Transport Reviews

ISSN: 0144-1647 (Print) 1464-5327 (Online) Journal homepage: www.tandfonline.com/journals/ttrv20

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To cite this article: Miguel Costa, Manuel Marques, Felix Wilhelm Siebert, Carlos Lima Azevedo & Filipe Moura (24 Aug 2025): Bridging the gap: a scoping review exploring the relationship between objective and subjective cycling safety, Transport Reviews, DOI: 10.1080/01441647.2025.2537200

To link to this article: https://doi.org/10.1080/01441647.2025.2537200

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TRANSPORT REVIEWS
https://doi.org/10.1080/01441647.2025.2537200

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Bridging the gap: a scoping review exploring the relationship between objective and subjective cycling safety

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ABSTRACT

Research on cycling safety helps create urban environments where cyclists feel and are safe. Cycling safety is studied from two perspectives: objective safety, which examines crashes' causes and consequences, and subjective safety, which explores individuals' perceptions of said crashes. While studying both aspects are important, they are often studied separately. However, understanding their relationship is vital to ensure policies and measures benefit both without unintended negative effects on each. This study reviews literature on the connection between objective and subjective safety. Results show this relationship is complex and context-dependent, with both alignments and discrepancies. Key methodologies, findings, and challenges are discussed to better understand how this relationship can be influenced. The roles of individual behaviour, self-selection, and risk homeostasis in shaping this dynamic are hypothesised and discussed. Overall, the findings highlight the importance of aligning urban planning and safety measures with cyclists' actual and perceived safety. Future research directions are proposed to help authorities and practitioners design interventions that effectively enhance both safety dimensions, ensuring cycling becomes a safer and more appealing mode of transportation.

ARTICLE HISTORY
Received 3 June 2024
Accepted 14 July 2025

KEYWORDS
Cycling safety; objective safety; subjective safety; objective–subjective safety relation; literature review

1. Introduction

Cycling plays a key role in cities' transition to more sustainable transportation modes as it serves as an important option for shorter trips, including first-and-last-mile links to transit. For those who cycle or intend to do so, cycling safety aspects are often considered as critical barriers to cycle (Aldred, 2016; Aziz et al., 2018;

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Félix et al., 2019; Parkin et al., 2007; Pearson et al., 2023; Sanders, 2015; Winters et al., 2012). Keeping cyclists safe from being involved in crashes is vital to prevent minor or life-changing injuries and death. At the same time, it is also crucial that cyclists feel safe and this sense of safety is hypothesised to be more significant than objective reality to increasing bicycle use (Manton et al., 2016). If cyclists consider cycling to be unsafe, they will opt for a different transport mode (Chaurand & Delhomme, 2013).

All in all, cycling safety research focuses on creating policies and measures to reduce crashes and injuries while improving cyclists' sense of safety. It involves studying risk, exposure to risk, and travel behaviour (Schepers et al., 2014). Cycling risk can be divided into two types: objective risk and subjective risk, with each type overviewed in Sections 1.1 and 1.2.

1.1. Objective safety

Objective road safety (also known as actual or observed safety) is a measure for road safety typically based on recorded numbers of road crashes and injuries or described as injury-related risk (Sørensen & Mosslemi, 2009). Objective cycling safety can be understood as a particular case of objective road safety when cyclists are involved in either crashes or measures of risk. Risk is normally understood as the probability of a crash or injury per unit of exposure to road traffic and/or other traffic factors (Vandenbulcke et al., 2014), with the most common measure being the number of crashes or injuries per distance travelled.

Improving objective safety can be achieved through the implementation of different measures from infrastructure design to policy enforcement, technological integration, or even promotion of safe individual practices. To design such strategies, authorities and researchers use a myriad of analytical approaches (Salmon et al., 2022; Scarano et al., 2023) to understand how different geographical, temporal, and causal factors influence crashes and risk, including different built environment characteristics (i.e. road and other physical environment elements such as road and roadside factors, road network, or land use), cycling volumes, and personal characteristics, to name a few (Salmon et al., 2022; Scarano et al., 2023; Utriainen et al., 2023).

Most studies rely on the available number of injuries, fatalities, or crashes which are typically recorded by police or hospitals. Yet, these are often fragmented, with unfeasible, unknown, or missing characteristics (Costa et al., 2022) and suffer from under-reporting of crashes (Winters & Branion-Calles, 2017), posing additional challenges. More, there is a lack of consensus on how to compare risk exposure (Vanparijs et al., 2015). This, together with the absence of open, reliable datasets capturing bicycle traffic flow limits frequentist research approaches, pushing researchers to focus on crash severity studies, despite accounting for volume being vital for correctly estimating crash risk (von Stülpnagel, Petinaud, et al., 2022).

An alternative to traditional police and hospital data is the use of surrogate objective measures, which are used to estimate crash likelihood indirectly based on observable behaviours or conditions. These measures can capture different aspects of traffic events (Johnsson et al., 2018), with near misses, time-to-collision, post-encroachment time, and lateral passing distance being among the most commonly used.

Understanding how passing distances and related factors affect cyclist safety (Aldred & Goodman, 2018; Beck et al., 2021; Rasch et al., 2022; Rubie et al., 2020, 2023; Thomas et al., 2019; von Stülpnagel, Hologa, et al., 2022) can provide valuable insights into unsafe interactions and help complement traditional crash datasets (Aldred & Goodman, 2018; Rubie et al., 2020).

1.2. Subjective safety

Subjective cycling safety (i.e. perceived safety) refers to an individual's personal perceptions and feelings regarding their potential safety while cycling. It differs from objective safety and encompasses individuals' risk perception, i.e. the process of assessing the level of risk of a situation and one's abitility to deal with such event effectively (Deery, 1999) rather than measuring statistical injury-related risk. In that sense, it is a psychological construct, rooted in how people perceive hazardous situations for themselves and/or others, rather than solely relying on the statistical probability of an incident occurring. This feeling of unsafety is usually shaped by a combination of different aspects and dimensions (Haworth et al., 2005; Sørensen & Mosslemi, 2009; von Stülpnagel & Binnig, 2022). These include beliefs and perceptions of how dangerous individuals perceive traffic to be, emotional and cognitive responses to perceiving the risk of an crash or injury, the thought of being involved in a crash and its consequences, among others (Sørensen & Mosslemi, 2009). It also includes personal experiences or interactions with other road users (Chataway et al., 2014; Sanders, 2015). Subjective safety can also manifest as highly specific to a particular location or time or to cycling in general. Similar to objective safety, it does not include other forms of personal risk assessments, e.g. if a road user feels at risk of robbery due to low light conditions (Ferreira et al., 2022).

Contrasting with objective safety which is based on police or hospital records, subjective safety research typically uses qualitative and quantitative questionnaires and interviews to collect data on individuals' perceptions to identify elements that negatively arouse individuals (Aldred & Woodcock, 2015; Kalra et al., 2023; Sanders, 2015). Questionnaires and surveys serve as a tool to evaluate cycling environments, contexts, and their characteristics and derive cause and effect relations in safety assessments (Fuest et al., 2023). In parallel, newer approaches have used naturalistic and semi-naturalistic data collection procedures, including using wearable sensors, videos, street-view images, mental maps, virtual reality, or eye tracking devices (Costa et al., 2025; Manton et al., 2016; Parkin et al., 2007; Schmidt & von Stülpnagel, 2018; von Stülpnagel & Binnig, 2022; von Stülpnagel & Krukar, 2018; Zeile et al., 2016).

The collected data is analysed using a wide range of statistical modelling approaches (Christ et al., 2023; Kalra et al., 2023) to identify and quantify the factors that influence the sense of safety. These tools enable researchers to examine the impact of various elements, such as traffic conditions, infrastructure design, cultural norms, travel distance and time, as well as the visible presence or absence of law enforcement (Ferreira et al., 2022). By isolating and understanding these variables, studies aim to uncover patterns and relationships that contribute to the perception of safety in different contexts, offering valuable insights for policymakers and urban planners seeking to foster environments where cyclists feel safer.

1.3. The relation between objective and subjective safety

Despite considerable efforts in studying objective and subjective safety separately in the past, the relationship between the two persist as a fair unknown in the field of cycling safety research today. For example, do higher objective safety levels influence subjective cycling safety? Or, does the occurrence of cycling crashes influence the public perception of cycling safety? Figure 1 presents a conceptual framework on the objective-subjective safety relation. Analyzing this diagram leads to four possible scenarios:

Quadrant 1: High objective safety and high subjective safety This scenario represents the ideal condition where cyclists perceive the environment as safe, and it is objectively safe. Such conditions promote comfortable and safe cycling experiences, likely encouraging a greater adoption of cycling. Cities and authorities aim to achieve this outcome.

Quadrant 2: Low objective safety and high subjective safety In this case, cyclists perceive the environment as safe, but it is objectively dangerous. This discrepancy creates a false sense of safety, which may encourage risky or maladaptive behaviour and increase the likelihood of crashes. This scenario is particularly concerning, as it can undermine safety efforts.

Quadrant 3: Low objective safety and low subjective safety Cyclists feel unsafe, and the environment is indeed hazardous. This combination increases crash risk and discourages cycling, potentially leading individuals to opt for alternative modes of transport.

Quadrant 4: High objective safety and low subjective safety In this situation, while the environment is objectively safe, cyclists perceive it as unsafe. This misalignment can deter cycling, even when adequate safety measures are in place, thereby limiting the effectiveness of infrastructure investments and nullifying their intended safety benefits.

Understanding how objective and subjective cycling safety relate can help create environments that are not only safe but also feel safe. While some research using surrogate measures have looked at both types of safety, this review focuses only at studies

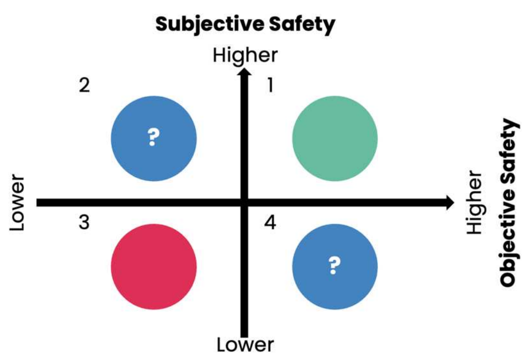

Figure 1. Conceptual relation between objective and subjective cycling safety. Four scenarios exist which impact cyclists' safety and the uptake of cycling in urban contexts.

focussed directly on crashes and their perceptions. For examples on these other works, readers can refer to, e.g. Rubie et al. (2023), von Stülpnagel, Hologa, et al. (2022), Beck et al. (2021), Rasch et al. (2022) and the review by Rubie et al. (2020). Additionally, other studies (e.g. Huber et al., 2023; Kapousizis et al., 2024; Tin Tin et al., 2014) explore how past crashes and safety perceptions influence other factors, but here, we focus specifically on the direct connection between objective and subjective safety.

Thus, this work focuses on reviewing studies that examine this relationship, specifically looking at crashes (objective risk) and how people perceive them (subjective risk). To achieve this, we first review existing research and examine the methods used. Then, we summarise key findings and discuss how factors like behaviour changes, self-selection, and risk homeostasis might shape the objective-subjective safety relation.

This article is structured as follows: after this section, we detail the methodological approach in Section 2, including the literature search strategy. Section 3 examines the results, which are then discussed in Section 4. Finally, Section 5 highlights the main findings and concludes this article.

2. Methodology

A scoping review strategy is employed in this study (framework previously outlined by Arksey & O'Malley, 2005). Contrary to systematic literature reviews that focus on a well-defined question and aim at providing answers to a relatively narrow topic, a scoping literature review tends to tackle a wider scope (typically covering multiple study approaches and designs) and a broader research question (Arksey & O'Malley, 2005). Scoping reviews can also serve as a preliminary approach to cover a research area's body of work and identify potential areas with enough background to warrant a future systematic review (Munn et al., 2018). Importantly, findings are typically not aggregated, nor are assessed qualitatively, but critical gaps and current limitations are identified (Arksey & O'Malley, 2005), which can be used to devise possible paths forward to tackle such gaps, which we undertake in Section 4.

In this scoping review we aim to answer the question: "What do we currently know about the objective–subjective cycling safety relation?" This work examines and summarises past and current approaches to identify and understand whether such a relation exists. Next, we describe the methodology used in the scoping review.

2.1. Search strategy and study selection

To retrieve relevant manuscripts for this review, a search strategy was developed to identify relevant scientific publications. Three electronic research databases were used:

- *Web of Science*[1] (WoS): WoS, sponsored by the Institute of Scientific Information and owned by Clarivate, is a research database that covers more than 196 million records, including more than 34 thousand peer-reviewed journals, and covering 254 subject categories (Clarivate, 2023);
- *Transport Research International Documentation*[2] (TRID): TRID contains the largest bibliographic resource on transportation research information, combining records from the Transportation Research Board's Transportation Research Information Services

Table 1. Search terms and criteria used in all databases.

Category	Search criteria
Keywords	((\objective safety” AND \perceived safety”) OR (\objective safety” AND \perception of safety”) OR (\objective safety” AND \subjective safety”) OR (\objective safety” AND \perceived risk”) OR (\objective safety” AND \perception of risk”) OR (\objective safety” AND \subjective risk”) OR (\observed safety” AND \perception of safety”) OR (\observed safety” AND \perceived safety”) OR (\observed safety” AND \subjective safety”) OR (\observed safety” AND \perceived risk”) OR (\observed safety” AND \perception of risk”) OR (\observed safety” AND \subjective risk”) OR (\actual safety” AND \perceived safety”) OR (\actual safety” AND \perception of safety”) OR (\actual safety” AND \subjective safety”) OR (\actual safety” AND \perceived risk”) OR (\actual safety” AND \perception of risk”) OR (\actual safety” AND \subjective risk”) OR (\crash risk” AND \perceived safety”) OR (\crash risk” AND \perception of safety”) OR (\crash risk” AND \subjective safety”) OR (\crash risk” AND \perceived risk”) OR (\crash risk” AND \perception of risk”) OR (\crash risk” AND \subjective risk”)) AND (cycling OR cyclist*)
Dates	2000 – 2024
Publication types	Journal article, Conference article, Book, Book chapter

Notes: “OR” and “AND” are boolean operators used to find records containing a combination of the specified keywords and “*” means any character used to break off the query word.

Database and the Organisation for Economic Cooperation and Development’s Joint Transport Research Centre’s International Transport Research Documentation Database (The National Academies of Sciences, Engineering, & Medicine, 2023);

- and *Scopus*[3]: Scopus is Elsevier’s research database, covering more than 93 million records from multiple publishers in over 240 disciplines (Elsevier, 2023).

The three databases were searched to identify published and indexed materials using specified keywords in their title, abstract, or keywords. All search criteria, including the keywords used, range of years to search, and publication types, are detailed in Table 1. The terms used a combination of “objective safety” (and similar designations), “subjective safety” (and similar terms), and “cycling” (and similar expressions). The inclusion criteria were designed to ensure the search includes entries covering both safety types. All material considered in this process was published or accepted to be published as of December 31st, 2024.

After searching the databases, 71 publications were identified. From these and after manually reviewing the full-text article, 47 were excluded for being duplicated, being irrelevant, or not being within scope. From the full-text review, five publications were further included from their references. In the end, nineteen publications were reviewed, which we now detail the full-text review results.

3. Results

We will now explore the results from the full-text review of the publications that met the search criteria. First, we give an overview on the selected publications. Next, we identify the data and methodologies used to explore the relation between the two types of safety. Then, we explore the type of relation found and the main topics covered. Table 2 presents a summary of the covered publications.

3.1. Overview of reviewed publications

Overall, cycling safety research is gaining in popularity with a growth in publications over time. Figure 2 shows the number of publications per year. To compare the attention that

Table 2. Summary of reviewed publications.

Authors	Title	Case Study	Methodology	Main results and conclusions	Relation found
Elvik and Bjornskau (2005)	How accurately does the public perceive differences in transport risks?: An exploratory analysis of scales representing perceived risk.	Norway	Exploratory analysis of how perceived risk is related with observed risk in Norway.	Positive correlation between statistically estimated risk and perceived risk for men cycling, and negative for women cycling	In certain circumstances
Fowler and Koorey (2006)	The Effects of the Pages Road Cycle Lane on Cyclist Safety and Traffic Flow Operations	Christchurch, New Zealand	Comparison between perceived safety and crash frequency after the introduction of cycling lanes.	Limited evidence suggest and improvement in both perceived safety and observed safety after the introduction of cycling lanes.	Yes
Ichikawa and Nakahara (2008)	Japanese high school students' usage of mobile phones while cycling	40 Japanese high schools	Inspect the perception and actual use of mobile phones among high schoolers while cycling and the experience of crashes/near-crashes	Crashes/near-crashes were less prevalent for those with a higher perception of danger of using the phone while riding	Yes
Cho et al. (2009)	The role of the built environment in explaining relationships between perceived and actual pedestrian and bicyclist safety	Washington, DC (United States of America)	Investigate how perceived and actual crash risk are related between each other and with respect to built environment characteristics using path analysis	Higher crash risk increases perceived crash risk and higher perceived risk is negatively associated with actual crash risk, as an effect of behavioral change	In certain circumstances
Sorensen and Mosslemi (2009)	Subjective and objective safety: The effect of road safety measures on subjective safety among vulnerable road users	Literature Review of more than 200 artciles	Compilation of available road safety measures for objective and subjective safety for pedestrians and cyclists and assess relationships and discrepancies between their effects on both types of safety.	From 125 total measures, 78 have a positive effect on both objective and subjective safety. Within the remaining 47, 20 have unclear effects on objective and subjective safety, and 25 have opposite effects on objective and subjective safety	In certain circumstances
Castanier et al. (2012)	Risk of crashing with a tram: Perceptions of pedestrians, cyclists, and motorists	10 French cities	Investigate the link between comparative judgements of risky behaviors, previous risky behaviors, and experiences of incidents or crashes involving trams	No significant results for cyclists between subjective assessments of risk and experiences of incidents or crashes	No
Winters et al. (2012)	Safe cycling: How do risk perceptions compare with observed risk?	Toronto and Vancouver (Canada)	Case-crossover which looks at the correlation between perceived risk (estimated from mean scores to a 5-point scale response) and observed	Routes types perceived as risker were found to be so, while routes perceived as safer were also found to be so. Some infrastructure types	In certain circumstances

(*Continued*)

Table 2. Continued.

Authors	Title	Case Study	Methodology	Main results and conclusions	Relation found
			injury risk (estimated using logistic regression)	(e.g., cycle tracks and multiuse paths) showed discrepancies	
Washington et al. (2012)	Relationships between Self-Reported Bicycling Injuries and Perceived Risk of Cyclists in Queensland	Queensland (Australia)	Explore the relation between injuries resulting from crashes and perceived risk as a function of exposure, risk aversion, and rider ability using simultaneous regressions.	Perceived risk does not appear to influence injury rates, nor do injury rates influence perceived risks of cycling	No
Chaurand and Delhomme (2013)	Cyclists and drivers in road interactions: A comparison of perceived crash risk	Paris (France)	Evaluate perceived risk in car-car, car-bike and bike-bike interactions and their likelihood of crashes	Discrepancy between perceived and objective risk which can help to mold behavior	No
Sanders (2015)	Perceived traffic risk for cyclists: the impact of near miss and collision experiences.	San Francisco Bay Area (United States of America)	Investigate whether experiences with collisions or near misses are associated with perceived traffic risk for cyclists.	Both near misses and collisions influenced cyclists' perceptions of risk in various degrees	Yes
Schmidt and von Stülpnagel (2018)	Risk Perception and Gaze Behavior during Urban Cycling—A Field Study	Freiburg im Breisgau (Germany)	Investigate the relation between subjective risk perception during cycling and gaze behavior in a naturalistic setting. Gaze is then compared with known objective and subjective dangerous locations.	Cyclists change their behavior when they thought a road segment to be dangerous, decreasing the probability of an accident. Areas with no accidents may only remain so because cyclists feel at risk. Conversely, actual danger may result from feeling comparatively safer at other locations, making cyclist miss potential threats	No
Useche et al. (2019)	Healthy but risky: A descriptive study on cyclists' encouraging and discouraging factors for using bicycles, habits and safety outcomes	20 Countries in Latin America, North America, and Europe	Analyze the relationship between encouraging and discouraging factors for cycling and cycling crashes suffered within the last 5 years	Individuals with a lower perception of risk are more likely to suffer cycling crashes and injuries	In certain circumstances
Branion-Calles et al. (2020)	Cyclist crash rates and risk factors in a prospective cohort in seven European cities	Antwerp (Belgium), Barcelona (Spain), London (United Kingdom), Örebro (Sweden), Rome (Italy), Vienna (Austria), and Zürich (Switzerland)	Quantify exposure-adjusted crash rates and model adjusted crash risk factors, including sociodemographic characteristics, attitudes about transportation, neighbourhood built environment features and location	Alignment between objective and perceived safety, with individuals who agreed that cycling was a safe were at lower risk for a crash than those that were neutral or disagreed	Yes

(*Continued*)

Table 2. Continued.

Authors	Title	Case Study	Methodology	Main results and conclusions	Relation found
Osama et al. (2020)	Determining if walkability and bikeability indices reflect pedestrian and cyclist safety	Vancouver (Canada)	Explore the association between bike score and cyclist crashes in Vancouver using multivariate Bayesian crash models with random and spatial effects	City areas with increased bikeability (which includes perceived safety and comfort) were associated with greater cyclist crash risk	Yes
von Stülpnagel and Lucas (2020)	Crash risk and subjective risk perception during urban cycling: Evidence for congruent and incongruent sources	Freiburg im Breisgau (Germany)	Analysis accident statistics and citizens' reports concerning cycling risks for a broad range of infrastructure and traffic network elements	General alignement between objective risk and subjective risk perception. However, in some situations there is a high deviation between the two	In certain circumstances
Amiour et al. (2022)	Objective and Perceived Traffic Safety for Children: A Systematic Literature Review of Traffic and Built Environment Characteristics Related to Safe Travel	Literature review of 38 articles	Comparison of literature results to investigate objective and perceived safety for children while walking or cycling	Empirical results from comparison of studies' results highlight that some built environment characteristics are aligned between safety types for walking and cycling safety, while for others there is no correlation or are not aligned	In certain circumstances
Janstrup et al. (2023)	Predicting injury-severity for cyclist crashes using natural language processing and neural network modelling	Denmark	Use of natural language processing to evaluate hospital admissions of perceived safety and injury reports	Strong correlation between identified topics from perceived safety questinnaires and actual safety	Yes
von Stülpnagel et al. (2022)	Crash risk and subjective risk perception during urban cycling: Accounting for cycling volume	Munich (Germany)	Spatial distribution of cycling crashes and crowdsourced data on subjective risky locations to investigate the effects of different infrastructure types, speed limits, and cycling volumes on both types of safety	Objective and subjective risks are mostly well aligned, but there are specific scenarios where cyclists underestimate the actual crash risk	In certain circumstances
Fuest et al. (2023)	I bet you feel safe! assessing cyclists' subjective safety by objective scores	Braunschweig (Germany)	Comparison of two distinct subjective safety metrics, and their comparison to known crash locations	Perceived scores using two different metrics could not deduce the occurrence of a crash, suggesting subjective safety is independent from objective safety	No

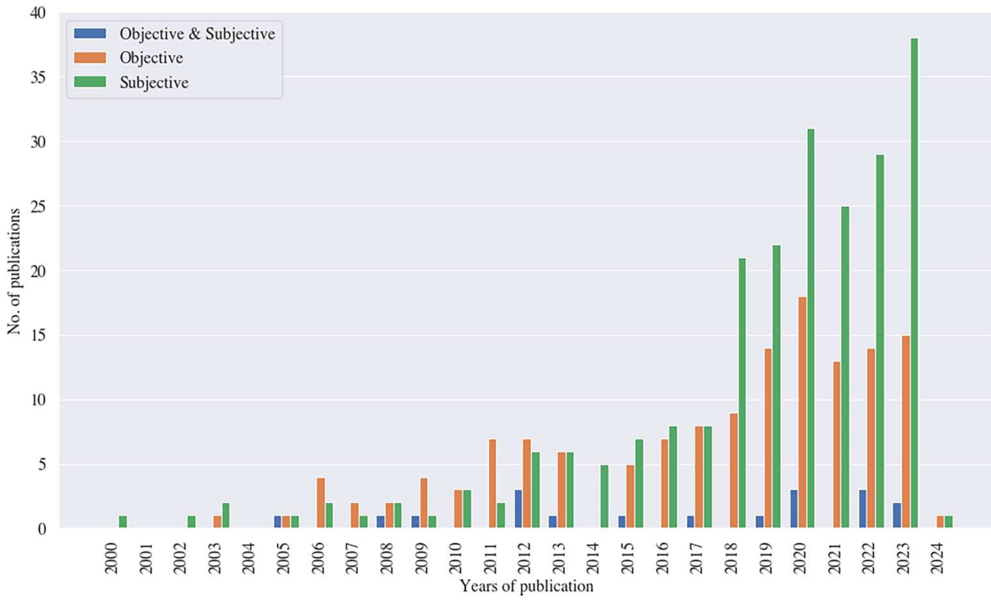

Figure 2. Amount of publications on objective safety only, subjective safety only, and joint objective and subjective safety topics between 2000–2024.

has been paid to exploring both aspects of safety in the same publication, the number of publications on objective cycling safety only and subjective cycling safety only are also displayed. These numbers were compiled using a similar approach to the one described in Section 2.1, but using either the objective or subjective safety keywords at a time, respectively. A steady increase in objective safety and an even steeper increase in the publications on subjective safety in recent years is shown. From 2005 onwards, researchers have begun to explore both topics of safety together, and the existence of a possible relationship between the two. Yet, despite a slight increase in the number of publications in recent times that explore both safety types jointly, it still only represents a very small fraction (below 4% of all publications in 2023) of the total number of publications on cycling safety.

Publications on both objective and subjective cycling safety are authored by an average of 1.5 authors, with seventeen being journal articles, one book chapter, one conference article, and one report. Of the journal articles, eight were published in Accident Analysis & Prevention, four in Transportation Research Part F: Traffic Psychology and Behaviour, two in Transportation Research Record, and the remaining journals contained only one publication of the included articles. European affiliated authors were responsible for thirteen publications, six from North America based authors, three from Oceania, and Africa and Asia affiliated authors having one publication each. Rul von Stülpnagel, Meghan Winters, and Patricia Delhomme were the most prolific authors with two publications each, while the remaining authors were only responsible for authoring one publication. Analyzing the co-citation network (which publications are cited within our included publications), we see that Winters et al. (2012) is the most prominent publication, serving as the anchor for most publications on the topic.

3.2. Type of relation found

The reviewed publications show a complex relation between objective and subjective cycling safety. Fourteen of the nineteen studies identified some type of existing relation, albeit with different types of relation being found. Corresponding levels of safety (i.e. Quadrant 1 and 3) have been found in eight publications for high levels of both safety types and in five for low levels of both safety types. Underestimates of safety (safety perceptions being lower than observed safety, Quadrant 4) have been found in eight articles, while overestimates (safety perceptions being higher than observed safety, Quadrant 2) have also been identified in eight publications. Such findings suggest that objective and perceived safety are sometimes related but dependent on the context and topic of study. Table 3 summarises the connections found, if any.

From the analysed articles, Ichikawa and Nakahara (2008) found an underestimation of safety only, with crashes and near-crashes being less prevalent for those with a higher perception of risk while cycling and using a mobile phone. Useche et al. (2019) and Osama et al. (2020) found safety to be only overestimated, with Useche et al. (2019)

Table 3. Summary of relations found between subjective and objective cycling safety and how the relation found links to different quadrants in the conceptual diagram depicted in Figure 1.

Publication	No relation	Relation found				
		Relation exists with limited evidence	High SS ↔ High OS (Quadrant 1)	High SS ↔ Low OS (Quadrant 2)	Low SS ↔ Low OS (Quadrant 3)	Low SS ↔ High OS (Quadrant 4)
Elvik and Bjørnskau (2005)			✓	✓	✓	✓
von Stülpnagel and Lucas (2020)			✓	✓	✓	✓
Amiour and Waygood (2022)			✓	✓	✓	✓
von Stülpnagel, Petinaud, et al. (2022)			✓	✓	✓	✓
Sørensen and Mosslemi (2009)			✓	✓		✓
Winters et al. (2012)			✓	✓		✓
Cho et al. (2009)					✓	✓
Ichikawa and Nakahara (2008)						✓
Useche et al. (2019)				✓		
Osama et al. (2020)				✓		
Branion-Calles et al. (2020)			✓			
Fowler and Koorey (2006)			✓			
Sanders (2015)		✓				
Janstrup et al. (2023)		✓				
Castanier et al. (2012)	✓					
Washington et al. (2012)	✓					
Chaurand and Delhomme (2013)	✓					
Schmidt and von Stülpnagel (2018)	✓					
Fuest et al. (2023)	✓					

Note: SS: Subjective Safety, OS: Objective Safety.

finding that individuals with lower perceived risk were more probable to be involved in a cycling crash and Osama et al. (2020) finding that city areas where bikeability was higher (associated with higher perception of safety) were associated with greater crash risk. Sanders (2015) and Janstrup et al. (2023) found a relation to exist but with limited evidence to be able to explore it. The remaining articles found the relation to be more complex, with examples lying in up to all four possible scenarios (Quadrants 1 to 4).

Another interesting aspect is that most studies identified that sometimes a connection exists, but that it is dependent entirely on the circumstances, often highlighting situations where a link was not found or was opposite to that of most cases. Within this set of publications, Elvik and Bjørnskau (2005) found a positive relation between perceived risk for men, and negative for women; Cho et al. (2009) highlighted that higher crash risk increased perceived risk, but increase perception of risk led to a decrease in actual risk; Sørensen and Mosslemi (2009) reviewed a number of road safety measures and their impacts on objective and subjective safety, finding that the vast majority improves both safety types, but some have unclear effects or may increase one safety type while decreasing the other; Winters et al. (2012) found out that some particular cycling routes and environments had congruent perceived risk and actual risk, but in others there were discrepancies between the two; Useche et al. (2019) found that individuals with lower perceived risk were more probable to be involved in a cycling crash; von Stülpnagel and Lucas (2020) found a general alignment between safety types, but in some situations there were some discrepancies, such as in one-way streets with bikeways in opposing direction or in locations with tram stops; Amiour and Waygood (2022) noticed a general alignment between subjective and objective safety for numerous built environment elements, while others showed no relation or were not aligned; and von Stülpnagel, Petinaud, et al. (2022) found a general alignment between safety types, but in some specific scenarios cyclists' would underestimate the actual crash risk.

Remarkably, five publications (Castanier et al., 2012; Chaurand & Delhomme, 2013; Fuest et al., 2023; Schmidt & von Stülpnagel, 2018; Washington et al., 2012) found no link between objective and subjective safety, suggesting that subjective safety is a construct independent from objective safety. However, despite no connection, several studies pointed out that behaviour changes may play a role in such discrepancies. In this sense, areas with no reported crashes may owe their crash-free status to cyclists' heightened perception of risk, showcasing the intricate relationship between perception and reality in the context of cycling safety. Ultimately, this raises additional challenges to how such relations can be identified or studied and the complexity of dynamics which needs to be analysed.

3.3. Data

Several studies use hospital and emergency department admission entries for measuring objective safety, such as Janstrup et al. (2023), which combines hospital admissions with self-reported perceptions of representative envrionments, and Winters et al. (2012), which uses a case-crossover approach to analyze injury data from adult cyclists. Similarly, Osama et al. (2020) integrates crash data from insurance companies with exposure metrics from a regional travel model and bikeability indices. Other research, such as Cho et al. (2009), combines police-reported crash data with perceived safety surveys.

Crowdsourced and self-reported data feature prominently in studies addressing subjective risk perception. von Stülpnagel and Lucas (2020) and von Stülpnagel, Petinaud, et al. (2022) explore relationships between crowd-reported cycling risks and police crash data, while studies like Sanders (2015) and Ichikawa and Nakahara (2008) rely on self-reported collisions and perceptions of safety. Surveys are a frequent tool, capturing demographic and attitudinal data (Branion-Calles et al., 2020), cycling habits and motives for cycling (Useche et al., 2019), and risk perception in specific environments (Fowler & Koorey, 2006), which combines qualitative survey responses with objective measures of traffic flow and crash records.

Finally, some studies adopt innovative approaches to capture behavioural data, such as Schmidt and von Stülpnagel (2018), which analyzes risk perception and gaze behaviour in real-world cycling scenarios, or Winters et al. (2012), which compares perceived and observed risks at various sites.

The studies reviewed highlight different levels of data availability and transferability, which significantly influence the scope and applicability of their findings. Many studies, such as Janstrup et al. (2023) and Cho et al. (2009), utilise official datasets like hospital admissions or police-reported crash records, which offer robust and reliable data but are often region-specific, challenging to replicate, and are not openly available for other researchers to analyze directly. Crowdsourced and self-reported data, as seen in von Stülpnagel and Lucas (2020) and Sanders (2015), provide a flexible and scalable approach to gathering subjective risk perceptions but may face issues of bias and inconsistent participation, limiting their comparability for different cycling contexts.

3.4. Methodology and modelling tools used

Interestingly, a relatively large number of approaches have been used to analyze the relationship between objective and subjective cycling safety, despite the relatively small number of works under study. These include rigorous statistical analyses based on solid evidence to find a link between objective and subjective cycling safety, including logistic regression and mean scores from a 5-point survey reponse (Winters et al., 2012), path analysis (a special case of structural equation modelling) (Cho et al., 2009), spatial models (Osama et al., 2020), machine learning tools (Janstrup et al., 2023), and gaze path analysis (Schmidt & von Stülpnagel, 2018). More nuanced qualitative assessments have also been used, including model result comparison (von Stülpnagel & Lucas, 2020; von Stülpnagel, Petinaud, et al., 2022) or comparing results from previous literature (Amiour & Waygood, 2022; Sørensen & Mosslemi, 2009).

Yet, regardless of the methodological strategy used, the vast majority seek to find correlation terms between both types of safety. Although such approaches do not prove causality (i.e. saying that one kind of safety directly affects the other), researchers may deduce some connection between the two. A smaller number of publications have taken a different approach where one-way effects were identified and assumed not to be present in the inverse direction. In practice, this has implications as it help planners prioritise which safety type should be tackled first.

Another key aspect shared between most studies is their approach to analyzing only one particular topic. Here, most studies have emphasised analyzing exposure to risk, common built environment typologies, or its impact on children. Despite shedding light on the convergence and divergence between objective risky situations and the subjective feelings of safety among cyclists, conducting such particular studies may not provide a holistic understanding of the factors influencing cycling safety as a whole.

3.5. Individual and demographic factors

Several studies look at the influence of individual and demographic characteristics on the two cycling safety types. For instance, Sanders (2015) considers variables such as age, gender, ethnicity, income, and driving frequency to understand perceived cycling risks. Similarly, Castanier et al. (2012) explores how age, attitudes, behaviours, and experiences shape cyclists' risk perception, while Ichikawa and Nakahara (2008) examines demographic factors, including phone usage and commuting habits among high school students. Additionally, Useche et al. (2019) and Washington et al. (2012) explore into cycling-related habits, such as cycling frequency, skill level, bike type, speed, and protective gear use, alongside attitudes toward risk. These studies underscore the role of individual-specific factors and behaviours in shaping how individuals perceive and experience cycling risk.

3.6. Infrastructure and built environment

The influence of infrastructure and the built environment is a recurring theme in cycling safety research. Several studies focus on specific infrastructure elements like cycle paths, roundabouts, intersections, and bus or tram stops as key determinants of perceived and actual cycling risk. For example, Winters et al. (2012) and Cho et al. (2009) examine neighbourhood characteristics and network metrics, emphasising how these features impact cyclist safety and comfort. Other studies, such as Fowler and Koorey (2006) and Amiour and Waygood (2022), highlight the role of traffic speed and volume in shaping perceived safety. Overall, most studies focus on the effects of the built environment on cycling safety, a logical focus given that its elements are most times changeable by urban planners and decision-makers to enhance both objective and subjective safety.

3.7. Traffic conditions, volume, and exposure

The relationship between traffic conditions, cycling volume, and exposure takes centre stage in several studies. von Stülpnagel, Petinaud, et al. (2022) and Osama et al. (2020) control for exposure when analyzing crash data, recognising that higher cycling volumes often correlate with changes in risk perception and crash rates. Amiour and Waygood (2022) highlights the importance of high traffic volume and vehicle speeds as primary concerns for parents and children. In sum, controlling for exposure appears to be vital in analyzing and understanding objective and subjective safety and how such exposure is experienced by cyclists.

4. Discussion

This scoping review on the relation between objective and subjective cycling safety has analysed nineteen articles. Cycling safety research has gained popularity recently, growing by approximately 15% over the last decade (Scarano et al., 2023). However, the relation between the two has remained rather unexplored.

The publications reviewed have pointed towards a complex relation. It appears to be context-dependent and contingent upon specific circumstances. For example, Elvik and Bjørnskau (2005) has pointed out gender-dependent variations, while Winters et al. (2012), von Stülpnagel and Lucas (2020), and von Stülpnagel, Petinaud, et al. (2022) have highlighted urban environments where there are discrepancies between objective risk and perception of risk. In this sense, Amiour and Waygood (2022) further underscored such variability by identifying elements in the built environment that either align, show no relation, or are opposite between subjective and objective safety. Sørensen and Mosslemi (2009)'s review of safety measures further strengthen such complex relation.

Several studies, including those by Chaurand and Delhomme (2013), Cho et al. (2009), and Schmidt and von Stülpnagel (2018), found partial or no direct link between objective and subjective cycling safety. However, these studies still acknowledge the potential role of behaviour changes in influencing the discrepancies found.

Such suggestion that other phenomenons may influence both subjective and objective safety creates an additional layer of complexity. We now explore how four possible processes influence this relation: cyclists' behaviour change, self-selection phenomenons, safety-in-number effects, and risk homeostasis processes. Finally, challenges and possible directions for future research are addressed.

4.1. Cyclists' behaviour

As identified by a few publications, cyclists may change their behaviour due to high perceived safety, leading to lower objective risk (Chaurand & Delhomme, 2013; Cho et al., 2009; Schmidt & von Stülpnagel, 2018). As Schmidt and von Stülpnagel (2018) put it, a heightened sense of risk exposure may instigate cyclists to look out for potential dangers, leading to lower levels of objective risks. Conversely, feeling safe may prompt cyclists to miss actual potential threats. Such effects may also be underpinned by individual skill, as cyclists who feel more in control (i.e. with higher levels of perceived safety) might feel they are more able to avoid any crash, leading to more risky behaviours (Lund & Rundmo, 2009) and higher actual risk (Chaurand & Delhomme, 2013; Cho et al., 2009; Rosenbloom et al., 2008). Similarly, one's experience may also act as a positive reinforcement to such behaviours (Chaurand & Delhomme, 2013), leading to lower levels of perceived safety, contributing to complexity in the relation between objective and subjective safety.

In this sense, if the aim is to minimise objective risk, increasing the sense of risk may be beneficial. Changes to the urban environment or use of education and training programs may increase or maintain perceived risk levels (Rosenbloom et al., 2008). However, such overestimation may cause undue stress and overload of attention resources, leading individuals to drop cycling and choose another mode of transportation (Chaurand & Delhomme, 2013). In addition, such a heightened sense of risk may also cause and reinforce an absence or underestimate of objective risk data. Conversely, if the aim is to provide cyclists with a higher sense of safety, then that might negatively affect the levels of actual safety.

Ultimately, however, we can expect that individuals' behaviour may play a role in this intricate connection between objective and subjective. This entails that future studies may need to capture this additional dimension when analyzing the objective–subjective relation and that understanding how efforts that target one or both types of safety is vital for successful cycling safety policies.

4.2. Self-selection

Self-selection phenomena may significantly influence how the relationship between objective and subjective cycling safety is shaped. Self-selection has been studied before relating to residential location and is linked with individuals' tendencies to opt for places of residency based on their abilities, needs, preferences, attitudes, and socioeconomic characteristics (De Abreu e Silva, 2014; Mokhtarian & Cao, 2008). This concept has since been extended to travel choices and modal preferences (Van Wee, 2009). For cycling, self-selection involves individuals choosing to cycle in urban areas based on personal preferences, perceptions, and comfort levels, often influenced by subjective safety or risk perception. From the review and discussion presented before, one can hypothesise that self-selection in cycling can also be linked to the dichotomy of objective safety versus perception of safety.

In terms of objective safety, individuals may choose to cycle in environments they perceive as physically safe, characterised by factors such as well-designed bike lanes, low traffic speeds, and favourable infrastructure. This self-selected group's decision to cycle could reflect their positive assessment of these safety measures. On the other hand, regarding perceptions of safety, those who choose cycling may perceive lower risks compared to individuals who opt for other transport modes. This self-selected group's lower perceived risk could explain their preference for cycling.

Future research should explore whether self-selection leads to an overestimation or underestimation of actual cycling risks and assess its role in the relationship between cycling behaviour and the objective – subjective safety relation. Examining how objective safety measures align with the self-selection of cyclists and their perceptions can also provide valuable insights into the complex dynamics of cycling behaviour.

4.3. Safety-in-numbers

The safety-in-numbers phenomenon suggests that as the number of cyclists increases, the individual risk of a crash decreases, though its mechanisms are not fully understood. Reviews and meta-analyses by Elvik and Bjørnskau (2017), Elvik and Goel (2019), and Kehoe et al. (2022) confirm its existence, albeit being very heterogeneous and more pronounced at the macro level (e.g. citywide) than at micro levels (e.g. intersections).

Possible explanations include that group riding may discouraging overtaking (von Stülpnagel & Bauder, 2022), there is an increased visibility of cyclists, and higher cyclist volumes may lead to to improved infrastructure, indirectly improving safety, as has been evidenced in pedestrian safety-in-numbers effects where indirect effects have been found (Heydari & Elvik, 2023; Heydari et al., 2020).

For subjective safety, this phenomenon may also apply, as the presence of other cyclists can reduce feelings of vulnerability (von Stülpnagel & Bauder, 2022). Yet, we also pose that increased volumes of cyclists may also induce further fears of collisions against other cyclists, especially for less proficient cyclists or those that cycle less often.

Understanding how safety-in-numbers affects both objective and subjective safety could help clarifying their relationship. This effect likely varies with local contexts, which can also help explaining discrepancies across cities.

4.4. Risk homeostasis

Finally, we also postulate that risk homeostasis processes may further contribute to how the objective–subjective safety relation is molded as perceived risk can be considered a psychological variable for explaining behaviour and involvement in crashes (Bazilinskyy et al., 2020). Following Wilde (1998)'s Risk Homeostasis Theory (RHT), individuals that perceive a reduction in risk (e.g. through changes induced by a safety measure), may compensate for such changes by carrying out more risk. In road safety, such phenomenons have been identified in drivers who perceived a low level of risk in hazardous events and would be likely to respond to such events less cautiously (Deery, 1999).

In the cycling context, one can also expect a similar phenomenon to occur, with cyclists' cycling behaviour changing according to lower expectations of risk hazards, potentially by riding their bicycle in a more risky way or responding with more riskier behaviour. The RHT also postulates that road users have a target (or accepted) level of risk at an individual level which weighs against actual risk and where and when a difference exists, one may move towards the other (Hoyes & Glendon, 1993). For cyclists, this would entail that even though a safety-promoting change may occur in the urban environment, cyclists would be motivated to compensate for such change to match their target level of risk. As a whole, this means that policies or practical measures that seek to balance out objective safety with subjective safety in the short term may have an impact in the long run as cyclists' behaviour may change leading to new discrepancies in the objective–subjective relation.

4.5. Challenges and possible future directions for research

In light of the reviewed works, we identify several key areas of research that could enhance our understanding of the relation between objective and subjective cycling safety and address existing limitations.

First and foremost, a greater emphasis must be placed on investigating the connection between objective and subjective risks, as this relationship is critical for ensuring the success of safety measures. Despite its importance, it remains rather underexplored, and addressing this gap is necessary to develop engineering, social, and management strategies that improve observed and perceived safety simultaneously and does not have opposing effects on either.

Second, we need to better examine individual characteristics such as cycling skill, experience, proficiency, and demographic factors. While some studies have touched on these topics, a deeper understanding is needed, particularly for potential cyclists and for vulnerable groups such as children and the elderly, whose perceptions and behaviours may differ significantly from other populations.

Third, the complexity of this relationship also calls for the adoption of innovative modelling and data analysis tools. Techniques like GIS mapping, micro-simulation, and virtual reality can provide insights into spatial patterns, exposure, and user responses in controlled environments. Instrumented bicycles, as used by Vieira et al. (2016), Costa et al. (2017), and Dozza and Fernandez (2013), can gather on-the-ground data, while cognitive load analysis and behavioural modelling can uncover potential conflicts and user reactions. We need to better understand how different behaviours might impact this relation, especially those that are linked with cyclists adapting their cycling habits or routes due to safety concerns. Machine learning and data fusion methods could further integrate crash data and user perceptions to provide a more holistic view of safety dynamics.

Fourth and lastly, a more interdisciplinary approach is essential. Collaboration between traffic psychologists and road safety engineers can leverage their combined expertise to design safer cycling environments and implement effective interventions. This integrated perspective will enable more informed and impactful decision-making in promoting cycling safety.

5. Conclusions

This study reviewed past and current research on the relationship between objective and subjective cycling safety in urban environments. Peer-reviewed publications from three databases were analysed, focussing on studies addressing cycling crashes and perceptions of these.

Findings reveal limited attention has been paid to this relationship, despite significant growth in research on objective and subjective safety individually. The results present a complex picture: while some studies suggest a direct link, others indicate context-dependent connections or independence between the two safety types. Some research hints that behaviour changes might shape the objective – subjective safety relation, helping explain variations across studies. We hypothesise that these behaviour changes, along with self-selection and risk homeostasis phenomena, influence this relationship in both the short and long term.

Understanding how actual safety connects to perceived safety is essential for designing effective interventions that improve both. This knowledge, coupled with innovative research approaches, could enhance future cycling safety studies and improve overall cyclist safety.

Notes

1. Available at https://www.webofscience.com/
2. Available at https://trid.trb.org/
3. Available at https://www.scopus.com/

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Fundação para a Ciência e a Tecnologia [PD/BD/142948/2018, UIDB/04625/2025, 10.54499/LA/P/0083/2020].

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