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Infrastructure matters: A systematic review of bicycle infrastructure design influencing cycling crash and injury risk

Chuisong Chen [a], Xiaoyu Lin [b,*], Gang Yu [b]

[a] Future Design School, Harbin Institute of Technology, China
[b] School of Architecture, Harbin Institute of Technology, Shenzhen, China

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ABSTRACT

Introduction: This study systematically reviews empirical research on urban cycling infrastructure design and its effects on cycling safety. Utilizing the PRISMA framework, the review synthesizes findings from peer-reviewed studies collected from major databases, ultimately incorporating 104 high-quality articles. *Method:* The primary contribution of this research addresses three essential questions. First, it identifies and critically assesses significant design elements, including physically separated cycle tracks, optimized intersection configurations, and tailored signal timings, that have demonstrated both positive and negative impacts on cycling safety. Secondly, the study explores the diverse array of safety metrics, analytical tools, and data sources used within existing literature. Traditional safety indicators, such as collision and injury rates, are discussed alongside surrogate safety measures and emerging digital data sources. This comprehensive synthesis highlights current advancements as well as persistent challenges, including inconsistent data granularity and systematic underreporting of incidents not involving motor vehicles. Thirdly, the review critically evaluates the methodological, theoretical, and practical obstacles that complicate the rigorous assessment of cycling infrastructure safety. Specific challenges discussed include the discrepancy between perceived and actual safety, complexities in controlling for confounding factors, and the limited availability of standardized evaluation frameworks. *Results:* Based on these insights, the study recommends future research directions focused on multidisciplinary collaboration, enhanced data integration, and methodological innovation to address existing knowledge gaps. Ultimately, the review provides a nuanced understanding of how urban built environment features influence cycling safety, providing evidence-based guidance to inform infrastructure planning and policy-making. *Practical Applications:* These findings aim to support academic inquiry and practical efforts dedicated to reducing cycling-related injuries and fatalities.

1. Introduction

Cycling offers significant benefits across multiple dimensions, including human health, built environment, and social equity. From the health perspective, cycling enhances cardiovascular health and reduces the risk of chronic diseases such as cardiovascular disease, diabetes, and certain types of cancer, while also helping to prevent obesity (Carvajal et al., 2020). Environmentally, as a zero-emission mode of transportation, cycling effectively reduces air pollution, improves urban air quality, and contributes to mitigating climate change by lowering greenhouse gas emissions. Additionally, cycling promotes social equity by increasing mobility and independence for both youth and the elderly, and by expanding the travel range of low-income individuals who cannot afford private vehicles (Di Mascio et al., 2018).

Compared to motor-vehicle drivers, cyclists face a significantly higher risk of injury. Studies have shown that in the Americas, the likelihood of a cyclist being injured per trip or per kilometer traveled is 7 to 70 times greater than that of a car occupant (Reynolds et al., 2009). Cyclists are also more likely to suffer severe injuries in traffic incidents. For instance, in Taiwan, 27.8% of 324 bicycle-related traumatic brain injuries recorded between 2001 and 2002 were classified as severe (Wang et al., 2009). Similarly, in New South Wales between 2010 and 2014, the number of cyclists with serious injuries was four times higher than those with minor injuries among 12,619 recorded cases (Seah et al., 2018). A study by Strauss et al. (2014), conducted in Canada, reported that in terms of fatal crashes, cyclists were 2.3 times and pedestrians 1.5

* Corresponding author.
E-mail address: linxiaoyu@hit.edu.cn (X. Lin).

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times more likely to suffer fatal injuries than motor-vehicle drivers.

The correlation between the improvement of bicycle infrastructure and the reduction in cycling crash rates has been well established in existing research. Compared to roads without dedicated cycling lanes, both near-miss incidents and actual collisions occur less frequently on roads equipped with bicycle facilities (Chou et al., 2024). The contribution of bicycle infrastructure to enhancing actual cycling safety is well-documented. However, as this review will show, the effectiveness of specific designs can be highly context-dependent, with factors such as traffic volume and intersection design significantly influencing safety outcomes. Moreover, such infrastructure also boosts perceived safety, thereby encouraging more people to choose cycling as a mode of transportation and increasing overall cycling rates (Klassen et al., 2014). However, cities often face spatial and financial constraints. In densely populated urban areas with established built environments, there is frequently insufficient space to accommodate dedicated cycling facilities. In budget-constrained communities, the cost of constructing such infrastructure can present a significant barrier (Liu & Marker, 2020). These limitations lead to unequal distribution of cycling facilities, with well-equipped segments attracting a large number of cyclists, which may paradoxically result in increased collision rates on those particular road sections due to cyclist concentration.

Given these challenges, rational and context-sensitive design of cycling infrastructure is critical. While some countries have established design guides, a lack of unified definitions and standards persists globally, making it difficult to ensure consistency in safety and usability across different regions (Harris et al., 2011). Furthermore, poorly designed infrastructure, such as "half-measures" like painted bike lanes without physical separation, can have adverse effects and may even increase crash risk (Vandenbulcke et al., 2014). To address these research gaps, this study raises the following research questions:

RQ1: Which specific design features of cycling infrastructure most significantly influence crash and injury risks, and through what underlying mechanisms do these features impact cyclist safety across diverse roadway contexts?

RQ2: In what ways do variations in data sources and methodological approaches affect the measurement, reporting and interpretation of cycling safety outcomes? What are the implications of these differences for establishing reliable crash modification factors?

RQ3: What are the key methodological, theoretical, and practical limitations currently hindering the rigorous evaluation of cycling safety, and how might future research strategically address these gaps to enhance the evidence base for infrastructure planning and policy?

2. Conceptual framework for cycling safety and infrastructure

2.1. Cycling safety metrics and definitions

Assessing cycling safety relies on a core set of outcome metrics that have evolved significantly over time to reflect advances in safety science. In a seminal review, Reynolds et al. (2009) identified three primary categories of safety outcomes: Injuries, Crashes, and Conflicts. Injuries refer to physical harm sustained by cyclists, typically classified using standardized medical frameworks such as the World Health Organization's International Classification of Diseases (ICD) (Harrison et al., 2021). Crashes encompass both collisions, where a cyclist strikes or is struck by another object and falls that occur without external contact. Conflicts are defined as interactions between road users in which at least one party must alter their speed or trajectory to avoid a collision. However, Reynolds et al. excluded studies that relied solely on conflicts as outcome measures, citing concerns related to limited sample sizes, short observation periods, and difficulties in determining whether the cyclist's safety was genuinely compromised.

Contemporary developments in safety research have expanded this framework through refined conflict analysis and the integration of proactive risk assessment techniques. In particular, near misses, which occur much more frequently than actual crashes, have become dependable indicators for detecting risky conditions before injuries happen. In this approach, surrogate safety measures (SSMs) have become more widely used. SSMs are clearly defined indicators used to indirectly assess safety risks in the absence of actual crash data, by observing traffic conflicts and near-miss events. One of the most widely used SSMs is Time-to-Collision (TTC), which is defined as the time remaining before two road users would collide if they continued at their current speeds and trajectories. Other related measures include Post-Encroachment Time (PET), which measures the time gap between when different users pass through the same space. The expansion of these metrics has been made possible by technological advancements in data collection. Recent studies now employ a range of innovative tools, including cyclist travel diaries, smartphone applications, crowdsourced mapping platforms, automated video analytics, instrumented bicycles, and advanced statistical modeling. These techniques greatly enhance the reliability and granularity of conflict-based assessments, effectively addressing earlier concerns raised by Reynolds et al. Notably, these innovations allow researchers to identify unsafe conditions without needing to rely solely on historical crash data, thereby aligning with international standards such as ISO 39001 on road traffic safety management.

In addition to these risk-focused metrics, other formal frameworks exist to evaluate the quality and suitability of infrastructure for cyclists. Tools such as the Bicycle Level of Service (BLOS), the Bicycle Level of Traffic Stress (BLTS), and the Bicycle Intersection Safety Index (BISI) provide standardized criteria to assess factors like traffic stress, comfort, and the overall compatibility of a facility for cycling (Brzeziński & Jesionkiewicz-Niedzińska, 2021; Deegan, 2016). Among these, BLTS has gained increasing adoption as it classifies road segments based on cyclists' perceived traffic stress under varying traffic conditions (Furth et al., 2016; Mekuria et al., 2012). While these frameworks typically focus on the quality of service rather than directly measuring conflicts, they represent another important set of tools used in the broader field of cycling safety assessment.

In contrast to Reynolds's research, this review includes studies that treat conflicts and near misses as primary safety indicators, provided they meet established quality standards. This broader framework allows for a better understanding of how infrastructure design influences cyclist safety and helps detect risky situations before they cause harm.

2.2. Infrastructure typologies and functional classifications

This section defines the key terms used to describe cycling-related infrastructure. All listed terms are drawn from studies identified in our literature review and reflect terminology commonly used in English-language academic research. Where applicable, definitions follow those provided in the European Cycling Lexicon-2023 Edition, a multilingual glossary developed by the European Economic and Social Committee to standardize cycling terms across policy and planning contexts. Table 1 presents commonly referenced infrastructure types, grouped according to their function and location within the road system.

3. Methods

3.1. Systematic review methodology

This study adopts a systematic review approach, focusing specifically on empirical studies that examine the safety impacts of cycling infrastructure design in urban contexts. A systematic review aims to synthesize existing research and findings, identify knowledge gaps within a particular field, and highlight directions for future research. Originally developed in the medical field, the systematic review methodology has since been widely applied to address issues in public policy, urban planning, and environmental studies (Bilotta et al., 2014; Oxman & Guyatt, 1993). It combines findings from prior studies using explicit,

Table 1
Key Cycling Infrastructure Terminology.

Category	Infrastructure	Description
Straightaway Design	Cycle track†	A paved lane intended exclusively for cyclists, located next to a major roadway or roundabout, and physically separated by a curb or barrier.
	Off-road path	A paved or unpaved trail separated from roadways, shared by cyclists and pedestrians, and not used by motor vehicles.
	Cycle lane†	A designated portion of the road surface, marked with paint or color, reserved for bicycle use but without physical separation from motor traffic.
	Sharrows	Road markings that indicate a shared lane environment for bicycles and motor vehicles, typically used where space is too limited for dedicated bike lanes.
	Cycle street†	A road where cyclists have visual priority, and motor vehicles are allowed but treated as guests, is often designed to resemble a wide cycle track. "*Visual priority*" here is typically achieved through distinctive pavement colors (such as red surfacing), clear bicycle symbols, and very low speed limit signs, aiming to create an atmosphere in which cars are treated as "*guests.*"
	Contraflow cycling†	Permits cyclists to travel in the opposite direction of motor traffic on a one-way street.
	Underpass†	A tunnel or passage that allows a cycling or pedestrian path to pass beneath a road or railway.
	Cycle superhighway	A high-capacity cycling corridor designed to support commuter cyclists with continuous, direct, and safe routes.
Intersection Design	Intersection	A location where two or more roads meet or cross at the same level.
	Roundabout†	A circular intersection designed for all vehicles, including large ones, typically with splitter islands and crosswalks set back from the central circle.
Traffic Calming	Advanced stop line†	A marked area ahead of motor traffic at an intersection, allowing cyclists to position themselves in front of cars at a red light.
	Speed bumps/ humps	Raised sections of roadway designed to reduce motor vehicle speeds; humps are longer and less steep than bumps, making them easier for cyclists to cross.
	Two-stage turn box	A designated area that helps cyclists make left turns at intersections in two steps, improving safety by avoiding conflicts with turning vehicles.
	Toucan crossing	A smart signalized crossing for both pedestrians and cyclists, equipped with sensors to detect users and adjust signal timing.
Other Elements	Tramway	While not part of cycling infrastructure, tram tracks are commonly encountered by cyclists and require careful navigation.

† Indicates terms adopted from the European Cycling Lexicon – 2023 Edition, available at: **https://www.eesc.europa.eu/en/our-work/publications-other-work/publications/european-cycling-lexicon-edition-2023**.

structured methods, thereby producing reliable and informative insights (Greenhalgh, 1997).

Systematic reviews work by identifying previous research on a clearly defined topic and using qualitative and/or quantitative methods to summarize the evidence or conclusions (Armstrong et al., 2011). Unlike narrative reviews that rely on selective interpretation, systematic reviews demand detailed and comprehensive investigations to ensure an in-depth understanding of the topic (Akobeng, 2005).

Most systematic reviews follow five essential steps (Armstrong et al., 2011):

- Formulating the research question and defining its scope
- Specifying data sources and search strategies
- Screening and selecting relevant studies
- Extracting and analyzing data, and
- Synthesizing and reporting findings

3.2. PRISMA framework

Various frameworks have been developed to guide the conduct of systematic reviews. In 1999, an international team proposed the QUOROM statement, a set of guidelines for reporting *meta*-analyses (Moher et al., 2000). In 2009, a group of 29 researchers revised and updated this guideline, renaming it the PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Liberati et al., 2009). PRISMA provides a detailed checklist designed to ensure clarity and transparency in reporting systematic reviews or *meta*-analyses. The checklist includes 27 items covering key components such as the title, abstract, introduction, methods, results, and discussion sections (Moher et al., 2009). By following this structure, researchers can systematically assess both the strengths and limitations of existing literature. The PRISMA framework is widely recognized for its clear structure and ease of use.

In this study, we adopted the PRISMA framework to guide the selection and thematic analysis of relevant articles for our systematic review. Specifically, we followed the PRISMA checklist to systematically identify, screen, and synthesize empirical studies on the safety impacts of cycling infrastructure within the built environment. Fig. 1 presents the literature screening flowchart following the PRISMA framework. It details the four stages from the initial database search to the final inclusion of 104 studies, namely Identification, Screening, Eligibility, and Inclusion.

3.3. The application of PRISMA framework

3.3.1. Search strategy

The systematic literature search was conducted in two major electronic databases: Scopus and Web of Science. The search strategy was developed around three key conceptual components:

- Cycling safety, crashes, and unsafe riding behavior
- Active transportation, micromobility, vulnerable road users, and cycling behavior
- The built environment and its synonyms (e.g., urban environment, urban space)

Relevant keywords associated with each conceptual domain were searched within article titles, abstracts, and keywords across both databases. The complete list of search terms is shown in Table 2.

3.3.2. Inclusion and exclusion criteria

The PICOS framework (Population, Intervention, Comparison, Outcomes, and Study Design) was applied to define the eligibility criteria for study selection (see Table 2). Peer-reviewed empirical studies published in English prior to December 7, 2024, were included. Grey literature and nonpeer-reviewed sources, such as reports, working papers, and book

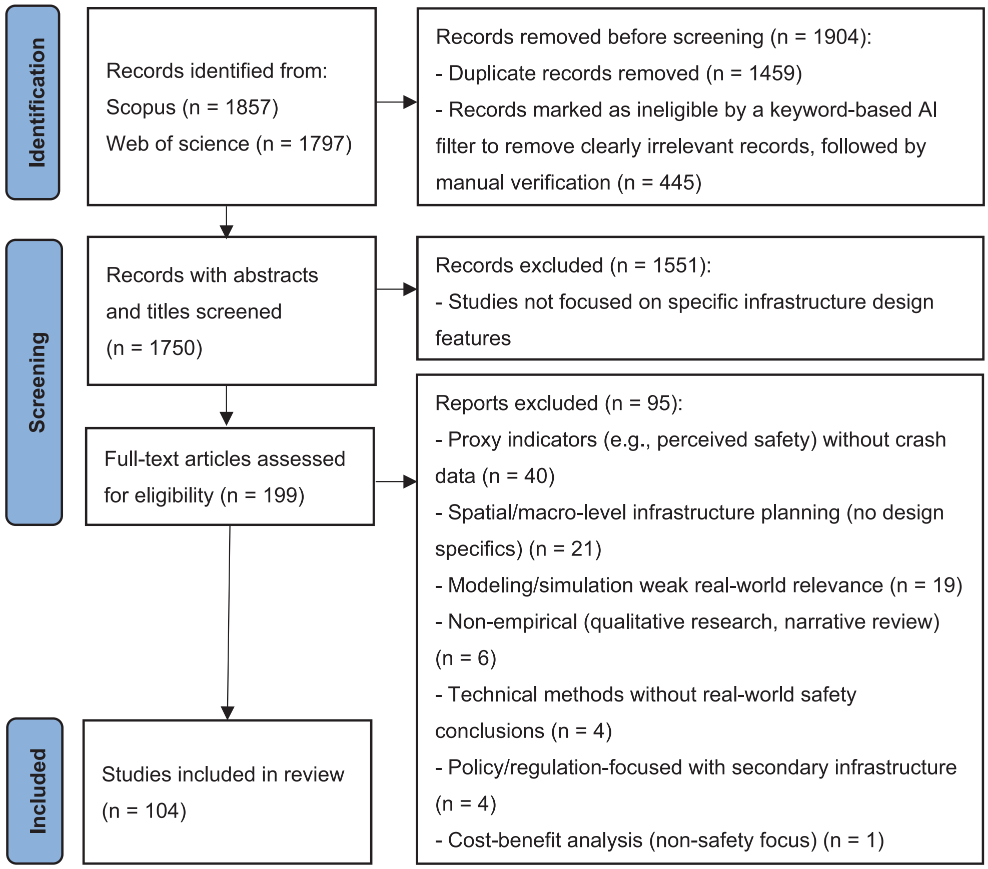

Fig. 1. PRISMA study selection flowchart.

chapters, were excluded.

To be eligible, a study had to meet the following criteria simultaneously:

- It examined the influence of urban built environment infrastructure design features (e.g., types of bicycle lanes, intersection layouts, signage systems) on cycling safety
- It reported at least one objective safety outcome, such as crash rates, injury occurrences, or traffic violations

Studies were excluded if they met any of the seven following conditions:

- Focused on non-traditional or electric vehicles, such as motorcycles, mopeds, or e-scooters
- Addressed cycling behaviors in rural or non-built environments
- Targeted specific clinical populations or health conditions
- Investigated non-design-related factors, such as land use, bike network density, weather, or crime rates
- Did not compare different infrastructure design features or lacked before-and-after intervention analysis
- Focused solely on subjective outcomes, such as perceived safety or travel preferences
- Employed non-empirical methods, such as conceptual models, qualitative interviews, or purely legal/policy discussions

Table 2
Keyword Structure for Systematic Search.

Domain	Search Terms
Cycling safety, crashes, and unsafe riding behavior	"risk*" OR "safety" OR "accident*" OR "crash*" OR "injure*" OR "collision*" OR "speeding" OR "wrong-way riding" OR "violations" OR "hazard*" OR "danger*" OR "death*" OR "casualty*" OR "fatal*"
Active travel, micromobility, vulnerable users, cycling behavior	"cycling" OR "cyclist*" OR "bike*" OR "bicycle*" OR "bike sharing" OR "cycling behavior*" OR "active transport*" OR "active mobility" OR "non-motorized transport*" OR "active travel" OR "micromobility" OR "vulnerable road users"
Built environment and related concepts	"built environment*" OR "urban environment*" OR "infrastructure" OR "public space*" OR "neighborhood*"

Note: Asterisks (*) indicate the use of wildcard symbols to capture all possible variations of a root word. Based on the scope and objectives of this review, the Boolean operator "AND" was used to combine these three sets of keyword categories during the search process.

3.3.3. *Selection process*

This study selection process followed three main stages: Identification, Screening and Selection, as illustrated in the PRISMA flow diagram (Fig. 1). A total of 3,654 records were initially identified through searches in Scopus and Web of Science.

During the screening phase, 1,459 duplicate records were detected and removed. The remaining 2,195 unique records were selected and reviewed, whose titles and abstracts were assessed to determine their relevance based on the study content. As a result, 199 articles were selected for further evaluation, which focused primarily on the empirical effects of built environment infrastructure on cycling safety.

After the screening stage, the remaining 199 articles were subjected to full-text assessment to determine their eligibility for inclusion. In our review, an empirical study is defined as a peer-reviewed publication that draws conclusions based on rigorously analyzed evidence derived from direct or indirect observation in real-world settings. Title and abstract screening were conducted by author CC. Articles were excluded at this stage if they clearly did not report relevant interventions or failed to meet the inclusion criteria. To ensure the robustness of the selection process, co-author XL independently reviewed a random 10% subset of the remaining articles and compared them against the eligibility criteria. In cases of uncertainty, the full text of the article was retrieved and reviewed. All studies meeting the initial inclusion criteria were then independently reviewed in full by two reviewers to confirm their eligibility.

Following the full-text screening, an additional 95 articles were excluded, resulting in a final sample of 104 studies for inclusion in the systematic review. The reasons for exclusion during the full-text assessment were documented in detail (Table 3).

3.3.4. *Data extraction*

At this stage, a data extraction form with six main categories was used to collect structured information from each included study. This allowed for quality assessment and thematic synthesis. The extracted categories included General Information, Study Design, Research Approach, Infrastructure Types, Results and Conclusion. It is important to note that all statistical metrics reported in this review, such as percentages, odds ratios (ORs), and incidence proportion ratios (IPRs), are cited directly from the original source studies. This review synthesizes these findings but does not perform a *meta*-analysis or recalculate any statistical estimates. Table 4 provides a detailed overview of the extracted items under each heading.

3.3.5. *Quality assessment*

To assess the risk of bias, we applied the QualSyst quality assessment tool, adapted from the Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields (Kmet et al., 2004).

Given the nature of the included studies, we used only the checklist designed for evaluating quantitative research quality (*Appendix 1:* Table 2. *QualSyst Tool for Assessment of the Quality of Included Studies*). Each of the 14 items on the checklist was scored based on the extent to which the criterion was met: "Yes" = 2; "Partial" = 1; "No" = 0. Items deemed not applicable (n/a) for a particular study design were excluded from the total score calculation. For each study, a summary score was calculated by dividing the total score obtained by the maximum possible score, adjusted for the number of n/a items (i.e., 28 minus [2 × number of n/a items]). To ensure quality control, a cross-checking process was implemented during the quality assessment. Any discrepancies between reviewers were resolved through discussion and consensus.

Table 3
PICOS Framework with Inclusion and Exclusion Criteria.

PICOS	Inclusion Criteria	Exclusion Criteria
Population	Individuals engaging in any form of traditional or electric two-wheeled cycling (e.g., commuting, leisure) within built environments; no restriction on gender or age.	Users of other two-wheeled vehicles such as motorcycles, mopeds, or scooters; cyclists in non-built environments (e.g., rural areas); clinical populations.
Intervention	Design features of cycling infrastructure, including basic facility design (e.g., lane types, physical separation); pavement color/materials; intersection layout (e.g., signalization, turning radius); lane configuration (e.g., width, continuity); signage (e.g., markings, direction signs); and lighting conditions.	Non-design factors such as land use or green/commercial space distribution; bike network density; natural environment (e.g., weather, topography); social safety (e.g., crime rate); legal/policy interventions; device-based interventions (e.g., theft-proof add-ons, sensors).
Comparison	Comparisons between different design features (e.g., separated vs. unseparated bike lanes); or before-after comparisons in the same location.	Studies lacking clear design comparisons (e.g., descriptive statistics only).
Outcomes	Objective safety outcomes such as crash rates, injury incidence, fatality rates, and traffic violations (e.g., wrong-way riding, speeding).	Subjective outcomes such as perceived safety or safety ratings; mode choice or route preference bias.
Study Design	Empirical studies with clearly defined experimental or observational designs.	Simulation studies (e.g., crash risk models); theoretical models or policy analyses; qualitative studies (e.g., interviews, focus groups); non-empirical reviews or commentaries.

4. Results

4.1. *Descriptive statistics*

A detailed analysis was conducted on all studies included in this review. The findings reveal that the number of publications examining the relationship between cycling infrastructure design and cycling safety has increased over time (see Fig. 2). Notably, there was a marked rise in publications in 2020 (n = 13) and 2021 (n = 15). This trend coincides with a reduction in motorized traffic during the COVID-19 pandemic (Nguyen et al., 2024), when cycling surged as a resilient and sustainable mode of transport. During this period, more people, including inexperienced riders, took to the roads, increasing the pressure on non-motorized transport infrastructure (López-Molina et al., 2022; Abbasi & Ko, 2024).

In terms of geographical distribution, the majority of included studies were conducted in Europe (48.1%, n = 50) and North America (32.7%, n = 34), followed by Asia (12.5%, n = 13), Oceania (10.6%, n = 11), and South America (1.9%, n = 2) (see Fig. 2). Approximately 6.7% (n = 7) of the studies were conducted across multiple countries or cities (*Appendix 1:* Table 1. *Overview of Study Characteristics*). Specifically, the United States (n = 19) contributed the highest number of studies, followed by Canada (n = 16), the United Kingdom (n = 10), and Australia (n = 10). In China (n = 9), a surge in research publications began in 2017, likely in response to the rapid expansion of bike-sharing programs at the end of 2016 (Chen et al., 2018).

The top 10 most-cited papers were identified from among the included review articles. Unsurprisingly, the most frequently cited study was the literature review by Reynolds et al. (2009) titled "*The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature,*" with 428 citations in Web of Science and 413 in Scopus. The

Table 4
Data Extraction Headings.

Heading	Data Extracted
General information	– Study ID (DOI) – Publication year – Source title – Country where the study was conducted
Study design	– Type of study (observational or experimental) – Temporal framework (cross-sectional, quasi-longitudinal, before-after, etc.) – Context (ecological, case study, etc.)
Research approach	– Safety metrics used (e.g., collision rate, injury rate, fatality/casualty rate, traffic violations) – Data sources (e.g., government databases, sensors) – Analytical methods (e.g., regression analysis, machine learning)
Infrastructure types	– Infrastructure design features related to cycling safety evaluated in the study
Results	– Reported effects of transport infrastructure design on cycling safety – Mechanisms explaining how design influences safety
Conclusion	– Identified biases – Recommendations for future research – Stated limitations

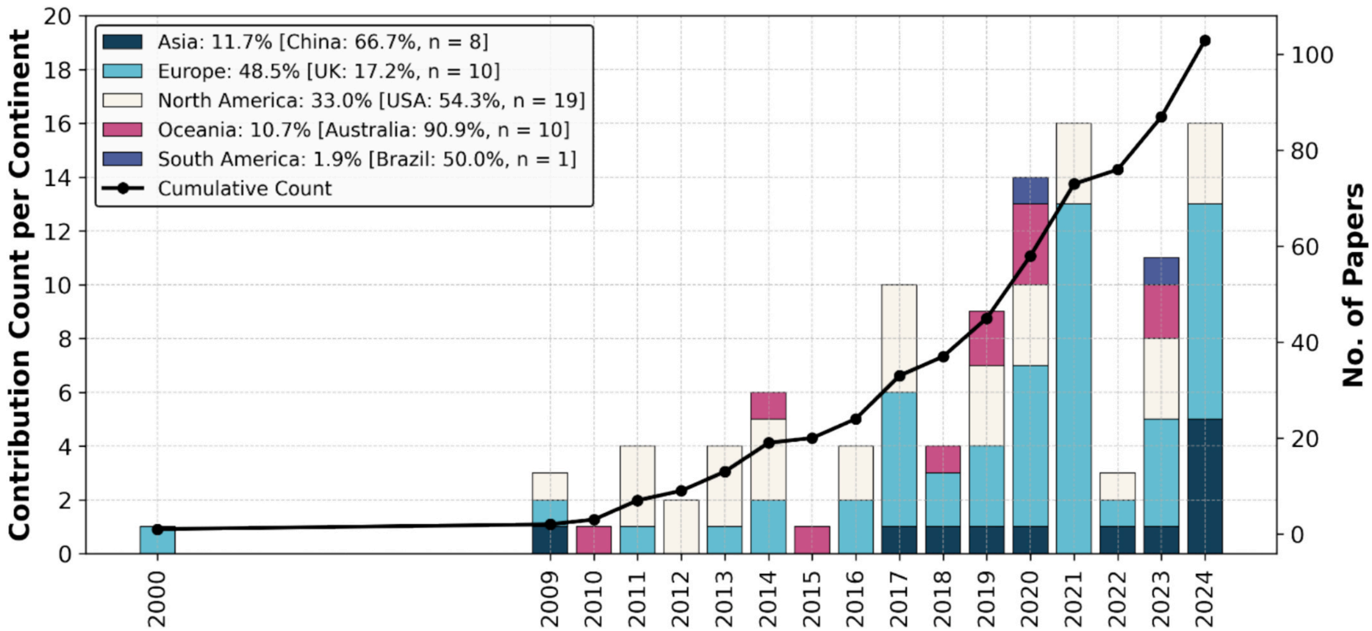

Fig. 2. Number of annual research studies on each continent.

second most-cited article was by Teschke et al. (2012), titled "*Route infrastructure and the risk of injuries to bicyclists: A case-crossover study,*" with 244 citations in Web of Science and 248 in Scopus (see Table 5). In addition to identifying the most frequently cited studies, our review also highlights key journals that have played a significant role in publishing research on the relationship between cycling infrastructure design and cyclist safety (see Table 6). The journal with the highest number of relevant publications is *Accident Analysis & Prevention*, which published 23 articles on this topic. Other prominent journals include the *Journal of Safety Research*, *Traffic Injury Prevention*, and various sections of *Transportation Research*.

Based on the above data, it can be observed that highly cited articles often feature pioneering approaches. For example, Case 1 (Strauss et al., 2013) was the first to jointly analyze cyclist injury occurrence and bicycle activity as combined outcomes. It also incorporated the underlying association mechanisms into a Bayesian framework to model and predict high-risk cycling areas. As stated in the original text: *"To our knowledge, no previous studies have tried to model cyclist injury risk and bicycle activity*

Table 5
Top 10 most-cited papers.

S/N	Title	Authors	Citations* (WoS)	(Scopus)
1	The impact of transportation infrastructure on bicycling injuries and crashes: a review of the literature	Reynolds et al.	428	413
2	Route infrastructure and the risk of injuries to bicyclists: A case-crossover study	Teschke et al.	244	248
3	Designing for the safety of pedestrians, cyclists, and motorists in urban environments	Dumbaugh and Li	150	142
4	Predicting cycling accident risk in Brussels: A spatial case-control approach	Vandenbulcke et al.	132	135
5	Using data mining techniques to predict the severity of bicycle crashes	Prati et al.	112	117
6	Comparing the effects of infrastructure on bicycling injury at intersections and non-intersections using a case-crossover design	Harris et al.	110	113
7	Aggravating and mitigating factors associated with cyclist injury severity in Denmark	Kaplan et al.	109	111
8	Safety impacts of bicycle infrastructure: A critical review	DiGioia et al.	97	109
9	Cyclist activity and injury risk analysis at signalized intersections: A Bayesian modelling approach	Strauss et al.	98	84
10	On-road bicycle facilities and bicycle crashes in Iowa, 2007–2010	Hamann and Peek-Asa	82	85

* Note: As of 23rd March 2025.

Table 6
Top 10 journals with relevant articles published annually.

S/N	Journal name	2000	2011–2013	2014–2016	2017–2019	2020–2022	2023–2025	Total
1	Accident Analysis And Prevention	–	2	3	7	8	3	23
2	Journal of Safety Research	–	–	1	2	–	4	7
3	Traffic Injury Prevention	–	1	1	2	–	1	5
4	Transportation Research Record	1	–	–	2	–	2	5
5	Injury Prevention	–	2	1	–	–	1	4
6	Journal of Transport And Health	–	–	–	1	1	2	4
7	Sustainability (Switzerland)	–	–	–	1	2	1	4
8	Journal of Transportation Safety And Security	–	–	1	–	1	1	3
9	Traffic Safety Research	–	–	–	–	–	3	3
10	BMC Public Health	–	–	2	1	–	–	3

Note: In 2001–2010, no paper in the top-ten journals.

Table 7
Study Design Types and Their Distribution Among Included Articles.

Study design		No.
Research type	Observational study	96
	Experimental study	8
Time-based	Cross-sectional	51
	Retrospective	37
	Before-and-after	9
	Longitudinal	7
	Prospective	3
Context-based	Ecological	52
	Field study	47
	Laboratory study	5

simultaneously." Case 2 (Teschke et al., 2012) innovatively adopted a case-crossover design commonly used in medical research. Unlike traditional designs that compare injury sites with external reference locations, this approach randomly selected control sites from the same trip as the injury site for each injured cyclist. Both the injury and control sites were thus drawn from the same journey, automatically controlling for stable and hard-to-measure confounding variables such as rider age, cycling skill, weather, and time of day. The original text states: "*A case-crossover design compared route infrastructure at each injury site to that of a randomly selected control site from the same trip.*"

On the other hand, articles published in top journals tend to reflect broader research trends in the field through detailed case studies. Over the past decade, there has been a growing effort toward conflict warning. This shift is partly due to the earlier reliance on actual safety measures such as police reports or manual counts, whereas recent technological advancements have enabled increased attention to surrogate measures, which have contributed significantly to the realization of conflict prediction.

4.2. *Risk of bias*

The average QualSyst quality score among the included studies was 0.77, with 71.2% (n = 74) of studies scoring above 0.70, indicating an overall good level of methodological quality. Individual quality scores for each study can be found in *Appendix 1:* Table 2*. QualSyst Tool for Assessment of the Quality of Included Studies*. The QualSyst tool was originally designed to apply a threshold within the range of 0.55 to 0.75 to determine inclusion in systematic reviews (Kmet et al., 2004). In this review, a cutoff score of 0.55 was adopted, allowing the inclusion of 93.3% (n = 97) of studies initially deemed relevant. This approach also ensured the inclusion of a small number of randomized controlled trials (RCTs) that, despite having limited sample sizes or design control, provided valuable complementary evidence on cycling safety and infrastructure design (Meuleners et al., 2023).

More specifically, studies were classified into four quality categories based on their final scores:

- > 0.80: strong methodological quality
- 0.71–0.79: good quality
- 0.55–0.70: acceptable
- < 0.55: low quality and therefore excluded from the final analysis (Rix & Sakamoto, 2022; Read et al., 2020; Thai Van & Balmefrezol, 2000; Cieśla, 2021; Ayad et al., 2024; Bauer et al., 2021; Casey et al., 2024)

It is worth noting that the majority of included studies employed observational designs, primarily cross-sectional, retrospective, or ecological approaches (see Table 7). Fig. 3 provides a comprehensive overview of the methodological quality assessment, illustrating the performance of the included studies against each of the 14 QualSyst criteria. The bar charts show the distribution of quality ratings, while the line graph highlights the average score for each item, allowing for a quick identification of common methodological strengths and weaknesses. A key insight from this analysis is the challenge of causal inference in this field. As shown in the figure, the criterion for controlling for confounding factors (Q12) received the lowest average score, indicating a frequent limitation in the existing literature. Due to the inherent

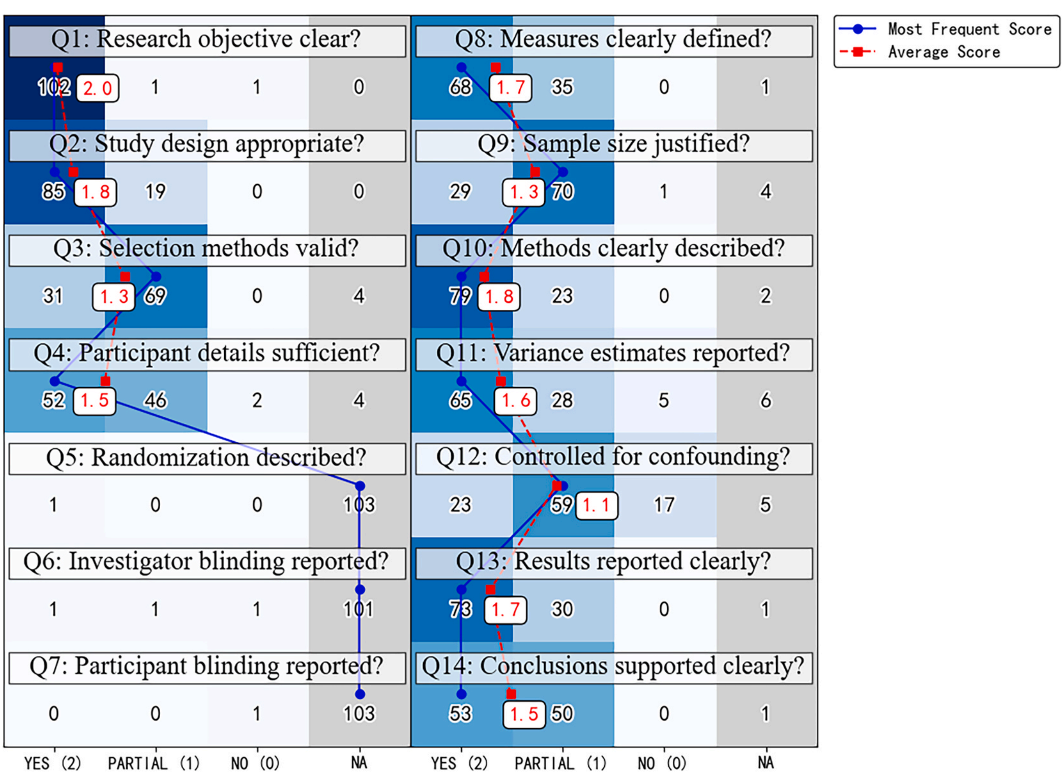

Fig. 3. Frequency of Unmet Items in the QualSyst Quality Assessment Checklist.

limitations of these designs in controlling for confounding factors, Item 12 ("*Controlled for confounding*") was among the most frequently unmet criteria in the quality assessment (see Fig. 3). The primary reason is that in on-site comparative studies, it is difficult to keep various factors consistent, such as the sample size, gender, and age of cyclists at different times, as well as the weather and other motor vehicle traffic conditions.

5. Thematic analysis of included studies

5.1. RQ1 – The impact of infrastructure design: Consensus, controversies, and evolving mechanisms

5.1.1. Consensus findings: The central role of physical separation

Across the reviewed literature, a consistent finding is that physically separating cyclists from motorized traffic is a highly effective way to improve cycling safety. This consensus is supported by evidence that has evolved over time. Early reviews, such as Reynolds et al. (2009), synthesized studies that primarily relied on crash and injury statistics from police or hospital records. These foundational studies established a strong correlation between the presence of separated infrastructure, like cycle tracks, and lower rates of cyclist injuries. For example, some analyses reported that separated paths could reduce injury risk by as much as 50% compared to cycling on roads without any bicycle-specific facilities (Cicchino et al., 2020; Harris et al., 2013).

More recent research included in this review has reinforced these early findings with new types of evidence. Studies now frequently use surrogate safety measures (SSMs) to analyze traffic interactions that do not result in a crash. For instance, video analysis of traffic conflicts shows that separated bike lanes significantly reduce the frequency of near-misses and dangerous interactions between cyclists and vehicles (Zangenehpour et al., 2016). Additionally, naturalistic cycling studies, which use instrumented bicycles to collect real-time data, provide detailed kinematic information. These data confirm that physical barriers reduce the likelihood of sudden evasive maneuvers by cyclists and minimize close-proximity passing events by motorists (Beck et al., 2019). Heavily protected bike lanes, which use concrete barriers or grade separation, demonstrate particularly strong protective effects, with some studies reporting adjusted odds ratios as low as 0.10 for injuries compared to mixed traffic conditions (Harris et al., 2013).

The mechanisms that explain these safety benefits are also well-documented. The most direct mechanism is the reduction of exposure to motor vehicle traffic, which eliminates many potential conflict types, especially mid-block collisions. Beyond simply preventing contact, physical separation also influences road user behavior. Studies have shown that dedicated infrastructure leads to lower motor vehicle speeds on adjacent travel lanes (Hosking et al., 2023). Furthermore, it creates a more predictable environment for all road users. Drivers are less likely to encroach into cycling space, and cyclists' trajectories are more clearly defined, which reduces uncertainty and potential for conflict, particularly at locations away from intersections (Johnson et al., 2010). This body of evidence, drawn from different methodologies over more than a decade, consistently points to physical separation as a fundamental principle for creating safer urban cycling environments.

5.1.2. Controversial and context-dependent designs: Beyond one-size-fits-all

While physical separation shows consistent safety benefits, the effectiveness of other common infrastructure types is less clear and often depends on the specific context in which they are implemented. This review identified significant inconsistencies in the reported safety outcomes for designs such as painted bike lanes and shared lane markings (sharrows). For instance, some studies on painted bike lanes, which provide visual but not physical separation, report crash reductions of up to 60% compared to roads with no markings (Hamann & Peek-Asa, 2013). However, other research indicates that these lanes can increase injury risks, with reported odds ratios ranging from 1.34 to 2.8, potentially because they provide a false sense of security without offering actual protection from motor vehicles (Adams et al., 2020; Garber et al., 2023). Similarly, studies on sharrows consistently show minimal to no improvement in objective safety, finding they have almost no impact on cyclist crash risk or driver speed behavior (Meuleners et al., 2023; Fournier et al., 2020; Jarry & Apparicio, 2021).

The reasons for these conflicting findings are often related to contextual factors that modify the performance of an infrastructure design. Traffic volume and speed are critical variables. A painted bike lane may function adequately on a low-speed, low-volume street, but it can become dangerous on a high-speed arterial road where the risk of severe collisions is much higher. The surrounding built environment also plays a key role. For example, a painted lane located next to on-street parking creates a high risk of "dooring" incidents, a hazard that is not present on streets without parking (Beck et al., 2019; Stevenson et al., 2015). The design of intersections along a corridor can also completely change the safety outcome of a mid-block treatment.

Furthermore, road geometry, such as lane width, presents another area of conflicting evidence. Some studies suggest that wider lanes may reduce crash probability in certain settings by providing more maneuvering space (Raihan et al., 2019). In contrast, other studies report that every additional meter of road width increases injury odds by 11–15%, likely because wider roads encourage higher vehicle speeds and more complex traffic movements (Kapousizis et al., 2021). Roundabouts are another example of a design with context-dependent safety outcomes. While often promoted for motor-vehicle safety, many studies included in this review found that traditional roundabout designs significantly increase crash risks for cyclists, with some reporting risks 3 to 8 times higher than at other intersection types (Harris et al., 2013; Meuleners et al., 2019; Fraser & Meuleners, 2020). This is often due to high vehicle speeds and poor sightlines between entering drivers and circulating cyclists. These examples show that an infrastructure design cannot be evaluated in isolation. Its safety performance is fundamentally linked to the specific operational and environmental context of its location.

5.1.3. Common features of high-risk areas: Intersections and transition zones

The reviewed studies consistently identify intersections as primary high-risk locations for cyclists. The data indicate that the odds of an injury-involved crash are significantly higher at intersections compared to mid-block road segments, with one study reporting the odds to be 3.4 times greater (Kapousizis et al., 2021). The elevated risk at these locations can be attributed to several factors. The most direct cause is the high density of conflict points, where the paths of cyclists and motor vehicles cross, merge, or diverge. This complexity is increased in designs that do not align with the expectations of road users. For example, bidirectional bike lanes at intersections can be particularly hazardous because they introduce cyclists traveling in a direction that drivers may not anticipate, increasing the risk of collisions with turning vehicles (Vandenbulcke et al., 2014; Lind et al., 2021). Furthermore, drivers' failure to yield to cyclists is a frequent contributing factor. This is

Table 8
Summary of Infrastructure Location Contexts in Reviewed Studies.

Location context	No.
Intersections (e.g., signalized crossings, roundabouts, railway crossings)	82
Mid-block segments (e.g., cycle tracks along corridors, on-road bike lanes, off-road paths)	75
Transition zones (locations where cycling facilities terminate or merge into mixed traffic)	9
Not location-specific	7

Note: The first three categories are not mutually exclusive; a single study may examine multiple location contexts. Studies classified as "Not location-specific" did not differentiate infrastructure by location and are mutually exclusive with the other categories.

sometimes linked to the "looked-but-failed-to-see" phenomenon, where a driver looks in the direction of an approaching cyclist but does not cognitively register their presence, often due to high cognitive load or attentional blindness (Deliali et al., 2021).

In addition to intersections, another type of high-risk area is the transition zone where dedicated cycling infrastructure begins or, more frequently, ends abruptly. The lack of a connected and continuous network is a recurring theme in safety research. One study found that approximately 30% of all reported bicycle crashes occurred within 100 m of a cycle path, typically at the points where cyclists must merge back into mixed traffic (Meuleners et al., 2020). These transitions force cyclists to execute complex maneuvers in environments where they may no longer have priority or protection. This discontinuity can create confusion for both cyclists and drivers regarding right-of-way and positioning. The absence of a seamless connection between different parts of a cycling network undermines the safety benefits of the individual high-quality segments. Therefore, ensuring network continuity and designing safer intersections and transition zones are critical for reducing overall cycling risk in urban areas. Table 8 summarizes the number of studies that addressed each infrastructure design topic discussed in this section.

5.2. RQ2 – The evolution of safety assessment: From crash data to surrogate measures

5.2.1. Limitations of traditional metrics and the rise of new data sources

The choice of data sources significantly influences the assessment of cycling safety. Traditional analyses have long relied on official crash databases from police or transportation departments (used in 68 studies) and hospital or medical records (used in 20 studies). While these sources provide valuable information on severe injury outcomes, they have well-known limitations. One of the most serious issues is the systematic underreporting of cycling incidents. Hospital data reveals that only about 40% of bicycle crash hospitalizations are documented in police records. This proportion falls to just 12% for crashes that do not involve a motor vehicle, meaning that a large number of incidents, including falls and cyclist-pedestrian collisions, are often missing from official statistics (Meuleners et al., 2020). This underreporting can lead to an incomplete understanding of overall cycling risk and a biased focus on cyclist-motorist collisions.

To overcome these limitations, researchers are increasingly turning to new and alternative data sources. This review found that direct observational methods are now common, including the use of video cameras (27 studies) and naturalistic cycling studies that equip bicycles with sensors and GPS (14 studies). These methods allow for the collection of detailed behavioral data and surrogate safety measures, providing insights into risky interactions that do not result in a crash. For example, some studies used instrumented bicycles to record over 18,500 vehicle-cyclist interactions, offering a large dataset for analyzing passing distances and other behaviors (Beck et al., 2019). Other research has leveraged crowdsourced data from mobile applications like Strava (used in two studies) to estimate cycling volumes and routes, which helps in calculating exposure to risk (Garber et al., 2023; Jeon & Woo, 2024). While these new data sources offer significant advantages in terms of data richness and volume, they also introduce their own biases. For example, crowdsourced data often over-represents recreational male cyclists and under-represents women, older riders and utilitarian riders, which requires statistical adjustments to ensure the sample is representative of the broader cycling population (Garber et al., 2023; Jestico et al., 2017). The selection of a data source is therefore a trade-off, and many researchers now recommend combining multiple data sources to create a more complete and accurate picture of cycling safety (Strauss et al., 2015; Younes et al., 2023).

5.2.2. The application and challenges of surrogate safety measures

To move beyond a reactive approach that relies on historical crash data, many studies in this review (33 studies) have adopted proactive methods using surrogate safety measures (SSMs). SSMs are observations of traffic events, such as conflicts or near-misses, that are more frequent than actual crashes and can serve as early indicators of risk. According to Hydén's safety pyramid, these conflict events offer a much larger dataset for analysis, which allows researchers to assess the safety of an infrastructure design more quickly and without waiting for a statistically significant number of crashes to occur (Hyden, 1987). Common time-based indicators used to quantify the severity of these conflicts include Post-Encroachment Time (PET) and Time-to-Collision (TTC), which measure the temporal proximity between road users (Mansell et al., 2024; Zangenehpour et al., 2016). Behavioral indicators, such as red-light running or lane intrusions (used in 38 studies), are also widely used to identify unsafe actions (see Table 9).

Near-miss incidents, analyzed in 14 studies, are another important surrogate measure. They provide valuable information on how cyclists adapt their behavior in response to infrastructure and can reveal design-related risks before injuries happen (Chou et al., 2024; Jarry & Apparicio, 2021). The methods for collecting near-miss data are varied. While self-report instruments like questionnaires and interviews are a common approach for capturing these events (used in 23 studies, see Table 10), a significant and growing number of studies now employ direct observation techniques. These include the analysis of video footage from naturalistic cycling studies and stationary cameras, which provide objective data on near-miss incidents. For example, some studies have used helmet-integrated sensors to automatically detect near-crash events, providing a rich source of objective data (Chou et al., 2024).

Despite the increasing use of SSMs, their application faces significant challenges. A major issue highlighted in the literature is the lack of standardized thresholds for what constitutes a dangerous conflict. Moreover, there is ongoing skepticism within the academic community regarding the predictive accuracy of SSMs. Many studies lack a formal validation process to confirm that a reduction in observed conflicts or near-misses will actually lead to a reduction in real-world crashes (Mansell et al., 2024; Zangenehpour et al., 2016). This theoretical gap limits the confidence with which findings based on SSMs can be used to inform policy and practice. However, further research is needed to validate the link between SSMs and actual crash outcomes to strengthen their role in proactive safety analysis.

Table 9
Summary of Safety Metrics in Reviewed Studies.

Safety metrics		No.
Actual safety measures	Crash/collision counts or rates	74
	Injury severity or mortality/fatality data	68
Surrogate measures of safety	Behavioral indicators (e.g., speed, passing distance, lane intrusion, red light running)	38
	Traffic conflicts (e.g., post-encroachment time, cutting into car traffic, right hook conflicts)	33
	Near-miss incidents	14

Note: Only objective indicators are included, without subjective indicators.

Table 10
Summary of Data Sources in Reviewed Studies.

Data sources	No.
Official crash/collision databases (e.g., ambulance data, police-registered, insurance claims, department of transportation)	68
Video observation (e.g., drone-captured, intersection surveillance cameras)	27
Field surveys (e.g., manual counts, site/virtual observation)	26
Questionnaires/interviews (e.g., self-reported crash details, injury severity)	23
Hospital/medical records (e.g., trauma registries, post-mortem reports)	20
Naturalistic cycling data (e.g., GPS tracking, airbag helmet, ultrasonic sensor)	14
Simulation data (e.g., driving simulator experiments, bicycle simulator)	10
Crowdsourced data (e.g., BikeMaps, Strava)	2

5.3. RQ3 – methodological hurdles and innovations

5.3.1. Pervasive methodological challenges

The reviewed literature reveals several persistent methodological challenges that complicate the study of cycling safety. One of the most significant issues is controlling for confounding variables, particularly in observational studies, which constituted 96 of the 104 studies analyzed (see Table 7). Factors such as cyclist volume, motor-vehicle traffic, weather, and individual rider skill all influence safety outcomes. It is often difficult to isolate the effect of a specific infrastructure feature from these other overlapping factors. For instance, in complex urban environments, road topology and signal phasing can simultaneously affect cyclist safety, making it hard to attribute a change in crash rates solely to a new bike lane (Bella & Ferrante, 2021). This difficulty in controlling for confounders can lead to selection bias, especially in case-control studies where control sites may systematically differ from crash sites in ways other than the infrastructure being studied (Meuleners et al., 2019).

Another major challenge is establishing a clear causal link between an infrastructure intervention and safety outcomes. Cross-sectional studies, the most common design type with 51 identified cases, can show associations but cannot prove causality because they analyze data at a single point in time (Abbasi & Ko, 2024; Dumbaugh & Li, 2010). Before-and-after studies (Liu and Marker, 2020) are designed to assess causality, but they face their own methodological problems. A primary concern is regression-to-the-mean bias. Interventions are often implemented at locations with a high number of recent crashes, and these sites may have experienced a reduction in crashes even without the intervention, simply by returning to their long-term average. This can lead to an overestimation of the intervention's effectiveness. Although advanced statistical methods like the Full Bayesian framework are designed to address this issue by controlling for exposure levels and regression effects, they remain underutilized in the field (Monzer & Hussein, 2024; DiGioia et al., 2017).

Finally, data quality and granularity present ongoing obstacles. Many official crash datasets lack precise spatial coordinates, making it difficult to determine whether a crash occurred on a specific facility, such as within a bike lane, or adjacent to it (Aiash & Robusté, 2024). Datasets also frequently suffer from underreporting of key contextual information, such as lighting conditions and speed limits (Younes et al., 2023). Furthermore, spatial autocorrelation, where crash occurrences in one location are related to those in nearby locations, poses a serious challenge to traditional statistical models that assume independence of observations. Studies have shown that spatial dependence can account for a significant portion of the unexplained variance in crash models, highlighting the need for more advanced spatial statistical techniques (Vandenbulcke et al., 2014; Abbasi & Ko, 2024; Prato et al., 2016). These methodological issues collectively make the rigorous evaluation of cycling infrastructure a complex task.

5.3.2. Methodological innovations to address challenges

In response to the methodological challenges of studying cycling safety, researchers have developed and applied several innovative approaches. To address the difficulty of controlling for individual-level confounding variables, Harris et al. (2011) introduced the case-crossover design to the field. In this approach, each cyclist involved in a crash serves as their own control. The infrastructure at the crash site is compared to the infrastructure at randomly selected non-crash sites along the same trip route. This design effectively controls for variables that are constant for an individual during a single trip, such as their cycling skill, risk tolerance, and the weather conditions, thereby helping to resolve the "denominator problem" that affects many traditional study designs. Subsequent research has further refined this method by using route prediction algorithms to reduce recall bias and by incorporating participant-drawn route maps to improve data accuracy (Cicchino et al., 2020; Adams et al., 2020).

To strengthen causal inference in before-and-after studies, more robust analytical frameworks are being adopted. The use of difference-in-differences methods (Hosking et al., 2023) and Full Bayesian models (Monzer & Hussein, 2024) helps to mitigate issues like regression-to-the-mean bias and temporal confounding effects. Longitudinal studies, though still few in number (seven cases), represent a significant advance. For example, a 14-year study in Seville demonstrated how the safety benefits of a bicycle network evolve over the long term, showing that short-term evaluations might underestimate the true positive effects of such infrastructure (Marqués & Hernández-Herrador, 2017). Similarly, a 13-year multilevel longitudinal analysis across several U.S. cities was able to separate the immediate protective effects of new infrastructure from the longer-term gains that result from behavioral adaptation (Marshall & Ferenchak, 2019).

To handle the complexities of spatial data, researchers have employed advanced spatial statistical models. For instance, Geographically Weighted Poisson Regression has been used to account for the spatial heterogeneity of infrastructure effects, showing how the safety impact of a bike lane can vary across different parts of a city (Abbasi & Ko, 2024). Hierarchical Bayesian models have also been applied to address the long-standing problem of spatial autocorrelation in ecological studies (Chen et al., 2018). While experimental studies remain rare due to practical and ethical constraints, some researchers have used simulator-based approaches to test driver-cyclist interactions in controlled environments (Fournier et al., 2020; Thorslund & Lindström, 2020). These methodological innovations demonstrate a clear progression in the field toward more rigorous and nuanced approaches for evaluating the safety of cycling infrastructure. To provide a quantitative overview of their adoption, Table 11 summarizes the frequency with which these advanced methods were applied across the 104 reviewed studies. The data indicates that while these innovative designs and models are present in the literature, their overall application remains limited, highlighting a significant opportunity for future research to employ more robust methodologies to strengthen the evidence base.

Table 11
Adoption of Methodological Innovations in Reviewed Studies.

Category	Methodological Innovation	No. of Studies
Advanced Study Designs	Longitudinal	7
	Case-crossover	11
Advanced Statistical Models	Bayesian models	8
	Geographically Weighted Regression	1
	Difference-in-differences	3
Simulation-Based Assessment	Driving or Cycling Simulator studies	6

6. Discussion

6.1. Principal findings and contributions of this review

This systematic review was structured around three interconnected research questions to provide a comprehensive analysis of the relationship between bicycle infrastructure design and cyclist safety. The primary contribution of this work is its integrated approach, which moves beyond reviewing individual infrastructure elements to also examine the methods used to evaluate them and the persistent challenges that affect research in this field. By bringing these three areas—design, measurement, and methodology—together, this review offers a more holistic understanding of the current state of knowledge.

In response to our first research question (RQ1), which focused on identifying impactful infrastructure features, this review confirms a strong consensus in the literature: physically separating cyclists from motor vehicles is the most consistently effective design strategy for reducing crash and injury risk. In addressing the second research question (RQ2) concerning safety measurement, we synthesized a wide range of metrics and data sources. Our analysis highlights a clear evolution in the field from a reliance on traditional, often underreported crash data toward the increasing use of proactive surrogate safety measures and new data sources like naturalistic cycling studies. This shift provides richer data but also introduces new challenges related to validation and data bias.

Finally, in answering the third research question (RQ3) about methodological barriers, we identified several recurring challenges, including the difficulty of controlling for confounding variables and establishing causality in observational studies. Unlike previous reviews that have often focused more narrowly on specific infrastructure types, this study provides a broad critique of the methodological landscape and documents the innovative approaches researchers are using to address these issues. The value of this "cross-referential integration" is that it reveals how these three areas are linked. For example, the effectiveness of a specific infrastructure design (RQ1) can only be reliably demonstrated with robust data and methods (RQ2), which are themselves limited by deeper methodological constraints (RQ3). This integrated perspective clarifies the complex problem structure of cycling safety research and provides a stronger foundation for future academic work and evidence-based practice.

6.2. Dialogue with existing literature

The field of cycling safety has been shaped by several important literature reviews, and this study builds upon their foundational work while offering a distinct and updated perspective. A frequently cited earlier review by Reynolds et al. (2009) was instrumental in establishing the link between transportation infrastructure and cyclist injuries. That review concluded that purpose-built, separated bicycle facilities were associated with the lowest injury risks. Our current review, which includes a large volume of research published since 2009, strongly confirms this fundamental conclusion. However, our work expands on this finding by synthesizing evidence from a new generation of studies that use more advanced methods, such as naturalistic cycling data and surrogate safety measures, to explain the mechanisms behind this safety benefit in greater detail.

Another significant contribution to the literature is the critical review by DiGioia et al. (2017). Their work focused on the methodological quality of existing studies and highlighted significant gaps, particularly in how research accounted for exposure to risk. Our review supports their critique and provides a broader examination of the methodological landscape. While DiGioia et al. focused on issues like exposure data, our study also systematically analyzes a wider range of challenges, including the limitations of different data sources (e.g., official statistics vs. crowdsourced data), the ongoing validation problem with surrogate safety measures, and the specific statistical approaches used to handle issues like spatial autocorrelation.

Therefore, the unique contribution of our review lies in its scope and integrated structure. Unlike previous reviews that have tended to focus primarily on either the effects of infrastructure (like Reynolds et al.) or the methodological quality of the studies (like DiGioia et al.), our work intentionally connects these two areas. By structuring our analysis around the three questions of design, measurement, and methodology, we provide a more comprehensive picture that shows how these elements influence one another. This approach allows us to not only confirm what is known about effective infrastructure but also to critically assess the quality and evolution of the evidence upon which that knowledge is based.

6.3. Implications for policy and practice

This systematic review offers several evidence-based insights for policymakers, urban planners, and transportation engineers working to create safer cycling environments. The most direct and consistent finding is that investing in physically separated infrastructure provides the strongest protective effects for cyclists. This supports policies that prioritize the construction of cycle tracks with physical barriers or grade separation, especially on roads with high motor-vehicle speeds and volumes. However, our review also highlights that simply installing one type of facility is not a complete solution. The safety effects of an infrastructure design are highly context-dependent, as shown by the inconsistent outcomes for painted bike lanes and the high risks associated with poorly designed roundabouts (Harris et al., 2013; Adams et al., 2020; Garber et al., 2023; Meuleners et al., 2019). This means that a "one-size-fits-all" approach is likely to be ineffective. Policymakers should therefore promote context-sensitive design guidelines that consider local traffic conditions, intersection complexity, and surrounding land use.

Another key implication relates to the importance of network connectivity. Our findings show that intersections and transition zones where infrastructure is discontinuous are major high-risk areas (Kapousizis et al., 2021; Meuleners et al., 2020). For practitioners with limited resources, this suggests that improving the continuity and connectivity of an existing network may be a more cost-effective strategy than building isolated segments of high-quality infrastructure. Efforts should be focused on eliminating gaps in the network and redesigning dangerous intersections to ensure seamless and safe transitions for cyclists. This requires a shift from a project-based approach to a network-based approach in planning and investment.

Finally, the implementation of effective cycling infrastructure is not only a technical challenge but also a political one. Even when designs meet technical standards, their safety can be compromised by decisions that prioritize motor vehicle throughput over multimodal safety, often due to resistance from motor-vehicle-oriented interest groups (Riggs et al., 2017). This review shows the importance of aligned policy commitment to support the goals of cyclist safety. This means that in addition to adopting technical design standards, public agencies must also engage in stakeholder analysis and develop strategies to overcome institutional barriers (Deegan, 2016). A strong and sustained political will is necessary to ensure that safety goals are not compromised during the planning and implementation process and that resources are allocated to build a truly safe and connected cycling network.

6.4. Limitations of this research

Despite its contributions, this study has several limitations. First, this is a systematic review and not a *meta*-analysis. We synthesized the findings from the included studies qualitatively but did not perform a quantitative analysis to calculate pooled effect estimates for different infrastructure types. Therefore, the statistical values presented, such as odds ratios and percentages, are directly cited from the original studies and should be interpreted within the context of each individual study.

Second, the scope of this review was intentionally focused on objective safety outcomes, such as crash and injury rates, and surrogate safety measures. As a result, we excluded studies that focused solely on perceived safety. While this approach maintains a clear focus on empirical safety evidence, it does not explore the important relationship between how safe cyclists feel and their actual behavior. Perceived risk can influence route choice, riding speed, and other behaviors that may indirectly affect safety outcomes. The lack of this causal layer may result in an incomplete understanding of the overall effectiveness of certain infrastructure designs.

Third, our analysis of injury severity did not account for the use of individual protective equipment, such as helmets. The severity of an injury is influenced by both the infrastructure design and personal safety measures taken by the cyclist. By not including this variable in our synthesis, the evaluation of infrastructure effectiveness on injury outcomes may be biased. Future research could build upon our work by integrating these additional dimensions to develop a more complete model of cycling safety.

6.5. Directions for future research

Based on the findings and limitations identified in this review, several specific directions for future research can be suggested to advance the understanding of cycling safety. First, there is a clear need for research that integrates objective safety measures with cyclists' subjective perceptions of safety. Our review highlights a gap in understanding how perceived risk influences behaviors like sudden braking or route detours, which in turn affect objective safety outcomes. Future studies could combine video observation of cyclist behavior with post-ride surveys or interviews to build a more complete causal model of how infrastructure design influences both perception and behavior.

Second, a critical area for future work is the validation of surrogate safety measures (SSMs). While the use of SSMs is increasing, our review confirms that their predictive link to actual crash and injury rates is not yet well-established (Mansell et al., 2024; Zangenehpour et al., 2016). Longitudinal studies that collect both SSM data and long-term crash data at the same locations are needed to validate whether a reduction in traffic conflicts reliably predicts a reduction in collisions. Such studies would greatly increase the confidence with which practitioners can use SSMs for proactive safety assessments.

Third, future research should focus more on network-level analysis and the safety of transition zones. While much is known about the safety of individual facility types, our review shows that discontinuities in the cycling network are major high-risk areas (Meuleners et al., 2020). Research questions could include identifying the design features that create the safest transitions between separated paths and mixed-traffic streets, and developing methods to quantify the safety benefits of a fully connected network compared to a fragmented one. Finally, a greater focus on methodological rigor is needed. This includes the wider adoption of advanced statistical models that can control for confounding variables and spatial autocorrelation (Monzer & Hussein, 2024; Prato et al., 2016), and the use of study designs, like case-crossover or longitudinal studies, that can support stronger causal inferences about the effects of infrastructure interventions.

7. Conclusions

This study conducted a systematic review to examine how urban bicycle infrastructure design influences cyclist safety. Its primary contribution is not simply to update the list of effective infrastructure types, but to establish a multi-dimensional analytical framework that connects three critical, yet often separately discussed, areas: the design features themselves, the safety metrics used to evaluate them, and the methodological challenges that limit the certainty of the findings. By integrating these three dimensions, this review provides a more complete picture of why certain knowledge gaps persist and clarifies the complex relationship between evidence, measurement, and research design in this field.

Our synthesis of 104 studies confirms that physically separated cycle tracks offer the most consistent and significant safety benefits for cyclists. The review also documents a clear methodological evolution in the field, with a growing shift from relying on traditional, often underreported crash data to using proactive surrogate safety measures. However, our analysis highlights that the predictive link between these surrogate measures and actual crash outcomes remains a significant challenge that requires further validation. Furthermore, we identified persistent methodological difficulties in the literature, particularly the challenge of controlling for confounding variables in the predominantly observational study designs, which complicates the establishment of clear causal relationships between specific interventions and safety improvements.

Ultimately, this review does not propose a universal "best infrastructure package" for all cities. Instead, it advocates for an evidence-based and context-aware approach to planning and evaluation. The findings underscore that creating safer cycling environments requires more than just implementing specific designs; it also requires sustained research, methodological innovation, and a strong policy commitment. As cities worldwide continue to promote sustainable mobility, ensuring the safety of cyclists is a core priority. The academic community has an essential role in building the robust evidence base needed to guide this important transformation.

CRediT authorship contribution statement

Chuisong Chen: Writing – original draft, Data curation, Conceptualization. **Xiaoyu Lin:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Gang Yu:** Writing – review & editing, Supervision.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsr.2026.06.008.

References

Abbasi, S., & Ko, J. (2024). Cycling safely: Examining the factors associated with bicycle accidents in Seoul. *South Korea. Accident Analysis & Prevention., 206*, Article 107691.
Adams T, Aldred R. Cycling Injury Risk in London: Impacts of Road Characteristics and Infrastructure. Findings [Internet]. 2020 Dec 14 [cited 2025 Jan 27]; Available from: https://findingspress.org/article/18226-cycling-injury-risk-in-london-impacts-of-road-characteristics-and-infrastructure.
Aiash, A., & Robusté, F. (2024). Evaluating bicycle lanes and stations safety in Barcelona: A Bayesian network approach to analyse injury severity. *International Journal of Crashworthiness., 29*, 1–9.
Akobeng, A. K. (2005). Understanding systematic reviews and meta-analysis. *Archives of Disease in Childhood., 90*(8), 845–848.
Armstrong, R., Hall, B. J., Doyle, J., & Waters, E. (2011). "Scoping the scope" of a cochrane review. *Journal of Public Health., 33*(1), 147–150.
Ayad, L., Imine, H., Lantieri, C., & De Crescenzio, F. (2024). Pedal towards safety: the development and evaluation of a risk index for cyclists. *Infrastructures, 9*(1), 14.
Bauer, M., Okraszewska, R., & Richter, M. (2021). Analysis of the causes and effects of cyclist-pedestrian accidents in biggest polish cities. *AoT, 58*(2), 115–135.
Beck, B., Chong, D., Olivier, J., Perkins, M., Tsay, A., Rushford, A., et al. (2019). How much space do drivers provide when passing cyclists? Understanding the impact of motor vehicle and infrastructure characteristics on passing distance. *Accident Analysis & Prevention., 128*, 253–260.
Bella, F., & Ferrante, C. (2021). Effects of the cross-section on the driver's behaviour approaching bicycle crossroads. *Transportation Research Part F: Traffic Psychology and Behaviour., 76*, 109–120.
Bilotta, G. S., Milner, A. M., & Boyd, I. (2014). On the use of systematic reviews to inform environmental policies. *Environmental Science & Policy., 42*, 67–77.
Brzeziński, A., & Jesionkiewicz-Niedzińska, K. (2021). Selected issues of designing cycling infrastructure in the aspect of road traffic safety. *RaBDiM, 20*(1), 75–89.
Carvajal, G. A., Sarmiento, O. L., Medaglia, A. L., Cabrales, S., Rodríguez, D. A., Quistberg, D. A., et al. (2020). Bicycle safety in Bogotá: A seven-year analysis of bicyclists' collisions and fatalities. *Accident Analysis & Prevention., 144*, Article 105596.
Casey, L., Gaspers, L., & Mandel, H. (2024). Overtaking in Stuttgart—analysis of the lateral distances between motor vehicles and bicycle traffic with reference to traffic volume and cycling infrastructure. *TSR, 24*(7), Article e000052.
Chen, P., Sun, F., Wang, Z., Gao, X., Jiao, J., & Tao, Z. (2018). Built environment effects on bike crash frequency and risk in Beijing. *Journal of Safety Research., 64*, 135–143.

Chou, K. Y., Paulsen, M., Jensen, A. F., Rasmussen, T. K., & Nielsen, O. A. (2024). Comparative modeling of risk factors for near-crashes from crowdsourced bicycle airbag helmet data and crashes from conventional police data. *Journal of Safety Research., 91*, 465–480.
Cicchino, J. B., McCarthy, M. L., Newgard, C. D., Wall, S. P., DiMaggio, C. J., Kulie, P. E., et al. (2020). Not all protected bike lanes are the same: Infrastructure and risk of cyclist collisions and falls leading to emergency department visits in three U.S. cities. *Accident Analysis & Prevention., 141*, Article 105490.
Cieśla, M. (2021). Modern urban transport infrastructure solutions to improve the safety of children as pedestrians and cyclists. *Infrastructures, 6*(7), 102.
Deegan, B. (2016). Cycling infrastructure in London. *Proceedings of the Institution of Civil Engineers - Engineering Sustainability, 169*(3), 92–100.
Deliali, K., Christofa, E., & Knodler, M., Jr (2021). The role of protected intersections in improving bicycle safety and driver right-turning behavior. *Accident Analysis & Prevention., 159*, Article 106295.
Di Mascio, P., Fusco, G., Grappasonni, G., Moretti, L., & Ragnoli, A. (2018). Geometrical and functional criteria as a methodological approach to implement a new cycle path in an existing urban road network: A case study in Rome. *Sustainability, 10*(8), 2951.
DiGioia, J., Watkins, K. E., Xu, Y., Rodgers, M., & Guensler, R. (2017). Safety impacts of bicycle infrastructure: A critical review. *Journal of Safety Research., 61*, 105–119.
Dumbaugh, E., & Li, W. (2010). Designing for the Safety of Pedestrians, Cyclists, and Motorists in Urban Environments. *Journal of the American Planning Association., 77*(1), 69–88.
Fournier, N., Bakhtiari, S., Valluru, K. D., Campbell, N., Christofa, E., Roberts, S., et al. (2020). Accounting for drivers' bicycling frequency and familiarity with bicycle infrastructure treatments when evaluating safety. *Accident Analysis & Prevention., 137*, Article 105410.
Fraser, M. L., & Meuleners, L. B. (2020). Risk factors for unsafe events involving a motor vehicle for group riders (cyclists): A naturalistic case-crossover study. *Accident Analysis & Prevention, 146*, Article 105758.
Furth, P. G., Mekuria, M. C., & Nixon, H. (2016). Network connectivity for low-stress bicycling transportation research record. *Journal of the Transportation Research Board., 1*(2587), 41–49.
Garber, M. D., Watkins, K. E., Flanders, W. D., Kramer, M. R., Lobelo, R. L. F., Mooney, S. J., et al. (2023). Bicycle infrastructure and the incidence rate of crashes with cars: A case-control study with Strava data in Atlanta. *Journal of Transport & Health., 32*, Article 101669.
Greenhalgh, T. (1997). How to read a paper: Papers that summarise other papers (systematic reviews and meta-analyses). *BMJ, 315*(7109), 672–675.
Hamann, C., & Peek-Asa, C. (2013). On-road bicycle facilities and bicycle crashes in Iowa, 2007-2010. *Accident Analysis & Prevention., 56*, 103–109.
Harris, M. A., Reynolds, C. C. O., Winters, M., Chipman, M., Cripton, P. A., Cusimano, M. D., et al. (2011). The Bicyclists' Injuries and the Cycling Environment study: A protocol to tackle methodological issues facing studies of bicycling safety. *Injury Prevention, 17*(5). e6-e6.
Harris, M. A., Reynolds, C. C. O., Winters, M., Cripton, P. A., Shen, H., Chipman, M. L., et al. (2013). Comparing the effects of infrastructure on bicycling injury at intersections and non-intersections using a case-crossover design. *Injury Prevention, 19*(5), 303–310.
Harrison, J. E., Weber, S., Jakob, R., & Chute, C. G. (2021). ICD-11: An international classification of diseases for the twenty-first century. *BMC Medical Informatics and Decision Making., 21*(6), 206.
Hosking, J., Mackie, H., Macmillan, A., Van Der Werf, B., Smith, M., Witten, K., et al. (2023). Effects of Te Ara Mua - Future Streets suburban street retrofit on traffic speed and volume: Controlled before-after study. *Journal of Transport & Health., 30*, Article 101601.
Hyden C. The development of a method for traffic safety evaluation: the swedish traffic conflicts technique. bulletin lund institute of technology, department [Internet]. 1987 [cited 2025 Apr 21];(70). Available from: https://trid.trb.org/View/239059.
Monzer, I. Y., & Hussein, M. (2024). Conventional or parking-protected bike lanes? A Full-Bayesian before-and-after assessment. *Traffic Injury Prevention., 25*(3), 482–491.
Jarry, V., & Apparicio, P. (2021). Ride in peace: How cycling infrastructure types affect traffic conflict occurrence in Montréal, Canada. *Safety, 7*(3), 63.
Jeon, J., & Woo, A. (2024). The effects of built environments on bicycle accidents around bike-sharing program stations using street view images and deep learning techniques: The moderating role of streetscape features. *Journal of Transport Geography., 121*, Article 103992.
Jestico, B., Nelson, T. A., Potter, J., & Winters, M. (2017). Multiuse trail intersection safety analysis: A crowdsourced data perspective. *Accident Analysis & Prevention., 103*, 65–71.
Johnson M, Charlton J, Newstead S, Oxley J. Painting a Designated Space: Cyclist and Driver Compliance at Cycling Infrastructure at Intersections. 2010.
Kapousizis, G., Goodman, A., & Aldred, R. (2021). Cycling injury risk in Britain: A case-crossover study of infrastructural and route environment correlates. *Accident Analysis & Prevention, 154*, Article 106063.
Klassen, J., El-Basyouny, K., & Islam, M. T. (2014). Analyzing the severity of bicycle-motor vehicle collision using spatial mixed logit models: A City of Edmonton case study. *Safety Science., 62*, 295–304.
Kmet, Leanne M. ; Cook, Linda S. ; Lee, Robert C. Standard Quality Assessment Criteria for Evaluating Primary Research Papers from a Variety of Fields [Internet]. University of Alberta Libraries; 2004 [cited 2025 Apr 21]. Available from: https://era.library.ualberta.ca/files/9s1619324.
Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., et al. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *Journal of Clinical Epidemiology., 62*(10), e1–e34.
Lind, A., Honey-Rosés, J., & Corbera, E. (2021). Rule compliance and desire lines in Barcelona's cycling network. *Transportation Letters, 13*(10), 728–737.
Liu, P., & Marker, S. (2020). Evaluation of contributory factors' effects on bicycle-car crash risk at signalized intersections. *Journal of Transportation Safety & Security., 12*(1), 82–93.
López-Molina, M., Llopis-Castelló, D., Pérez-Zuriaga, A. M., Alonso-Troyano, C., & García, A. (2022). Skid resistance analysis of urban bike lane pavements for safe micromobility. *Sustainability, 15*(1), 698.
Mansell, R., Persaud, B., Milligan, C., & Pushka, A. (2024). Investigating factors that affect conflicts between bicyclists and right turning vehicles at signalized intersections. *TSR, 22*(6), Article e000040.
Marqués, R., & Hernández-Herrador, V. (2017). On the effect of networks of cycle-tracks on the risk of cycling. the case of Seville. *Accident Analysis & Prevention., 102*, 181–190.
Marshall, W. E., & Ferenchak, N. N. (2019 Jun). Why cities with high bicycling rates are safer for all road users. *Journal of Transport & Health., 13*, Article 100539.
M.C. Mekuria, P.G. Furth, H. Nixon. Low-stress bicycling and network connectivity Retrieved from MINETA Transportation Institute Report. 2012 May;11-19.
Meuleners, L. B., Fraser, M., Johnson, M., Stevenson, M., Rose, G., & Oxley, J. (2020). Characteristics of the road infrastructure and injurious cyclist crashes resulting in a hospitalisation. *Accident Analysis & Prevention., 136*, Article 105407.
Meuleners, L., Fraser, M., & Roberts, P. (2023). Improving cycling safety through infrastructure design: A bicycle simulator study. *Transportation Research Interdisciplinary Perspectives., 18*, Article 100768.
Meuleners, L. B., Stevenson, M., Fraser, M., Oxley, J., Rose, G., & Johnson, M. (2019). Safer cycling and the urban road environment: A case control study. *Accident Analysis & Prevention, 129*, 342–349.
Moher, D., Cook, D. J., Eastwood, S., Olkin, I., Rennie, D., & Stroup, D. F. (2000). Improving the quality of reports of meta-analyses of randomised controlled trials: The QUOROM statement. *Oncology Research and Treatment, 23*(6), 597–602.
Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med. 2009;6(7):e1000097.
Nguyen QC, Alirezaei M, Yue X, Mane H, Li D, Zhao L, et al. Leveraging computer vision for predicting collision risks: a cross-sectional analysis of 2019-2021 fatal collisions in the USA. Inj Prev. 2024 Jun 6;ip-2023-045153.
Oxman, A. D., & Guyatt, G. H. (1993). The Science of reviewing researcha. *Annals of the New York Academy of Sciences., 703*(1), 125–134.
Prato, C. G., Kaplan, S., Rasmussen, T. K., & Hels, T. (2016). Infrastructure and spatial effects on the frequency of cyclist-motorist collisions in the Copenhagen Region. *Journal of Transportation Safety & Security., 8*(4), 346–360.
Raihan, M. A., Alluri, P., Wu, W., & Gan, A. (2019). Estimation of bicycle crash modification factors (CMFs) on urban facilities using zero inflated negative binomial models. *Accident Analysis & Prevention, 123*, 303–313.
Read, G. J. M., Salmon, P. M., Goode, N., Van Mulken, M., Lenné, M. G., Stevens, N., et al. (2020). Interaction-centred design: An end user evaluation of road intersection concepts developed using the cognitive work analysis design toolkit (CWA-DT). *Ergonomics, 63*(10), 1221–1239.
Reynolds, C. C., Harris, M. A., Teschke, K., Cripton, P. A., & Winters, M. (2009). The impact of transportation infrastructure on bicycling injuries and crashes: A review of the literature. *Environmental Health, 8*(1), 47.
Riggs, W., & Gilderbloom "Hans", J. I. (2017). How multi-lane, one-way street design shapes neighbourhood life: Collisions, crime and community. *Local Environment., 22*(8), 917–933.
Rix, K., & Sakamoto, I. (2022). Infrastructure and Injury prevention in cycling. *Physical Medicine and Rehabilitation Clinics of North America., 33*(1), 123–134.
Seah, R., Lystad, R. P., & Mitchell, R. (2018). Risk factors associated with severity of hospitalised injury outcomes for vulnerable road users in New South Wales, Australia: A population-based study. *Journal of the Australasian College of Road Safety., 29*(1), 30–38.
Stevenson, M., Johnson, M., Oxley, J., Meuleners, L., Gabbe, B., & Rose, G. (2015). Safer cycling in the urban road environment: Study approach and protocols guiding an Australian study. *Injury Prevention, 21*(1). e3-e3.
Strauss, J., Miranda-Moreno, L. F., & Morency, P. (2013). Cyclist activity and injury risk analysis at signalized intersections: A Bayesian modelling approach. *Accident Analysis & Prevention., 59*, 9–17.
Strauss, J., Miranda-Moreno, L. F., & Morency, P. (2014). Multimodal injury risk analysis of road users at signalized and non-signalized intersections. *Accident Analysis & Prevention., 71*, 201–209.
Strauss, J., Miranda-Moreno, L. F., & Morency, P. (2015). Mapping cyclist activity and injury risk in a network combining smartphone GPS data and bicycle counts. *Accident Analysis & Prevention, 83*, 132–142.
Teschke, K., Harris, M. A., Reynolds, C. C. O., Winters, M., Babul, S., Chipman, M., et al. (2012). Route infrastructure and the risk of injuries to bicyclists: a case-crossover study. *American Journal of Public Health, 102*(12), 2336–2343.
Thai Van, M. J., & Balmefrezol, P. (2000). Design of roundabouts in france: historical context and state of the art. *Transportation Research Record: Journal of the Transportation Research Board., 1737*(1), 92–97.
Thorslund, B., & Lindström, A. (2020). Cyclist strategies and behaviour at intersections. Conscious and un-conscious strategies regarding positioning. *Transportation Research Part F: Traffic Psychology and Behaviour., 70*, 149–162.
Vandenbulcke, G., Thomas, I., & Int, P. L. (2014). Predicting cycling accident risk in Brussels: A spatial case-control approach. *Accident Analysis & Prevention., 62*, 341–357.

Wang, J. T. J., Li, J. S., Chiu, W. T., Chen, S. H., Tsai, S. D., Yu, W. Y., et al. (2009). Characteristics of bicycle-related head injuries among school-aged children in Taipei area. *Surgical Neurology., 72*, S36–S40.

Younes, H., Noland, R. B., Von Hagen, L. A., & Meehan, S. (2023). Pedestrian- and bicyclist-involved crashes: Associations with spatial factors, pedestrian infrastructure, and equity impacts. *Journal of Safety Research., 86*, 137–147.

Zangenehpour, S., Strauss, J., Miranda-Moreno, L. F., & Saunier, N. (2016). Are signalized intersections with cycle tracks safer? A case-control study based on automated surrogate safety analysis using video data. *Accident Analysis & Prevention., 86*, 161–172.

Chuisong CHEN is a Master's student specializing in the relationship between the built environment and cycling safety at the School of Future Design, Harbin Institute of Technology. His research interests also extend to human–environment interaction and spatial experience in urban settings. With experience as a research assistant, he has contributed to projects exploring how design can promote safer and more engaging urban environments.

Xiaoyu LIN is an Associate Professor at Harbin Institute of Technology, Shenzhen. She received her PhD from the University of Hong Kong, where she also worked for three years at the Chinese Urbanism and Architecture Research Center. Her current research focuses on the urbanization in the Greater Bay Area and methods for urban-rural regeneration. With over six years of professional experience in research on urban-rural issues, she is distinguished to explore sustainable spatial design approaches that reflect local cultural characteristics.

Gang YU is a Professor in the School of Architecture at Harbin Institute of Technology, Shenzhen, and received his PhD from Southeast University. His research focuses on urban and architectural design and theory, digital architecture, and interactive architecture. He has served as Principal Investigator for 3 completed projects supported by the National Natural Science Foundation of China (NSFC) and has been involved in multiple national and provincial/ministerial research initiatives. His publications include over 40 papers, 2 authored books, 1 edited volume, and 2 translated works.