well-being that a respondent associates with a particular scenario. This notion is rooted in microeconomic theory, where utility represents the attractiveness of an option as perceived by an individual. In our case, if a scenario is perceived as safer, it will be associated with a higher level of utility. This perceived utility, in turn, influences the rating the respondent assigns to that scenario: the greater the perceived utility in terms of safety, the higher the rating is likely to be.

We used the Apollo package in R to estimate the HMXL model ([Hess and Palma, 2023](#); [Hess and Palma, 2019](#)).

#### 4.1 Model specification and structure

**Table 6** shows the variables used in the model. In the questionnaire, participants' age was recorded as an ordinal categorical variable (0 = under 18 years; 1 = 18–24 years; 2 = 25–29 years; 3 = 30–39 years; 4 = 40–49 years; 5 = 50–64 years; 6 = 65–74 years; 7 = over 74 years). As the majority of respondents were aged between 25 and 64 years, we opted to treat age as a binary variable. In addition, although cycling frequency and duration (in minutes) of habitual cycling trips were originally collected as ordinal variables, we decided to treat them as binary variables. This made it easier to identify habitual cyclists and allowed us to study trips longer than 30 min. Compared to previous research by [von Stülpnagel and Rintelen \(2024\)](#) and [von Stülpnagel and Binnig \(2022\)](#), we decided to include a territorial variable to examine if the district of residence can influence the perception of safety. Therefore, a variable was introduced in the model to identify residents of the Mitte district.

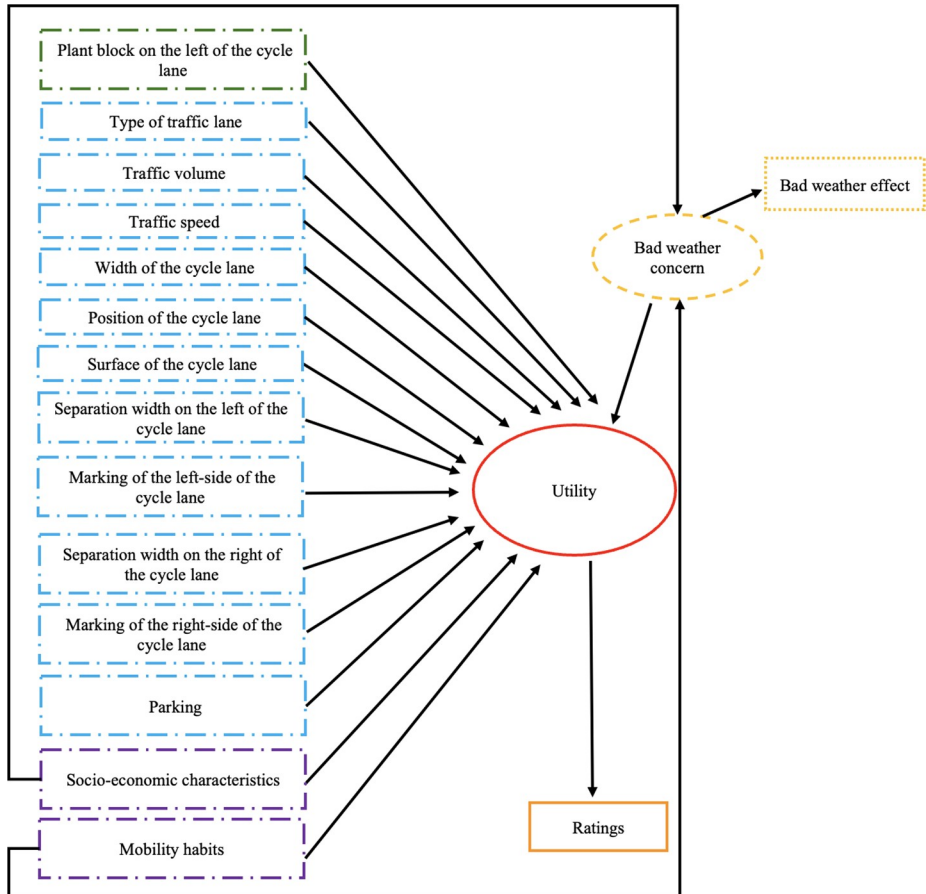
The questionnaire originally measured all indicators using a five-point Likert scale. However, we decided to treat the included indicator, “Weather Sensitivity”, as a binary variable. In this classification, the value of 1 represents individuals who are sensitive to bad weather when cycling (corresponding to Likert scale values of 3 and 4), while a value of 0 represents those who are not sensitive (corresponding to Likert scale values of 0, 1 and 2). This approach, aimed at capturing a latent dimension, was developed by aggregating different questions answered by regular and non-regular cyclists, thus ensuring its validity across both groups. About 16% of the participants said they were sensitive to bad weather when cycling, compared to 84% who said they were not, in both scenarios. Note that, for reasons related to model convergence and the scarcity of category 0 (about 3.5% in both scenarios), the ordinal dependent variable was modified by combining the values 0 and 1 into a single category, resulting in a three-point scale: 1 (strongly disagree), 2 (somewhat agree) and 3 (strongly agree).

**Plate 1** and **Figure 1** show the structure of the two models. At the bottom of the diagram there is a solid orange box which represents the ratings given by the respondents taking into account the perceived level of safety. The ratings are influenced by the perceived utility, represented by a red oval with a solid line. Utility is influenced by the attributes of the images (represented by green dashed boxes for the attribute associated with LGI and light blue dashed boxes for the other attributes), socio-economic characteristics and mobility habits of

**Table 6.** Variables treated in our two models

Group	Variable	Type	Description
Socio-economic characteristics	Gender	Dummy	1 = female; 0 = male
	Parent status (being parents of children of above 12 years old)	Dummy	1 = parent; 0 = otherwise
	Age	Dummy	1 = 25–64 years old; 0 = otherwise
	Cycling frequency	Dummy	1 = 1–3 times per week to (almost) daily; 0 = otherwise
	Having long trips by bicycle (<30 min)	Dummy	1 = Yes; 0 = No
	Own bicycle property	Dummy	1 = bicycle owned; 0 = otherwise
	Living in Mitte district	Dummy	1 = Mitte dweller; 0 = otherwise
Measurement indicator	Weather sensitivity	Dummy	1 = sensible; 0 = otherwise
Ordinal dependent variable	Safety rating	Ordinal	1 = unsafe; 2 = rather safe; 3 = safe

**Source(s):** Authors' own work



**Figure 1.** Structure of the two hybrid mixed logit models of the CP scenario

**Source:** Authors' own work

the individuals (both represented by purple dotted boxes). In addition, utility is also influenced by a latent variable represented by a yellow dashed oval, with the corresponding yellow dotted box representing its indicator. The latent variable is also influenced by the mobility habits and socio-economic characteristics of the individuals.

## 5. Results and discussion

### 5.1 Measurement equation

Table 7 shows the results of the measurement equation. The analysis showed a positive relationship between the indicator and the latent variable *Weather sensitivity* in both the CP and MS scenarios. This latent variable can be interpreted as a measure of the perception of bad weather as a demotivating factor and an obstacle to cycling. The result is consistent with the findings reported by Böcker *et al.* (2016), Campos Ferreira *et al.* (2022) and Goldman and Wessel (2021), as well as the observations of Garder (1998).

**Table 7.** Estimates of the parameters of the measurement equations for the two scenarios

Latent variables measurement parameters	Estimate	t-ratio	p-value
<i>LV: Weather sensitivity (CP scenario)</i>			
Bad weather effect ( $\zeta_{\text{badweathereffect}}$ )	0.2556	6.4	$7 \times 10^{-11}$ *
Bad weather effect indicator threshold 0	1.6940	52.	$<2 \times 10^{-16}$ *
<i>LV: Weather sensitivity (MS scenario)</i>			
Bad weather effect ( $\zeta_{\text{badweathereffect}}$ )	0.1147	2.3	0.012*
Bad weather effect indicator threshold 0	1.7205	43.	$<2 \times 10^{-16}$ *

**Note(s):** Signif. codes: 0 ‘\*\*’ 0.001 ‘\*’ 0.01 ‘.’ 0.05 ‘.’ 0.1 ‘.’ 1

**Source(s):** Authors’ own work

### 5.2 Structural equation

**Table 8** presents the results of the structural equation. For the CP scenario, the perception of *Weather Sensitivity* when cycling is negatively associated with the youngest individuals (aged 18–24) in our sample. This result is in line with our expectations. It reflects young people’s greater resilience and adaptability to adverse weather conditions, as well as their lower perceived risk aversion when cycling compared to other demographic groups (Goldmann and Wessel, 2021). With regard to the MS scenario, the results indicate that the perception of *Weather Sensitivity* as a demotivating factor is positively associated with older people (aged 65–74), highlighting their greater sensitivity to weather conditions. This result is in line with our expectations and also with the existing literature, which indicates that older people are less willing to take risks when cycling due to adverse weather conditions or bad seasons (Lusk et al., 2014; Winters et al., 2015; Van Cauwenberg et al., 2018).

### 5.3 The ordered logit component

The estimation results of the ordered logit (OL) component are reported in **Tables 9** and **10**. This component has the safety rating as an ordinal dependent variable. This part of the model highlights the influence of specific attributes of the evaluated images (depicted by the green and light blue boxes in **Figures 1** and **2**), as well as the respondents’ socio-economic characteristics and mobility habits (represented by the purple boxes) on their utility (represented by the red oval). In the utility functions of both scenarios, we have also included a latent variable *Weather sensitivity* (represented by the yellow oval). This variable is included in the utility function of both scenarios. The objective is to determine whether this latent variable influences the utility and thus the respondents’ evaluations.

These results are based on 241,315 observations and 15,311 individuals in the CP scenario and 157,043 observations and 14,958 individuals in the MS scenario.

**Table 8.** Estimates of the parameters of the structural equations for the two scenarios

Latent variables structural parameters	Estimate	t-ratio	p-value
<i>LV: Weather sensitivity (CP scenario)</i>			
Young – dummy: 1 young; 0 others ( $y_{\text{young}}$ )	0.2556	6.4	$7 \times 10^{-11}$ *
<i>LV: Weather sensitivity (MS scenario)</i>			
Senior – dummy: 1 senior; 0 others ( $y_{\text{senior}}$ )	0.0725	2.4	0.009**

**Note(s):** Signif. codes: 0 ‘\*\*’ 0.001 ‘\*’ 0.01 ‘.’ 0.05 ‘.’ 0.1 ‘.’ 1

**Source(s):** Authors’ own work

**Table 9.** Estimation results of the OL component for the CP scenario

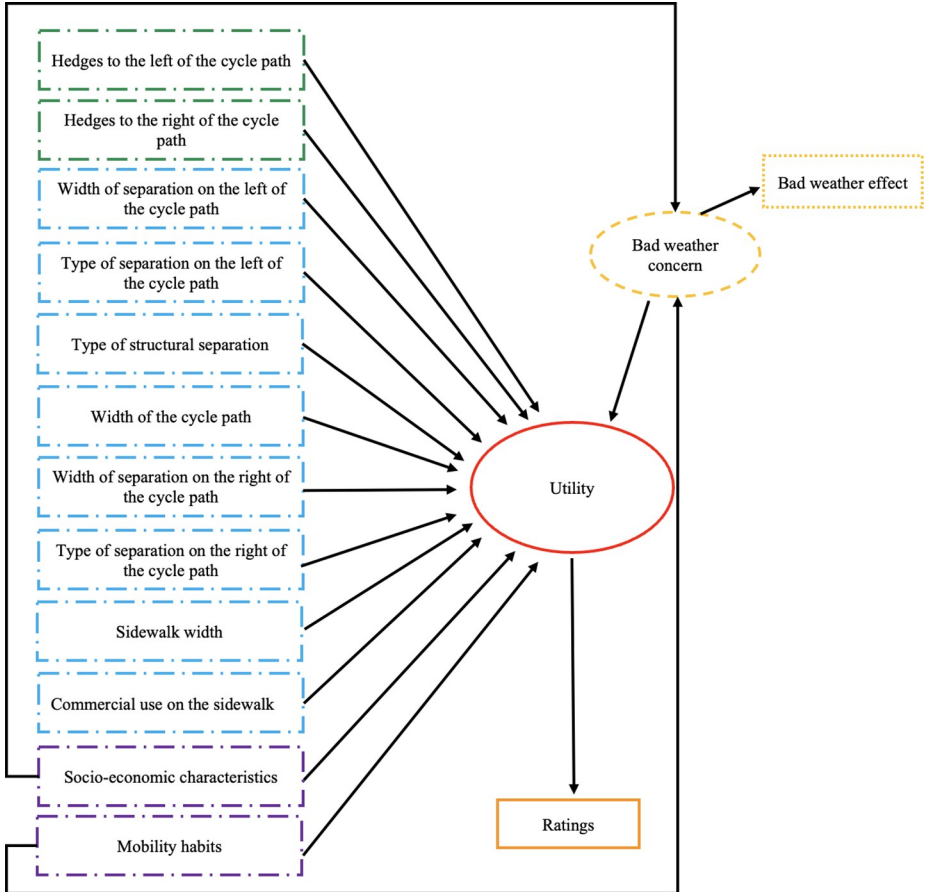
Variables	Estimates	t-ratio	p-value
<i>CP scenario: HMXL model</i>			
Hedge on the left of the cp – 1 if presence; 0 not presence	0.4049	5.2	$8 \times 10^{-8}***$
Hedge on the right of the cp – 1 if presence; 0 not presence	0.5070	4.2	$1 \times 10^{-5}***$
Hedge on the right of the cp * female (interaction term) ( $\beta_{\text{hedgeR} * \text{gender}}$ )	0.2866	3.7	$1 \times 10^{-4}***$
Hedge on the left of the cp * age (interaction term) ( $\beta_{\text{hedgeL} * \text{age}}$ )	-0.0553	-0.7	0.243
Hedge on the right of the cp * age (interaction term) ( $\beta_{\text{hedgeR} * \text{age}}$ )	0.1756	1.5	0.067.
Hedge on the left of the cp * having children (interaction term) ( $\beta_{\text{hedgeL} * \text{parent.status}}$ )	-0.1051	-1.7	0.045*
Hedge on the right of the cp * having children (interaction term) ( $\beta_{\text{hedgeR} * \text{parent.status}}$ )	0.1921	2.2	0.013*
Hedge on the left of the cp * having a bike (interaction term) ( $\beta_{\text{hedgeL} * \text{bike availability}}$ )	0.0291	2.0	0.025*
Hedge on the right of the cp * having a bike (interaction term) ( $\beta_{\text{hedgeR} * \text{bike availability}}$ )	-0.0161	-0.8	0.209
Hedge on the left of the cp * being a regular cyclist (interaction term) ( $\beta_{\text{hedgeL} * \text{cyclist}}$ )	-0.0291	-0.5	0.299
Hedge on the right of the cp * being a regular cyclist (interaction term) ( $\beta_{\text{hedgeR} * \text{cyclist}}$ )	0.1656	2.1	0.018*
Wide cycle path	2.6488	84.3	$<2 \times 10^{-16}***$
Wide separation on the left of the cp	-0.4874	-26.6	$<2 \times 10^{-16}***$
Wide separation on the right of the cp	-0.7430	37.5	$<2 \times 10^{-16}***$
Presence of grass strips on the left of the cp	0.0630	3.4	$3 \times 10^{-4}***$
Presence of grass strips on the right of the cp	0.4428	19.9	$<2 \times 10^{-16}***$
Presence of bollards on the left of the cp	0.1944	8.0	$7 \times 10^{-16}***$
Narrow pavement on the right of the cp	-0.4698	-20.1	$<2 \times 10^{-16}***$
Presence of pavement shop on the right of the cp	-0.3102	-16.5	$<2 \times 10^{-16}***$
<i>Socioeconomic variables</i>			
Gender – 1 female; 0 male	0.4104	5.2	$9 \times 10^{-8}***$
Age – 1 from 25 to 64 years old; 0 other	-0.4978	-3.5	$3 \times 10^{-4}***$
Having children < 12 years old – 1 yes; 0 no	0.0693	0.9	0.196
Having a bike – 1 yes; 0 no	-0.0050	-0.9	0.175
Using bike for route longer than 30 min – 1 yes; 0 no	-0.3828	-3.6	$1 \times 10^{-4}***$
Being a regular cyclist – 1 yes; 0 no	-0.2407	-2.7	0.003**
Being resident in Mitte – Random parameter normal distribution			
Mean ( $\mu_{\text{Mitte}}$ )	-0.1762	-1.3	0.090.
Standard deviation ( $\sigma_{\text{Mitte}}$ )	0.0592	1.5	0.069.
<i>Latent variable</i>			
Weather sensitivity – latent variable ( $\lambda_{\text{weathersensitivity}}$ )	2.6138	73.9	$<2 \times 10^{-16}***$
<b>Note(s):</b> Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘.’			
<b>Source(s):</b> Authors’ own work			

Different specifications of the hybrid choice model were tested using Halton inter-individual draws. The final model was selected on the basis of goodness-of-fit indices, robustness of results and consistency of estimated parameters. For the CP scenario, the initial log-likelihood (LL) of the selected hybrid choice model is -307,413; the final LL value is -177,270, with an adjusted R-squared (Adj. Rho-squared) of 0.34. A total of 33 parameters were analysed in this model. For the MS scenario, the initial LL is -186,448, while the final value is -111,461, with an adjusted R-squared (Adj. Rho-squared) of 0.37, including 29 parameters in the estimation.

Our results indicate that the presence of LGI contributes significantly to improving perceptions of safety. In the CP scenario, the inclusion of hedges along the cycle path has a clear and positive impact, confirming previous findings (Furth, 2021; Lin and Lou, 2022; Lusk et al., 2020). The right-side hedge facing the pavement appears especially effective, followed by the left-side hedge facing the roadway or parked cars. A similar pattern emerges in the MS scenario, where plant blocks placed between the cycle lane and motor vehicle

**Table 10.** Estimation results of the OL component for the MS scenario

Variables	Estimates	t-ratio	p-value
<i>MS scenario: HMXL model</i>			
Plant block on the left of the bike lane – 1 if presence; 0 not presence	1.9868	14.8	$<2 \times 10^{-16}***$
Plant block on the left of the bike lane * having children < 12 year old (interaction term) ( $\beta_{\text{plant block L} * \text{parent.status}}$ )	0.5794	3.3	$4 \times 10^{-4}***$
Plant block on the left of the bike lane * living in Mitte (interaction term) ( $\beta_{\text{plant block L} * \text{Mitte}}$ )	0.4601	1.7	0.048*
Plant block on the left of the bike lane * regular cyclist (interaction term) ( $\beta_{\text{plant block L} * \text{Cyclist}}$ )	-0.5487	-3.3	$5 \times 10^{-4}***$
Plant block on the left of the bike lane * long bike route > 30 min (interaction term) ( $\beta_{\text{plant block L} * \text{long route}}$ )	-0.2500	-1.0	0.162
Wide bike lane on the main street – 1 if presence; 0 not presence	2.0932	61.2	$<2 \times 10^{-16}***$
Absence of cycle lane on the main street – 1 if absent; 0 present	-4.6341	-51.1	$<2 \times 10^{-16}***$
Bus lane close to the bike lane – 1 if presence; 0 not presence	3.8724	23.1	$<2 \times 10^{-16}***$
Vehicle lane close to the bike lane – 1 if presence; 0 not presence	0.1414	5.6	$9 \times 10^{-9}***$
Normal traffic volume – 1 if presence; 0 not presence	0.1299	5.2	$1 \times 10^{-7}***$
30km/h limit traffic speed – 1 if presence; 0 not presence	0.1585	6.2	$2 \times 10^{-10}***$
Coloured surface of the bike lane – 1 if presence; 0 not presence	0.9382	34.0	$<2 \times 10^{-16}***$
Narrow separation on the right of the bike lane – 1 if presence; 0 not presence	-2.1748	-54.1	$<2 \times 10^{-16}***$
Dashed line on the left of the bike lane – 1 if presence; 0 not presence	-0.6283	-18.3	$<2 \times 10^{-16}***$
Double line on the left of the bike lane – 1 if presence; 0 not presence	-2.3572	-54.1	$<2 \times 10^{-16}***$
Prohibited area line on the right of the bike lane – 1 if presence; 0 not presence	-2.3172	-53.8	$<2 \times 10^{-16}***$
High bollards on the left of the bike lane – 1 if presence; 0 not presence	1.6991	18.3	$<2 \times 10^{-16}***$
<i>Socioeconomic variables</i>			
Having children < 12 years old – 1 yes; 0 no	-0.2241	-2.2	0.014*
Having a bike – 1 yes; 0 no	-0.0017	-0.6	0.273
Using bike for route longer than 30 min – 1 yes; 0 no	0.2542	2.5	0.007***
Being a regular cyclist – 1 yes; 0 no	0.3336	4.0	$3 \times 10^{-5}***$
Mean ( $\mu_{\text{Mitte}}$ )	-0.2261	-1.4	0.078.
Standard deviation ( $\sigma_{\text{Mitte}}$ )	-1.3143	-6.4	$6 \times 10^{-11}***$
<i>Latent variable</i>			
Weather sensitivity – latent variable ( $\lambda_{\text{weathersensitivity}}$ )	2.9681	64.5	$<2 \times 10^{-16}***$
<b>Note(s):</b> Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘.’			
<b>Source(s):</b> Authors’ own work			



**Figure 2.** Structure of the two hybrid mixed logit models of the MS scenario  
**Source:** Authors' own work

traffic significantly improve perceived safety. These findings highlight the functional value of LGI not just as an aesthetic feature or as both as physical barriers and as buffers against traffic noise and air pollution (Jia *et al.*, 2021; Kamińska *et al.*, 2023; Willberg *et al.*, 2023) but as a key element in improving the perceived safety of cycling routes.

We also explored interactions between green infrastructure and socio-demographic variables. In the CP scenario, the presence of LGI on the right side of the path positively affects perceived safety especially among women, parents with young children, and regular cyclists, with the strongest effect observed for women. In the MS scenario, plant blocks improve safety perceptions particularly among parents and residents of Mitte, where heavy traffic and space constraints make traditional greenery less feasible. In such contexts, compact green solutions like plant blocks offer a space-efficient and visually pleasant alternative to grey barriers.

As expected, the width of the cycling infrastructure emerges as a significant predictor of perceived safety, confirming previous findings (von Stülpnagel and Binnig, 2022; von Stülpnagel and Rintelen, 2024). The absence of cycling lanes, especially in high-traffic

scenarios, significantly reduces safety perceptions, reinforcing the importance of dedicated infrastructure. Beyond width, some surface and design features also contribute positively – notably coloured asphalt (Auteliano and Felice, 2021; Karlsen and Fyhri, 2020) and the presence of physical separators like bollards (Hardinghaus and Papantoniou, 2020). These findings align with recent literature showing that visible and tangible protection enhances cyclists' comfort and confidence. By contrast, minimal markings such as dashed or double lines appear insufficient, particularly in busy urban contexts, where physical separation is crucial. Elements such as narrow buffers next to parked cars can also worsen perceived safety, likely due to concerns about close vehicle interactions. Finally, features of the surrounding urban environment also matter: wide pavements and reduced speed limits contribute to a greater sense of safety (Caulfield *et al.*, 2012; Mertens *et al.*, 2017; Sener *et al.*, 2009), but these effects remain secondary compared to the influence of green infrastructure, which appears to combine protective, perceptual, and environmental benefits in a uniquely effective way.

Socio-economic characteristics significantly shape safety perceptions, with distinct effects observed in the two scenarios. In the CP scenario, women reported higher perceived safety, confirming findings from von Stülpnagel and Rintelen (2024) and aligning with broader literature showing that women are generally more risk averse and favour protected cycling infrastructure (Dill *et al.*, 2014; Graystone *et al.*, 2022; Hardinghaus and Weschke, 2022). Parents of children under 12 also expressed greater perceived safety in this context, likely reflecting a preference for infrastructure that physically separates cyclists from motor vehicle traffic, allowing safer cycling with children.

In the MS scenario, frequent cyclists and those accustomed to longer commutes (over 30 min) showed significantly higher safety ratings when cycle lanes were present, suggesting a strong appreciation for direct, uninterrupted routes that reduce exposure to vehicular traffic. This is consistent with findings that more experienced cyclists prioritise infrastructure that supports speed and efficiency over shared or indirect paths.

Some heterogeneity in safety perception also emerges with respect to respondents' residential location. In both the CP and MS scenarios, residents of the central Mitte district attributed slightly lower safety ratings to the presence of cycle paths and cycle lanes. This result is consistent with expectations: in areas like Mitte, where cycling infrastructure is already extensive and well-integrated into the urban fabric, the marginal impact of additional infrastructure on perceived safety may be less pronounced. In contrast, in less equipped districts, the presence of dedicated cycling infrastructure likely represents a more visible and meaningful improvement in perceived safety. This highlights how baseline infrastructure levels shape the perceived benefits of new interventions and underlines the need for spatially differentiated planning strategies.

Finally, sensitivity to adverse weather conditions while cycling increases safety perception ratings in both the CP ( $\lambda_{\text{badweather}} = 2.6138$ ) and MS ( $\lambda_{\text{badweather}} = 2.9681$ ) scenarios. Cycling is by nature a mode that is directly affected by weather conditions (An *et al.*, 2019). However, our data suggest that weather sensitivity in cycling is not necessarily correlated with lower perceived safety. It may be more strongly related to the presence and quality of cycling infrastructure. In fact, our results suggest that cycling infrastructure increases perceptions of safety, particularly for people who are more concerned about adverse weather conditions.

## 6. Discussion and conclusions

The role of LGI in shaping cyclists' perceptions of safety remains an underexplored area in the academic literature. While a growing number of studies have investigated how physical separation and infrastructural design affect perceived cycling safety, the specific contribution

of vegetation elements such as hedges, plant blocks or trees has received limited empirical attention, particularly in urban contexts. Our study addresses this gap by leveraging a rich data set collected in Berlin, previously analysed in other research but never used to assess the relevance of LGI in shaping safety perceptions. This data set, based on image-based scenario ratings, offers a unique opportunity to isolate the effects of LGI while controlling for other design features and latent psychological traits.

Our findings show that LGI is not only a visually pleasant addition to urban cycling infrastructure, but a structurally important component that can substantially improve perceived safety. Crucially, we demonstrate that this effect is not uniform across the population. Perceptions of safety vary systematically depending on gender, age, parenting responsibilities, cycling frequency and residential location. Women, parents of young children and less frequent cyclists are particularly responsive to the presence of LGI, especially in scenarios where the infrastructure is physically separated from traffic. At the same time, residents in less infrastructurally developed areas express greater sensitivity to these features, suggesting that the perceived benefit of LGI is amplified in contexts where baseline conditions are weaker. These differentiated effects underline the importance of context-aware and socially inclusive planning approaches and indicate that LGI can serve as a strategic tool to address perceived safety barriers among vulnerable or hesitant user groups.

Our results provide several practical insights for urban planning and mobility policy aimed at increasing cycling uptake through improved infrastructure design. First, they reinforce the idea that the mere presence of cycling infrastructure is not sufficient to foster a sense of safety: design quality – and in particular, the integration of green elements – plays a decisive role. LGI, when appropriately implemented, serves not only as a buffer against traffic but also as a perceptual and psychological shield that enhances cyclists' comfort and confidence. Where space allows, elements such as hedges and vegetated strips should be prioritised, especially on the pavement-facing side of the cycle path, as this configuration produced the strongest positive effect on perceived safety, particularly for women and parents with young children. In more space-constrained environments – such as the central district of Mitte – compact green features like plant blocks offer an effective and spatially efficient alternative, acting as visual and physical buffers with minimal impact on available road width.

Importantly, our findings support the idea that infrastructure investments should be sensitive to the needs of specific user groups. Different demographic segments respond differently to infrastructure attributes: while women and parents with young children report higher perceived safety in the presence of green, physically separated infrastructure, frequent cyclists and long-distance commuters tend to value directness, width and continuity of cycling lanes over separation alone. Moreover, residents of central areas – where cycling infrastructure is already more established – respond less to marginal additions and may benefit more from qualitative improvements, such as surface treatments or the introduction of greenery, rather than merely expanding infrastructure quantity. These differentiated responses suggest the need for targeted interventions based on local context and user characteristics.

In addition, our findings call for an approach to infrastructure design that embraces multifunctionality. LGI should not be treated as a decorative or optional feature, but as an integral component of street design. Hedges, plant blocks and vegetated buffers contribute to air quality improvement, noise reduction and spatial legibility, while also providing a visible physical boundary that enhances both perceived and actual safety. Municipal guidelines and design manuals should therefore incorporate green buffers as standard design elements, not optional additions. For example, new developments should allocate minimum widths for

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green buffers alongside cycle paths, while existing grey dividers – such as bollards or concrete curbs – can be retrofitted with modular green alternatives where space and maintenance capacity allow.

Our study also reveals the potential of green and well-designed cycling infrastructure to mitigate the deterrent effects of adverse weather conditions, a factor often outside the control of policy makers. Even among weather-sensitive users, perceptions of safety remained high where cycle paths were sufficiently protected and visually distinct. This suggests that infrastructure can act as a buffer against environmental discomfort. To this end, textured or water-absorbing surfaces, tree canopies and tall vegetated barriers can be used to improve comfort and shelter in rain or wind. Complementary investments – such as covered bike parking, public lockers and changing facilities at transport hubs or workplaces – can further support year-round cycling and help normalise the idea of cycling in less-than-ideal conditions.

Finally, our findings contribute to a broader reflection on equity in infrastructure planning. Much of current cycling infrastructure remains implicitly designed around the needs of experienced, often male cyclists. However, our analysis shows that older adults, women and residents of peripheral areas are especially responsive to the presence of LGI and other safety-enhancing features. Investing in these elements can therefore help redress existing imbalances in cycling participation. To support this, planning processes should integrate updated and diversified data collection strategies. Future studies should expand beyond the central districts and ensure broader inclusion of underrepresented age and gender groups. New tools such as virtual reality environments or interactive simulations could complement traditional image-rating methods and reduce hypothetical bias, offering a richer and more realistic understanding of cyclists' preferences.

However, our study has some limitations. Firstly, the sample was predominantly male and consisted mostly of regular cyclists, which may limit the generalisability of the findings to the wider population, including women and less frequent cyclists. Future research should target these underrepresented groups to gain deeper insights into their perceptions of cycling safety. Secondly, the study was conducted in Berlin, a city with unique characteristics, such as its specific urban form, mobility culture and infrastructure. Due to these factors, the results may not be fully representative of other European or global cities. Further research could explore how these dynamics vary across different urban environments and how cycling infrastructure can be adapted to specific local contexts.

In addition, while our study is grounded in a European context, future studies should examine whether similar effects are observed in non-European cities with different urban forms, climate conditions or mobility cultures. This could enhance the generalisability of the findings. The data was collected between December 2019 and February 2020, before the COVID-19 pandemic, which has significantly altered mobility patterns worldwide. Updated data could help validate or compare our findings in light of these changes.

Furthermore, the use of binary indicators for latent analysis limited the inclusion of certain variables. Future research should focus on incorporating a broader range of latent factors, particularly psychological and attitudinal ones, which are often difficult to capture. Finally, although we used an image rating method to assess preferences for cycling infrastructure, the hypothetical nature of these images introduces bias, as not all elements have been implemented in practice. Therefore, actual responses may differ from stated preferences.

Finally, we acknowledge the potential influence of unobserved confounding variables. For example, personal cycling experiences, emotional responses to different street types, or familiarity with the depicted settings could all influence safety perceptions independently of

infrastructure features. While these factors are difficult to control for in stated preference designs, future research could incorporate *in situ* experiments or physiological measures (e.g. heart rate variability) to better isolate the causal influence of infrastructure features.

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### Author contributions

C.R.: conceptualization, formal analysis, methodology, writing – original draft, writing – review and editing. L.R.: conceptualization, methodology, formal analysis, writing – original draft, writing – review and editing, supervision.

### Notes

- [1.] The attributes analysed for the three scenarios are the following. For the “cycle lane on secondary streets”: 1. traffic direction; 2. presence of car parking; 3. road markings. For the “cycle lane on main streets”: 1. cycle lane width; 2. cycle lane surface; 3. left buffer; 4. right buffer. 5. speed limit; 6. traffic direction; 7. traffic volume. For the “cycle path on the pavement”: 1. buffer type; 2. presence of commercial activities on the pavement.
- [2.] Please note that the coloured lines in the picture represent different types of cycling infrastructure in Berlin: 1. Fahrradrouthauptnetz (red line): main cycling route network; 2. Radfernwege (blue line): long-distance cycling routes; 3. Berliner Mauerweg (gray-green line): Berlin Wall Trail, marked as a hiking path but also accessible for cycling; 4. Ergänzungsnetz (green line): supplementary network, still under development.

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