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For whom is sharing really scaring? capturing unobserved heterogeneity in perceived comfort when cycling in shared spaces

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ABSTRACT

Shared spaces for active mobility prioritize the safety and comfort of vulnerable road users by segregating them from motorized vehicles. However, the diverse speed regimes of pedestrians and cyclists can lead to encounters that may affect their comfort. In addition, the very perception of comfort may vary across individuals depending on their demographics, and therefore the determinants of comfort and their effects may not be fixed across all individuals. Despite these complexities, there is limited research in understanding the heterogeneous interactions between cyclists and other road users in shared spaces. To bridge this gap, we conducted an intercept survey complemented by an experimental section involving 594 cyclists in Sweden. This study focuses on gaining insights into cyclists' experiences, particularly their comfort levels during 'passing' and 'meeting' events with other road users in shared spaces. We then used the collected data to develop a random effect latent class ordered probit model to scrutinize the determinants of cycling comfort in passing and meeting scenarios. The latent class specification is employed to account for unobserved heterogeneity in the data. Findings reveal that female cyclists generally perceive less comfort compared to their male counterparts in both scenarios. Passing events have a more negative impact on older adults, leading to less comfort compared to younger cyclists. We also found that previous cycling experience increases comfort in shared facilities, particularly for older adults. These results highlight the intricate nature of perceived comfort in interactions, particularly concerning demographic characteristics, contributing to the promotion of user diversity in shared spaces.

1. Introduction

Facilitating the adoption of sustainable mobility is imperative to tackle challenges linked to motorized vehicles, including air pollution, traffic congestion, and environmental concerns (Agarwal et al., 2020; Fyhri et al., 2023; Haghani et al., 2023). Consequently, global initiatives and policy packages have been devised to enhance the role of cycling as a mode of transport (Heinen & Handy, 2020). Various strategies, such as bike sharing systems, incentive programs, education, and the introduction of dedicated infrastructure, have been explored as part of this effort (Abolhassani et al., 2019; De Kruijf et al., 2018; Pucher & Buehler, 2016). These initiatives generate more user conflicts and separating cyclists from other road users has been an important challenge. Notably, providing dedicated

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infrastructure for cyclists has emerged as a promising approach to promote and sustain cycling in transportation systems while reducing conflicts (Fishman, 2016; Pucher & Buehler, 2016). However, improving cycling infrastructure faces several challenges (Aldred et al., 2019).

First, the limited available publicly available space is shared with different modes of transport, and other land uses, constraining the ability to expand cycling infrastructure (Hull & O'holleran, 2014). Second, the development of infrastructure is hampered by cost constraints, and limited funding could impede its expansion (Hong et al., 2020). Third, in most countries the cycling sector lacks the political will to prioritize cycling infrastructure at the expense of other priorities (Aldred et al., 2019).

In response to these challenges, shared spaces for vulnerable road users have been proposed as a solution. Shared spaces involve designing public spaces to be pedestrian- and cyclist-friendly areas to enhance safety and comfort (Liang et al., 2021). These spaces can be dedicated to non-motorized vehicles or incorporate both motorized and non-motorized spaces with low-speed motorized vehicles (Beitel et al., 2018). While this concept is theoretically appealing as it separates vulnerable road users from motorized vehicles, the practical implementation poses challenges. Shared spaces may accommodate various active transport modes, including cycling, electrically assisted cycling (e-bikes), and other micromobility (e-scooters), and walking, each with different speed regimes. These variances can lead to user conflicts and challenges in maintaining comfort within such facilities (Che et al., 2021; Gkekas et al., 2020). There is growing pressure to integrate more diverse vulnerable road users in the same space.

Comprehending and addressing the implications of heterogeneity within shared spaces is not just a theoretical consideration; it directly influences the success of these spaces in practice. Such an understanding will pave the way for informed design, implementation, and management strategies, fostering a safer, more comfortable, and inclusive environment for all road users. In this context, the study of cyclists' comfort, as explored in our research, becomes a pivotal element in unraveling the complexities and ensuring the success of shared spaces for vulnerable road users. Comfort, however, is a psychological construct which is not directly observable and hence it may vary from one person to another. This unobserved heterogeneity increases the complexity of taking comfort into account when designing shared spaces.

A review of the literature revealed a scarcity of theoretical and empirical studies addressing the comfort associated with cyclists' behaviors and perceptions in shared facilities (Kazemzadeh & Bansal, 2021a). To fill this knowledge gap, we conducted a survey involving 594 cyclists in Lund, Sweden, immediately after their use of shared spaces. The primary objective of the study was to explore how 'passing'[1] and 'meeting' interactions could pose challenges for cyclists, with passing denoting same-direction encounters and meeting denoting opposite-direction encounters. We collected a wide range of data on cyclists' demographic characteristics, travel habits and history, as well as their associated comfort when interacting with other road users. The findings aim to contribute to the existing literature by analyzing cyclists' comfort while considering the nuanced dynamics of encounter directions.

The subsequent sections are organized as follows: Section 2 provides an overview of the contextual literature, Section 3 outlines the adopted methodology for this study. Section 4 presents the study's results, while Section 5 is devoted to the discussion of these results. Section 6 discusses policy and practice relevance. The conclusion (Section 7) follows.

2. Literature review

This section provides an overview of the contextual literature regarding i) Status quo of shared space, ii) Methods for assessing cycling comfort, and iii) Knowledge gaps and research needs.

2.1. Status quo of shared space

The term *shared space* is not used to categorize entire streets and places as either shared or not shared, especially considering the lack of standardization in streetscape design, necessitating a context-sensitive approach. Instead, shared space serves as a comprehensive term encompassing various streetscape treatments, all aimed at fostering a more pedestrian- and cyclist-friendly environment (Kaparias et al., 2013; Karndacharuk et al., 2014a). The literature encompasses both types of shared spaces, those exclusively for non-motorized users and those shared with motorized users at low speeds (Essa et al., 2018; Kaparias et al., 2012).

Regarding studies focused on shared spaces dedicated to active road users, various investigations have evaluated the interaction of pedestrians and cyclists within these spaces (Basbas et al., 2019; Beitel et al., 2018; Hatfield & Prabhakharan, 2016; Nikiforiadis et al., 2023; Zhang et al., 2023). For example, Che et al. (2021) analyzed the interaction of pedestrians and cyclists in a shared space in Singapore, suggesting that pedestrians adjust their behavior based on their perceived risk level, behaving more cautiously when risks are higher and less cautiously than cyclists. Similarly, research by Nikiforiadis et al. (2020) in Greece found that passings have a similar negative impact on users' perceptions as meetings.

Passing becomes a significant concern during interactions between cyclists and motorized vehicles, especially given the substantial difference in their speeds (Farah et al., 2019; Rasch et al., 2022). Several studies have explored the interaction between motorized and non-motorized vehicles in shared spaces (Kaparias et al., 2015; Kaparias et al., 2013; Kaparias et al., 2012; Kaparias & Wang, 2020). Tzouras et al. (2023) evaluated shared spaces for pedestrians and vehicles, suggesting that an increase in pedestrian space fosters a sense of dominance, as evidenced by heightened pedestrian crossings. In a similar vein, Karndacharuk et al. (2014b) conducted a safety analysis of a shared zone in New Zealand, noting that the vehicle speed study underscored the necessity of incorporating traffic calming

[1] It is worth noting that 'passing' could also be referred to as 'overtaking' in cycling literature, particularly within discussions on the level of service domains.

measures into shared space design, particularly during off-peak periods, to restrain vehicle operating speeds.

2.2. Methods for assessing cycling comfort

Defining the concept of comfort proves to be a complex task, as it is context-dependent and challenging to measure through both revealed- and stated-preference studies. Comfort, in this context, acts as an umbrella term representing the harmony between humans and the environment, encapsulating the balance of physical, psychological, and sociological aspects (Slater, 1985). Given this multifaceted nature, measuring comfort becomes intricate, especially considering the challenges in conveying this information to road users and expecting them to rank their experiences. Nevertheless, previous research, both in revealed- and stated-preference studies, has considered different proxies to define comfort.

In revealed behavior studies, comfort is typically associated with interrelated indicators (Kazemzadeh & Ronchi, 2022). First, the frequency of passing and meeting events is crucial, as these interactions can influence the level of comfort for users sharing the road (HCM, 2016). Second, deviations in the intended trajectory of cyclists, resulting from adjustments in speed and lateral/longitudinal distance to other road users, play a significant role in affecting comfort (Hummer et al., 2006; Kazemzadeh & Bansal, 2021b). Variables often measured and associated with influencing comfort include speed, density, frequency of interaction, steering angles, lateral distance, and active and delayed encounters (Alsaleh & Sayed, 2020; Mohammed et al., 2019). Observation, experimentation, and simulation studies are common methods for conducting such research studies (Li et al., 2013; Yuan et al., 2018).

In acknowledging the foundational research in the field, it is imperative to highlight the study by Hummer et al. (2005),[2] which stands as one of the pioneering efforts in evaluating cyclists' comfort on shared use paths and developing a comprehensive LOS index for such environments. Their analysis incorporated key factors, including path width, user volume, the frequency of meeting and passing events, and the presence of a centerline, setting a precedent for subsequent research in this domain. This work has significantly influenced our approach, particularly as we navigate the evolving challenges of shared spaces, such as the integration of emerging micromobility devices like e-bikes and e-scooters, which present new dimensions of user interaction and considerations for comfort.

On the other hand, stated preference studies often consider socio-demographic characteristics of participants, physical characteristics of infrastructure, and aesthetic features of roads (Bernhoft & Carstensen, 2008; Prati et al., 2019). Variables such as age, income, household structure, posted speed of the road, road width, and types of separation are taken into account (Jensen, 2007; Shu et al., 2018). Video-, image-, and questionnaire-based surveys are the primary methods used to quantify cyclists' comfort in the literature (Fitch et al., 2022; Griswold et al., 2018). Regardless of the method of comfort data collection and analysis, previous research typically reports comfort through letter-based indices (e.g., A through F), such as Level of Service (LOS), suitability, and compatibility (Kazemzadeh & Ronchi, 2022). However, understanding user comfort in shared spaces is relatively understudied, and consequently, there is a lack of indices to evaluate the comfort of such facilities.

In this study, we define 'comfort' through the lens of hypothetical experiences in shared spaces, particularly during passing and meeting events, in line with the cycling literature's delineation of service quality and the LOS concept. It is important to acknowledge that such experiences could also be contextualized differently across studies, with terms such as stress, suitability, compatibility, and enjoyment reflecting the multifaceted nature of the cycling experience (Hartwich et al., 2018).

2.3. Knowledge gaps and research needs

The literature on understanding cycling comfort has developed rapidly over the past three decades; however, several knowledge gaps remain to be addressed. First, the rapid influx of emerging transport modes, such as e-scooters with different navigation characteristics, has increased the heterogeneity of shared spaces. This influx could elevate the frequency and type of road user interactions. Second, the direction of encounters in stated-preference-based studies within the comfort literature is understudied due to the setup of these studies, yet it provides valuable information for the design of shared spaces. Third, validating the substantial work of revealed behavior studies on encounter comfort requires the support of stated preference studies to compare them with users' perceived comfort in different types of encounters. Finally, the perception of comfort can vary significantly across individuals, indicating that the determinants of comfort and their effects may not be uniform across demographic groups.

This study introduces three key contributions to address the knowledge gaps in the literature. First, it advances the literature by understanding user comfort in a dedicated shared space for non-motorized vehicles. Second, this is one of the pioneering studies that consider the direction of encounters in understanding user comfort in shared spaces that enables the validation of revealed preference studies. Third, we highlight the importance of, and empirically capture the differences in the effects of factors contributing to the perception of comfort among two different age groups. Finally, we lay the groundwork for the development of a dedicated LOS index for shared spaces.

[2] For readers interested in more exploration of Hummer et al.'s contributions, we recommend their report, which provides a thorough discussion of their methodology and findings: Hummer, J., Rouphail, N., Toole, J., Patten, R., Schneider, R. J., Green, J., Hughes, R., & Fain, S. (2006). Evaluation of Safety, Design, and Operation of Shared-Use Paths–Final Report.

3. Methodology

3.1. Survey location

Data collection occurred in Lund, Sweden, a city situated in the southern part of Sweden, hosting a population of approximately 125,000 (Citypopulation, 2022). Lund is characterized by a notable reliance on cycling as a major mode of transport, resulting in a high ridership that presents many opportunities for multimodal encounters that could affect comfort levels (Koglin & Glasare, 2020). The city features several shared spaces, especially in the downtown area, designated for vulnerable road users and spaces covered by cobblestone where both motorized and non-motorized users share the infrastructure.

To underscore the relevance of our findings beyond the specific context of Lund, it is important to recognize that the characteristics of the shared space selected for this case study are emblematic of similar environments that facilitate active mobility worldwide. Consequently, the insights derived from participants' perceptions and opinions—shaped by their unique demographics, travel habits, and experiences—are not confined to this locale. Rather, these insights offer perspectives on cyclist interactions within shared spaces in general, suggesting their applicability across diverse urban settings.

This study exclusively focused on facilities sharing infrastructure with vulnerable road users. To identify a shared space with a high percentage of diverse road users, we investigated several shared spaces in Lund's downtown area. Lilla Fiskaregatan, was selected for its relatively high volume of different vulnerable road users and served as the designated shared space in this study.

3.2. Data collection

Data collection occurred from the first week of June to the last week of July in 2021, utilizing the intercept survey method. Intercept surveys involve researchers approaching actively cycling individuals, briefly interrupting their ride to invite their participation in the study (Kalra et al., 2022). This method has been shown successful in prior research on cycling comfort (Bai et al., 2017; Bigazzi & Gehrke, 2018; Fyhri et al., 2021; Kazemzadeh et al., 2021). On average, we successfully recruited approximately 16 participants per day, amounting to a comprehensive dataset over 42 days. The data collection was meticulously planned to account for environmental consistency, specifically selecting days with similar, favorable weather conditions to minimize external influences. We conducted the survey exclusively on weekdays, from morning until late afternoon, to maintain homogeneity in the participant pool regarding trip purpose and travel patterns. This decision was informed by the potential variability in cycling behavior between weekdays and weekends, which could skew the survey results. By focusing on weekdays and ensuring data collection under uniform daylight and weather conditions—sunny, with no strong winds—we aimed to provide a reliable and representative snapshot of cyclist experiences in shared spaces. To ensure the safety of cyclists, intercept locations were strategically chosen after the conclusion of the shared space, providing a suitable spot for cyclists to naturally reduce their speed or come to a complete stop when accessing the main street. Cyclists were approached, and their willingness to allocate 10–15 min for completing a paper-based questionnaire was sought. Cyclists were randomly approached with the only requirement being that respondents needed to be over 16 years old. Upon interception, cyclists were briefed on the survey's purpose and we emphasized the importance of recalling their recent experiences with cycling, preferably over the past few days. Despite our efforts to randomly select participants, we encountered refusals, which could introduce a selection bias into our study. This challenge is not unique to our research but is a common limitation across various survey methodologies, including online surveys and choice experiments, where response rates and participant dropout can similarly affect data representativeness. At the survey's start, we provided a clear explanation of basic terms used in the survey, such as shared space, passing, and meeting interactions. More specifically, prior to presenting questions related to users' perceptions of passing and meeting interactions, we offered both textual and schematic representations of these scenarios to ensure unambiguous understanding. We specifically defined 'passing' as instances where the survey participant overtakes slower road users. This specifically excludes instances where the survey participant is overtaken by faster road users. Additionally, 'meeting' was described as encounters with road users moving in opposite directions. We emphasized our availability for any clarifications needed by participants to prevent misunderstandings. While conducting the survey, we maintained a respectful distance from participants to ensure their privacy and prevent any influence on their responses. Participants were assured of their freedom to terminate the questionnaire at any time, and the survey guaranteed anonymity, collecting no personal information that could be used to track participants afterward. Survey participation was voluntary without financial incentives.

3.3. Data

The survey encompassed four question blocks, covering socio-demographic characteristics, travel habits and history, experienced comfort, and safety concerns in shared spaces. Questions regarding perceived safety, in the last block, were excluded from the study's analysis. In assessing cyclists' comfort, our survey employed targeted questions about the comfort experienced during passing and meeting scenarios. Respondents indicate their comfort on a scale where '1′ denotes 'uncomfortable', '2′ signifies 'neutral', and '3′ represents 'comfortable', when navigating around other users. This rating system was designed to highlight the maneuvering challenges faced by cyclists and accurately depict their comfort levels in shared spaces. Our approach is informed by the LOS framework in cycling literature, providing a realistic assessment of cyclists' experiences in shared spaces (Kazemzadeh & Ronchi, 2022).

The categorization of demographic characteristics of users was tailored to the distinctive demographic profile of Lund, a city renowned for its university community. We classified participants' education levels into three categories: up to diploma, diploma up to master, and above master. This classification recognizes the substantial presence of students and recent graduates within the town.

Additionally, we set the income categorization threshold at 20,000 SEK to mirror the estimated average salary in this student-centric environment. These demographic categories are carefully chosen based on Lund's demographic specifics and align with cycling research's recommendations for customizing study designs to suit particular populations.

A total of 673 cyclists completed the questionnaire. After cleaning the data, 594 questionnaires were retained for subsequent analysis, excluding surveys with incomplete responses. Table 1 provides the summary statistics for the cyclists involved in this study, while Fig. 1 illustrates the area of data collection.

3.4. Data analysis

Ordered discrete choice models are widely used in the statistical literature to understand the relationship between an ordered dependent variable (comfort in this context) and one or more independent variables (Afghari et al., 2020). However, conventional ordered models, such as ordered probit/logit models, assume that the estimated parameters for the independent variables are constant across all individuals. However, the unobserved heterogeneity in perceived comfort can cause the effects of the independent variables to vary among different individuals. Neglecting such varied effects can introduce potential bias and erroneous statistical inferences. Therefore, developing models that allow for the possibility that some or all of the model's parameters for the independent variables differ among individuals (or groups of individuals) has become increasingly important for obtaining more accurate estimates of comfort.

Various statistical approaches have been adopted to address this issue in similar contexts of traffic safety, such as random parameters logit and probit models (Oviedo-Trespalacios et al., 2020; Afghari et al., 2020) allowing for varying the parameters across observations. Latent class modeling is another approach that has been introduced to probabilistically divide the sample into homogeneous clusters in order to account for unobserved heterogeneity (Afghari et al., 2020; Griswold et al., 2018). The advantage of class models over the previously mentioned models lies in accounting for the possibility of common parameters among unobserved groups (classes) of observations and not requiring a parametric assumption regarding the distribution of unobserved heterogeneity in the data. In this study, we utilize a latent class ordered probit model to investigate the determinants of cyclist comfort, handling simultaneously both the ordered nature of perceived rated comfort and unobserved heterogeneities.

Latent class modelling technique assumes that there are finite classes over the population and the parameters of the statistical model (e.g. ordered discrete choice model in this study) can vary in these classes. This mechanism accounts for possible unobserved heterogeneity that may exist in data. In contrast with other clustering techniques, the latent class technique presents various advantages (Liu & Fan, 2020). It does not necessitate specifying a priori the number of classes in the data; the most suitable number can be determined by comparing the statistical fit of the models. Additionally, it can accommodate various types of variables (frequencies,

Table 1
Summary statistics of the variables used in the study (N = 594).

Variable	Description	Sample share
Gender	1: female, 0: otherwise	0.56
Age	Year (Max: 73; Min:16; Ave:32; SD:11)	
Education level	Less than diploma	0.30
	Diploma	0.37
	Higher education (Masters or higher)	0.33
Income	1: income over 20,000 SEK, 0: otherwise	0.42
Household structure (number of people in the household)	0	0.48
	1–2	0.49
	>2	0.03
Having a job/study	1: yes, 0: otherwise	0.64
Cycling experience	1: no experience	0.04
	2: monthly use	0.14
	3: weekly use	0.56
	4: daily use	0.26
Being a frequent e-scooter user	1: have daily e-scooter experience, 0: otherwise	0.50
Wearing a helmet while cycling	1: yes, 0: otherwise	0.42
Bike owner	1: yes, 0: otherwise	0.42
Car owner	1: yes, 0: otherwise	0.33
E-scooter owner	1: yes, 0: otherwise	0.17
E-bike owner	1: yes, 0: otherwise	0.23
Frequent bus user	1: yes, 0: otherwise	0.59
Using active mode to access public transport	1: yes, 0: otherwise	0.18
Preferred mode for short distance trips (up to 10 km)	1: active mode, 0: otherwise	0.69
Preferred mode for long distance trips (over to 10 km)	1: active mode, 0: otherwise	0.38
Opinion on whether the cycling system needs improvement	1: yes, 0: otherwise	0.35
Perceived comfort in passing	1: uncomfortable	0.36
	2: neutral	0.28
	3: comfortable	0.36
Perceived comfort in meeting	1: uncomfortable	0.15
	2: neutral	0.53
	3: comfortable	0.32

Fig. 1. Illustration of Shared Space for Data Collection.

categorical, continuous, nominal, and combinations of these types) without prior standardization, preventing bias in the results. The most important advantage of the latent class modelling, however, is that observations are allowed to belong to all classes with different probabilities. This is in sharp contrast with the conventional clustering techniques which deterministically separate the data into clusters.

Our survey asked participants to evaluate their comfort levels in separate passing and meeting scenarios. For example, one scenario describes a participant passing another cyclist, asking them to rate their comfort, while another scenario involves a meeting situation with an oncoming cyclist, requiring a similar comfort assessment. To synthesize these evaluations into a comprehensive measure of perceived comfort, we consistently applied demographic variables as constants across scenarios while varying the specifics of each participant's encounters (i.e., passing or meeting scenarios). This allowed us to construct a nuanced picture of comfort levels across different interaction types. Furthermore, we introduced a dummy variable to distinctly analyze the impact of meeting scenarios on perceived comfort, coded as '1′ for meeting instances and '0′ otherwise. This modeling choice acknowledges the distinct experiential qualities of meetings compared to passings. The introduction of this dummy variable, alongside the aggregation of scenario-specific comfort ratings, creates a panel data structure. We approached this complexity through random effects modeling, capturing the variability in responses to diverse interaction scenarios and enhancing our analysis's depth and relevance to shared space dynamics.

To specify the latent class model, we first define the dependent variable as the level of comfort that cyclist *i* perceives in scenario *j* (j = 1: meeting, j = 0: otherwise) and we denote it by Y_{ij}. We define three levels for this dependent variable including 1: uncomfortable, 2: neutral, and 3: comfortable. Let *s (s = 1, 2, 3)* represent these ordinal levels. To construct the ordered response model, an underlying latent variable is first defined by a linear propensity function for the dependent variable as in the following:

$$y_{ij}^{*} = \boldsymbol{\beta X_{ij}} + \varepsilon_{ij} + \nu_i \tag{1}$$

where β is the vector of parameters, X_{ij} is the vector of covariates (cyclist's demographic characteristics, scenario features, etc.) and ε_{ij} is idiosyncratic error terms assumed to be identically and independently distributed (with normal distribution) across observations in this equation. ν_i is an additional random term that only varies across individuals (with *I* index) and is constant across scenarios (without the *j* index). This additional error term follows a standard normal distribution and accounts for the panel structure of the data (i.e. repeated observations of the same individual but different scenarios). The latent variable is then mapped to the actual categories of the dependent variable by thresholds (α) such that:

$$Y_{ij} = \begin{cases} 1 & if\, y_{ij}^{*} \leq \alpha_1 \\ 2 & if\, \alpha_1 < y_{ij}^{*} \leq \alpha_2 \\ 3 & if\, \alpha_2 < y_{ij}^{*} \leq \alpha_3 \end{cases} \tag{2}$$

where α_1, α_2, α_3 denote the threshold values for the categories of perceived comfort and are unknown parameters to be estimated. This model is referred to as the random effects ordered probit model and can be estimated through the method of maximum likelihood estimation. The probability of perceived comfort for cyclist *i* in scenario *j* belonging to each category can then be expressed as:

$$\begin{aligned} prob\left(y_{ij}=1\right) &= \Phi\left(\alpha_1 - \boldsymbol{\beta X_{ij}} - \nu_i\right) \\ prob\left(y_{ij}=2\right) &= \Phi\left(\alpha_2 - \boldsymbol{\beta X_{ij}} - \nu_i\right) - \Phi\left(\alpha_1 - \beta \boldsymbol{X_{ij}} - \nu_i\right) \\ prob\left(y_{ij}=3\right) &= \Phi\left(\alpha_3 - \boldsymbol{\beta X_{ij}} - \nu_i\right) - \Phi\left(\alpha_2 - \beta \boldsymbol{X_{ij}} - \nu_i\right) \end{aligned} \tag{3}$$

where Φ(·) represents the cumulative probability function of normal distribution. This model is now extended into the latent class specification to account for unobserved heterogeneity in data.

Assuming that there are *M* number of latent classes over the population, the probability of observations belonging to each distinct class, $P(C_m)$, can be computed using a logit model with the following specifications:

$$P(C_m) = \frac{e^{U_m}}{\sum_{m=1}^{M} e^{U_m}} \text{ and } \quad U_m = \Omega_m Z_m \tag{4}$$

where ***Ω*** is the vector of parameters (including an intercept), and ***Z*** is the vector of class-specific covariates. Such covariates determine the probabilities of observations being assigned to each specific class. Within each class, the probability of comfort levels conditioned to that class can be computed using the equation (3). Applying the rules of conditional probabilities, the marginal probability of the latent class random effect ordered probit model is stated as:

$$P(y_{ij}) = \sum_{m=1}^{M} P(y_{ij}|C_m) \times P(C_m) \tag{5}$$

where $P(y_{ij})$ is the unconditional probability of comfort levels, $P(y_{ij}|C_m)$ is the conditional probability of comfort in class C_m (same as equation (3), and $P(C_m)$ is the probability of class C_m. The maximum likelihood estimation approach is employed for the estimation of the latent class random effect ordered probit model.

In the above formulation of the latent class model, the classes are assumed to be latent across observations, and thus the number of latent classes is not known a priori. Therefore, the model is empirically tested with a different number of classes (*M*), and the preferred number of classes is selected based on the model with the superior statistical fit. Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) are employed to compare the statistical fit of the model candidates (Washington et al., 2020):

$$AIC = -2LL + 2P \tag{6}$$

$$BIC = -2LL + PLog(N) \tag{7}$$

where *LL* is the log-likelihood of the estimated model at convergence, *P* is the number of estimated parameters, and *N* is the number of observations or sample size. The model with lower *AIC* and *BIC* is regarded as a superior model in terms of statistical fit.

4. Results

Different variants of the latent class random effect probit models were initially fitted to empirical data in this study, employing different class configurations. The models' statistical fit was subsequently compared to identify the most optimal model. Explanatory variables were incorporated into the models through a stepwise variable selection criterion, a method proven effective in previous latent class modelling (Afghari et al., 2020). Throughout all model specifications, potential multicollinearity among explanatory variables was assessed by computing correlation coefficients. Variables exhibiting high correlations (>0.7) were excluded from the models. The statistical fit of these models are detailed in Table 2. The ordered probit model featuring two latent classes demonstrates a lower AIC and BIC (2359.6 and 2451.7, respectively) in comparison with the other model variations. This observation suggests that the model with two latent classes is superior (in terms of the statistical fit) than the other models. Consequently, the latent class random effect probit model with two classes is identified as the preferred model for drawing inferences regarding the impact of explanatory variables on the perceived comfort. The results of this selected model for the sample data are presented in Table 3.

Results indicate that observations fall into class 1 and class 2 with 57.1 % and 42.9 % probabilities, respectively, implying the presence of two distinct cyclist profiles in the sample. The average predicted levels of comfort within these two categories (Fig. 2) are 47 % and 72 %, implying that the first category is associated with less comfortable cyclists, whereas the second category is associated with more comfortable cyclists.

Table 2
Summary statistics of the model selection fit.

Variable	Random effect Ordered probit model	Random effect latent class ordered probit model with 2 classes	Random effect latent class ordered probit model with 3 classes	Random effect latent class ordered probit model with 4 classes
Likelihood at convergence	−1224.59	−1158.81	−1224.59	−1173.58
Number of parameters* estimated in the model	9	21	33	45
AIC	2467.2	2359.6	2515.2	2437.2
BIC	2506.7	2451.7	2659.9	2634.6

* These parameters are the coefficients of the explanatory variables used in our modelling process. The variation in the number of these parameters across models results from testing different numbers of explanatory variables and latent classes to identify the most suitable model for analysis.

Table 3
Results of the latent class random effect ordered probit model of comfort (N = 594).

Variable	Latent class 1			Latent class 2		
	Estimate	Standard Error	t-Statistic	Estimate	Standard Error	t-Statistic
	Class membership model component					
Age	0.081	0.012	6.75	r	r	r
Education	−0.288	0.151	−1.907	r	r	r
Class probabilities (sample share)	0.571			0.429		
	Cyclist' comfort model component					
Threshold uncomfortable to neutral	−1.802	0.399	−4.516	4.426	0.711	6.225
Threshold neutral to comfortable	1.524	0.103	14.8	1.670	0.142	11.76
Sex: Female	−0.469	0.111	−4.423	−0.816	0.154	−5.299
Cycling experience	0.171	0.079	2.165	–	–	–
Being a frequent e-scooter user	–	–	–	−0.115	0.081	−1.419
User's convenient with the transport system	–	–	–	–	–	–
Wearing a helmet	–	–	–	–	–	–
Education * Income	–	–	–	−0.269	0.086	−3.128
Direction of encounter: Meeting	1.348	0.175	7.703	−1.085	0.252	−4.306

Note: –: not statistically significant; r: reference in the class membership model component.

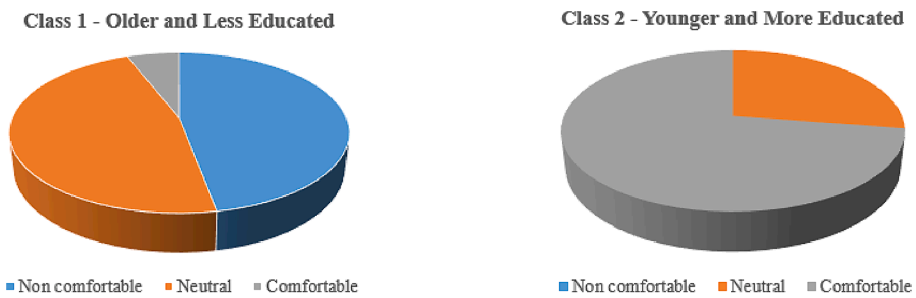

Fig. 2. The Average Predicted Levels of Comfort for each Class.

Interestingly, the determinants of class probabilities paint a similar picture of these categories. The first class tends to include older cyclists with lower education levels, whereas the second class consists predominantly of younger adults with higher education levels.

In addition, our analysis demonstrates that female adults in both classes perceive less comfort in shared spaces than their male counterparts, with this effect more pronounced in the second class (estimate: −0.816) than in the first (estimate: −0.469). Additionally, cycling experience is positively correlated with comfort (estimate: 0.171) only in the first class, indicating that cycling experience enhances comfort perception. On the contrary, frequent e-scooter usage (estimate: −0.115) is associated with decreased comfort in the second class. However, the statistical significance of this relationship is low. The interaction between income and education (estimate: −0.269) is statistically significant only in the second class and indicates that individuals with higher income and education levels in this class experience less comfort.

Interestingly, the impact of 'meeting' versus 'passing' scenarios exhibits a notable difference between the two classes, not just in the direction but also in the magnitude, reflecting the complex nature of cyclists' experiences in shared spaces. In the first class, 'meeting' scenarios are linked to an increase in perceived comfort (estimate: 1.348) compared to 'passing,' suggesting that these direct encounters enhance cyclists' comfort levels. In sharp contrast, the second class demonstrates a marked shift, with 'meeting' scenarios associated with a decrease in perceived comfort (estimate: −1.085) relative to 'passing', albeit with a smaller effect size.

5. Discussion

5.1. Class membership model component

As stated succinctly, the sample data revealed two distinct categories of cyclists in this study: older cyclists with lower education levels and less perceived comfort versus younger cyclists with higher education levels and more perceived comfort. Given that cycling demands physical effort, and age may significantly impact users' effort levels, this variable proves crucial in comprehending cyclists' behaviour and their perception of comfort (Aldred et al., 2016). Additionally, the educational background has been shown to influence the user type in various micromobility modes, such as e-scooters and, to some extent, cycling (Aldred et al., 2016; Laa & Leth, 2020). Cognitive abilities, which may change with age, play a role in how users evaluate their comfort, particularly when assessing their ease in navigating shared spaces. Older respondents could be more risk averse as well, internalizing physical injury vulnerability with changes in comfort when facing interactions with other road users. Age-related differences in the behaviour of active transportation modes have been documented in the literature. For instance, mobility restrictions typical of older age have been associated with difficulties in completing crossings on time (Lachapelle & Cloutier, 2017). Juxtaposing these two characteristics implies a dominant user behaviour that could differ from other counterparts. This multifaceted approach strengthens the foundation for delineating distinct classes based on age and education, enriching the insights into cyclists' perceptions and experiences in shared spaces.

5.2. Cyclist's comfort model component

The results from the cyclists' comfort model component reveal varied effects of explanatory variables across the two classes. These disparities, encompassing distinct sets of statistically significant variables and disparate parameter estimates for the same variables, underscore the effectiveness of the latent class probit model in addressing the unobserved heterogeneity in the data.

In both classes, female adults consistently report lower comfort levels in shared spaces than males. This finding aligns with the existing literature suggesting that female cyclists are generally more affected by disturbing factors (Kazemzadeh & Ronchi, 2022). For example, female cyclists may feel less at ease in shared facilities with motorized vehicles compared to their male counterparts (Garrard et al., 2008; Prati et al., 2019). Consequently, the study emphasizes the need for further investigation into actions that could improve the perception of comfort in shared spaces for female cyclists, increasing inclusion in active transportation. Additionally, while it is widely acknowledged that dedicated spaces enhance perceived safety and comfort for all users, particularly women, our results reveal that women still experience lower comfort levels in such spaces relative to men (Dill et al., 2014; Monsere et al., 2012). Further exploration is needed to understand the nuanced dynamics contributing to female cyclists feeling less comfortable than males even in dedicated spaces for active mobility.

Interestingly, being a frequent e-scooter user has an unexpected negative effect on comfort within the second class. In other words, within the second latent class, individuals with frequent e-scooter usage reported experiencing lower levels of comfort when navigating shared spaces with other vulnerable road users. It appears that e-scooter users might have different expectations or experiences that lead to a perception of decreased comfort in these interactions. Generally, the experience with one type of micromobility could be assumed to increase the experience with the other type too, which, in this case, e-scooter riding could improve navigation of cyclists in shared spaces. Yet, our findings show that this is not the case. This counterintuitive finding might be due to several reasons: first, the effortless acceleration of e-scooters may give young riders a false sense of ease. This could impact their ability to navigate a bike in crowded settings, where physical exertion and precise maneuvering are essential for safety and comfort (Kazemzadeh et al., 2023). That they previously self-selected into e-scooter use may be an indication that they are less comfortable on a bicycle. Second, e-scooters have distinct speed, agility, and riding posture compared to cycling. These differences could significantly minimize the impact of e-scooter riding experience on cycling (Almannaa et al., 2021). In contrast, this variable is not statistically significant within the first class, which could be due to the dominance of e-scooter usage by younger and highly educated adults (Laa & Leth, 2020). The above effects may also imply that navigating shared spaces could be a novel experience for cyclists, considering the recent presence of emerging transport modes. Thus, more research is needed to understand how the presence of other types of micromobility, as well as the experience of riding them, could affect cyclists' experience and subsequently comfort across different demographics.

Cycling experience is statistically significant in the first class with a positive sign, meaning that having experience of cycling is associated with increased perception of comfort. This finding is intuitive, as older adults (which are more likely to belong to the first class) might have more years of experience of cycling. Also, cycling experience makes cyclists more alert to different situations and improves their confidence when judging speed and distance, a characteristic observed exclusively in the first class. In contrast, this variable does not have a statistically significant impact on the perception of comfort within the second class.

The interaction of education and income was introduced as a new variable in the model. This variable is statistically significant and has a negative sign within the second class. Cyclists with higher levels of education and income perceive less comfort in shared spaces. Reflecting on the second class, which is more likely related to females with a higher level of education, could help interpret this finding. This demographic's heightened sensitivity to space conflicts may stem from higher expectations of the transportation system, particularly in terms of cycling infrastructure quality. Such expectations are supported by findings that women generally demand higher standards in cycling facilities (Chaurand & Delhomme, 2013). Furthermore, individuals with higher education levels tend to view cycling more favorably due to its health and environmental benefits (Hudde, 2022), consequently expecting enhancements in comfort and infrastructure. This heightened expectation might contribute to decreased comfort, highlighting a gap in the literature where further research is needed to explore this relationship and provide empirical evidence. Given the younger demographic and comparatively lower cycling experience of users in this class, they may find encounters in shared spaces less comfortable. This is likely attributed to their limited experience navigating such environments, particularly in interactions with diverse road users, making them more sensitive to conditions that diminish comfort compared to their more experienced counterparts. In contrast, this variable is not statistically significant within the first class, further emphasizing the importance of modeling capability to show the impact of the same variable on different user categories.

An essential aspect of our study explores the impact of the type of encounter (passing or meeting) on cyclists' comfort, offering a nuanced contribution to urban cycling research. While the general body of cycling literature, spanning over three decades, posits that nonverbal communication in meeting scenarios typically eases interaction and enhances comfort (Kazemzadeh et al., 2020), our findings present a more complex picture.

The first class demonstrates an intriguing finding; 'meeting' scenarios result in an increase in comfort (estimate: 1.348) relative to 'passing', aligning closely with the literature's assertions regarding the benefits of nonverbal communication. This indicates that for older cyclists, who predominantly constitute the first class, passing events are perceived as less comfortable, likely due to the higher demands these scenarios place on spatial awareness and speed judgment.

Conversely, in the second class, contrary to the anticipated negative impact on comfort derived from nonverbal cues during meetings, we observed a decrease in comfort in 'meeting' scenarios (estimate: −1.085). This suggests that, within this class, the anticipated ease of interaction through nonverbal communication does not translate into an increase in comfort. Instead, the requirement for direct negotiation and spatial sharing in these encounters may reduce comfort, challenging the prevailing assumption that meetings inherently contribute to higher comfort levels in shared spaces.

This divergence in comfort perception between meeting and passing scenarios across different cyclist classes underscores the nuanced nature of cyclists' experiences in shared spaces. It highlights the crucial role of demographic factors and the complexities of nonverbal navigation strategies in shaping comfort. These insights challenge us to reconsider the dynamics of cyclist encounters in urban planning and to acknowledge that the comfort associated with nonverbal communication during meetings may vary significantly among different cyclist groups.

Our study thereby extends the discourse on urban cycling, suggesting that while nonverbal communication in meeting scenarios can facilitate interaction, the context and demographic characteristics of cyclists significantly influence how these encounters impact comfort. This complexity calls for a more differentiated approach to designing cycling infrastructure, one that accommodates the diverse experiences and needs of the urban cycling community.

We also tested several other variables that we thought might have an impact on the user in our modeling trials. For instance, we assumed that wearing a helmet for users could be an important indicator for the perception of comfort, which turned out to be not statistically significant but is kept in our final model specification. Further research is needed to understand how safety concerns (e.g., users' habits of wearing helmets) and the overall perception of the transport system's comfort could affect users' perception of comfort in shared spaces.

Understanding the underlying reasons behind these nuanced findings opens new avenues for designing targeted interventions aimed at enhancing user comfort and, concurrently, fostering the inclusivity of heterogeneous user groups. By exploring the intricacies of how different demographics perceive and navigate shared spaces, urban planners and policymakers can tailor interventions to address specific needs, ultimately cultivating a more equitable and comfortable environment for all road users. These insights serve as a foundation for the development of evidence-based strategies that prioritize user experience, contributing to the creation of safer and more user-friendly shared spaces.

6. Practical relevance for understanding cyclists behavior

The existing body of research focused on understanding cyclists' perceived comfort in passing and meeting situations predominantly relies on observational methods, with limited exploration through experimentation and simulation studies (Guo et al., 2021). Consequently, the emphasis has primarily been on analyzing the traffic flow dynamics of road user interactions. While recognizing the significance of this analytical approach, it is crucial to incorporate the demographic characteristics of cyclists when evaluating their behaviour in shared spaces. Specifically, stated comfort levels in actual mixed cycling environments can help validate other data collection efforts.

Understanding the role of cyclists' demographic characteristics in their comfort perception is vital, given its potential impact on the inclusion of the transportation system. Numerous studies have indicated that active transport is typically dominated by young, employed males (Heinen et al., 2010). This demographic trend implies that a considerable portion of the population, including older adults and females, is underrepresented in the utilization of active modes. Our findings validate that the perception of comfort in passing and meeting events significantly differs between younger and older adults, a variable that has often been overlooked in previous research.

Our results highlight that older adults express greater comfort in meeting situations compared to passing situations. This underscores the need for enhancing the shared space experience for older adults, providing adequate passing opportunities where faster moving road users are present. For example, increasing awareness among road users and implementing clearer, more visible signage could support older cyclists, prolonging their cycling activity and improving their overall experience on the road (Ryan et al., 2016).

Additionally, our findings reveal that the experience of cycling increases user comfort in shared facilities, particularly for older adults, while the experience of e-scooters decreases comfort, particularly for younger adults. This is an intriguing and consequential discovery, especially considering the prevalence of e-scooters in shared spaces. This implies that road users who self-select into using e-scooters generally perceive less comfort while cycling and are often novice micromobility users. This finding highlights the necessity for designs that are inclusive and enhance comfort, catering to populations seeking to minimize risk and maximize comfort. This insight is crucial for crafting interventions that prioritize the diverse needs of cyclists and other road users, promoting a more inclusive and comfortable environment for all.

As designers and policy makers grapple with emerging technologies (e.g., e-scooters) and their access in shared spaces, it becomes increasingly important to understand the effect of increasing interactions of different types on comfort levels for existing and future shared space users. On the one hand, increasing technology could provide benefits by generating added utility among existing of prospective shared space users. On the other hand, mixing more vehicles with different types of operating characteristics can reduce comfort for all shared space users and diminish the overall space. Expansive policy on technology access is being deployed (e.g., geofencing e-scooters, excluding e-bikes) on the premise of maintaining or improving comfort, with little evidence of factors that impact comfort for different populations. This work is among the first that aims to understand factors among existing cyclists that affect comfort.

7. Conclusions

The dynamics of user interaction, influenced by varying speeds and navigation characteristics, present a complex scenario that needs dedicated human factors research. However, a comprehensive exploration of the comfort associated with road user interactions, especially in shared spaces, remains lacking. To begin to address this knowledge gap, our study conducted a stated preference investigation in Lund, Sweden, a city where cycling prevails as a dominant mode of transport. Our preliminary work sought to understand how cyclists interact with other road users during passing or meeting events. The collected data served as explanatory variables in a random effect latent class ordered probit model designed to probe into the determinants of cyclists' comfort in these scenarios. The latent class specification was employed to account for unobserved heterogeneity of cyclists.

The study's findings reveal that female cyclists generally perceive less comfort compared to their male counterparts. Additionally, older adults experience more comfort during meeting events compared to passing events, and report lower levels of comfort than their younger counterparts. This discovery underscores the intricate nature of perceived comfort during interactions, emphasizing the role of demographic characteristics. The implications of these findings extend to enhancing heterogeneous user groups within shared spaces that promote comfortable riding for "all ages and abilities". Moreover, the outcomes contribute to the development of level-of-service indices for shared roads and add valuable insights to validate studies conducted through observation and experimentation in the analysis of passing and meeting events in shared spaces. Expanding on this work could contribute toward designing better shared spaces that include a mix of users that can co-exist in pedestrianized urban infrastructure.

While our study makes valuable contributions, it is important to acknowledge its limitations. Firstly, the examination of comfort is limited to cyclists, neglecting the perspectives of pedestrians, e-bike riders, and e-scooter riders who also utilize shared spaces. Secondly, methodologically, the study did not explore various variables within each class due to the limited sampling approach, potentially hindering a more comprehensive understanding. Furthermore, while we endeavored to select participants for our survey randomly, the refusal of some individuals to participate could introduce biases into our sampling method. This limitation, however, is not exclusive to our study but is a recognized challenge in survey-based research. Notwithstanding these challenges, our data collection approach aligns with established methodologies in cycling literature, as evidenced by similar strategies employed in previous studies (Bai et al., 2017; Monsere et al., 2012). Moreover, while our study provides valuable insights into cyclists' experiences in a specific shared space within a single city in Sweden, it represents only one sample from an urban environment. The generalizability of our findings may be influenced by the particular demographic and travel characteristics of our participants. Therefore, it is imperative for future research to replicate and extend this study in varied geographical settings. Investigations in cities of differing sizes and with diverse user demographics are essential to enrich our understanding of the cycling experience in shared facilities. Such studies will contribute to a more comprehensive and nuanced body of knowledge, supporting the development of inclusive and effective urban mobility solutions.

Lastly, the study's focus on intercepting cyclists in shared spaces could be augmented by observational methods, recording trajectories, and comparing stated comfort with observed navigation through a shared space. These limitations highlight crucial areas for future research, particularly the need to explore the experiences of a broader range of road users, incorporate diverse methodological approaches, and consider the impact of different environmental conditions and urban contexts on user comfort.

CRediT authorship contribution statement

Khashayar Kazemzadeh: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Software, Conceptualization. **Amir Pooyan Afghari:** Writing – review & editing, Validation, Software, Methodology, Formal analysis. **Christopher R. Cherry:** Writing – review & editing, Validation.

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.

Data availability

Data will be made available on request.

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