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Research Article

Shaping the future of cycling safety: A research agenda for the next two decades☆

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ABSTRACT

The global shift toward sustainable transportation has raised the profile of cycling. Yet cycling safety still faces persistent challenges (e.g., fragmented governance, inequitable infrastructure, scarce research) that are often overshadowed by motorized transport agendas. This paper presents findings from a workshop held at the 12th International Cycling Safety Conference (ICSC2024) in Imabari, Japan, which brought together an interdisciplinary group of 31 experts (researchers, practitioners, and policymakers) to explore prospective research directions for cycling safety over the next two decades. Drawing on submitted abstracts, group dialogues, and post-event reflections, we used participatory methods, speculative exercises, and collaborative discussions to conduct a thematic analysis that organized key factors into five domains: society, policy, infrastructure, vehicles, and road users. This framework supports a long-term research agenda to address the interconnected challenges of cycling safety. Key priorities include: (i) behavioral and societal studies to make cycling safer and more appealing for diverse users; (ii) development of AI-enabled safety technologies; (iii) establishment of international infrastructure standards; and (iv) tools to anticipate risks linked to emerging vehicle technologies. Additional directions involve the use of eXtended Reality (XR) for behavioral research, multimodal integration, and the ethical

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and privacy dimensions of data collection. Practically, the findings highlight the importance of participatory and multidisciplinary approaches for tackling real-world safety issues and guiding future research.

1. Introduction

The worldwide shift toward sustainable mobility makes ensuring cycling safety a priority [1,2]. Worldwide, the number of cyclists has risen sharply, driven by rapid urbanization, policy initiatives that incentivize active mobility, public health concerns, and individual efforts to reduce emissions and address climate change [3,4]. Despite well-documented benefits for community health, environmental sustainability, and urban mobility [5], safety concerns persist as traffic crashes involving cyclists remain a significant global issue [6,7].

Although numerous safety initiatives are underway worldwide, persistent risks and disparities in safety outcomes highlight the need for comprehensive, systematic research to develop effective strategies for safer, more participatory, and user-centered cycling environments across urban and rural contexts [8–11]. The urgency for a dedicated research agenda on cycling safety is further highlighted by growing evidence that current measures are insufficient to prevent fatalities and injuries, particularly in rapidly urbanizing regions [12,13]. Without timely action, global commitments such as the UN Sustainable Development Goals (SDGs), particularly Goal 11 –Sustainable Cities and Communities– may fall short of targets to provide safe and accessible transport systems for all.

Historical examples of missed opportunities show the consequences of failing to prioritize cyclist safety in transport planning. Recent studies have shown that cities that embraced automobile dominance without planning for multimodal safety have struggled to retrofit infrastructure to protect vulnerable road users, often at high economic and social cost [14]. At the same time, emerging risks from new technologies (e.g., autonomous vehicles and smart mobility solutions) call for proactive study to avoid unintended effects. A strategic, forward-looking research agenda is needed not only to address current gaps but also to anticipate future challenges, so that cycling remains a viable, safe, and equitable mode of transportation in evolving urban contexts.

Technology offers both opportunities and tensions for cycling safety. While some innovations aim to enhance safety, implementation raises questions about competing values, including equity and justice [15]. Much current development in motorized mobility emphasizes convenience and performance rather than out-of-vehicle safety – especially for cyclists– such that, without deliberate design, advances can introduce new risks or deepen existing inequities [16]. On the one hand, connected and automated vehicles (CAVs) exemplify this problem: current systems do not consistently prioritize cyclists, and detection still struggles to recognize them, creating serious safety risks [17]. On the other hand, CAVs would consistently comply with the rules of the road and could use road capacity more efficiently; if that efficiency is translated into space reallocation, cities could expand protected facilities and improve conditions for cycling [18–20]. To fulfill technology's promise, these value conflicts should be addressed proactively, and frameworks that prioritize both safety and fairness in technological development should be integrated. A practical first step is to generate robust evidence and understanding through targeted research on cycling safety.

Meeting these challenges calls for a forward-looking research agenda that anticipates emerging risks and makes prudent use of innovation. Despite cycling's role in sustainable transport systems, research and practice have devoted comparatively less attention to cycling safety compared to other modes [21,22]. In practical terms, “more research” entails closing data gaps on exposure, behavior, near-misses, and crashes; testing design interventions at high-risk conflict points – such as junction protection, network continuity, speed management, and safer heavy-vehicle operations; evaluating the effects of emerging technologies on people outside vehicles; and advancing equity and inclusion so that safety measures are effective across diverse user groups and contexts. Integrating the expertise of cycling safety researchers and practitioners is essential to uncover overlooked issues, generate actionable evidence, and strengthen the overall resilience of transport systems.

Building on this need, we argue that a future-oriented, foresight-based perspective is crucial to ensure that cycling remains a safe, equitable, and integral component of sustainable mobility. While technological and societal change is accelerating, systematic foresight remains rare in cycling safety research. Expanding its use can help anticipate risks, identify opportunities, and guide proactive strategies that align infrastructure, policy, and behavior with long-term sustainability goals.

In this context, the paper presents the outcomes of a collaborative foresight workshop convened to develop a forward-looking global research agenda for cycling safety. The study aims to identify emerging research priorities and methodological directions that can inform evidence-based strategies for safer, more equitable, and sustainable cycling environments worldwide.

2. Future-centric frameworks for shaping future cycling safety research

Developing a robust research agenda for cycling safety requires looking beyond immediate issues to prepare for a range of possible futures. Speculative semiotics, grounded in semiotic theory, focuses on constructing and analyzing hypothetical scenarios to examine the meanings, implications, and trajectories of future developments [23]. This approach enables experts to build and critique plausible research imaginaries and to consider how their work might evolve with societal, technological, and environmental change. Through reflective scrutiny of assumptions, priorities, and methods, speculative semiotics can inform current choices while orienting the field toward future needs.

Applications of speculative semiotics have shown value for exploring long-term research trajectories. In sustainable computing, researchers used fictional abstracts to imagine outcomes that highlight bottom-up resilience, shifts in paradigms, and technological advances, while acknowledging persistent social structures [24]. In their exploration of speculative methodologies, Pargman et al. (2019) illustrated how fictional abstracts can probe the societal implications of emerging technologies and their alignment with human values by envisioning research 50 years ahead. This work fostered critical dialogue and prompted new lines of inquiry to question assumptions and guide responsible innovation. Similarly, workshops using speculative methodologies have addressed sustainability challenges in Information and Communication Technologies (ICTs), allowing stakeholders to consider societal impacts and align strategies with practical objectives such as emissions reduction and urban planning [25].

Fictional abstracts have also been used in the gig economy (whose related research increasingly addresses ethics and justice matters [26]) to support collaboration on labor rights and ethical technology design, uncovering tacit assumptions and aligning research with social priorities [27]. Building on these methods, speculative semiotics was applied to cycling safety to generate research imaginaries, identify risks, opportunities, and gaps, and set a forward-looking research agenda.

Building on speculative semiotics, whose character is usually prospective, the integration of structured frameworks such as the futures cone provides a critical balance between imaginative exploration and systematic rigor in crafting forward-looking research agendas. The futures cone, a widely used instrument in futures studies, organizes potential trajectories into four categories: *possible* (futures that could occur given known physical laws), *plausible* (futures grounded in current knowledge and trends), *probable* (futures likely under existing

trajectories), and *preferable* (futures aligned with societal values or aspirations). This categorization allows researchers to map a spectrum of futures, examine uncertainty, and design strategies that connect present actions with long-term goals. In participatory healthcare research, the same structure has guided collaborative efforts to widen the space of potential futures, address complex uncertainties, and foster alignment among diverse stakeholders [28].

From our standpoint, and based on similar experiences in the literature, such as [29,30], the combination of speculative and structured methodologies offers a coherent way to envision and plan for the future of cycling safety research. Speculative semiotics encourages transformative thinking by exploring hypothetical scenarios and examining the societal, technological, and cultural implications of potential futures. This lens surfaces latent risks, opportunities, and gaps that might otherwise remain unrecognized. The futures cone framework, shown in Fig. 1, complements this perspective by situating imaginative explorations within a structured temporal frame that can be flexibly adapted to short, medium, or long time horizons, clarifying the distinction between exploratory possibilities and actionable strategies.

A compelling example of the effectiveness of this methodological combination is provided by Torkamaan et al. [29], who paired speculative sociotechnical imaginaries with a structured Human-Centered AI framework to develop a forward-looking research agenda for integrating large language models into sociotechnical systems. Through multiphase workshops, participants from different disciplines envisioned transformative futures, weighed societal implications, and refined actionable strategies.

Moreover, speculative exercises tend to represent a beneficial tool for researchers, as they facilitate the identification of emergent challenges and opportunities, while structured frameworks ensure alignment with long-term societal goals [24,31–33]. In our case, this combination encouraged creative exploration and guided pragmatic implementation steps, producing a coherent agenda.

Likewise, aligning speculative methodologies with structured tools such as the futures cone allows cycling safety research to keep innovation in view while maintaining practical relevance. Together, these methods address the complexity and uncertainty of evolving social and technological conditions, and they provide a clear pathway from exploratory ideas to decision-ready actions. At a practical level, this involves translating speculative outputs into testable questions, pilot designs, and evaluation criteria that integrate near-term steps with longer-term ambitions, supporting integrated approaches to building safer and more sustainable cycling environments.

3. Methods

3.1. The workshop

The workshop, titled "*Moving from the Present to the Future: Upcoming Issues, Methods, and Challenges in Cycling Safety Research*", was organized as part of the 12th International Cycling Safety Conference 2024 in Imabari, Japan. Its aim was to bring together researchers, practitioners, and policymakers to explore the future of cycling safety research over the next two decades. In terms of methods, interactive tools and procedures –such as scenario planning, expert panels, and brainstorming sessions (see Fig. 2)– were used to generate ideas and map future research pathways. Participants were asked to submit a free-format abstract of up to 500 words in advance, addressing the question, "*What research would you be doing in 20 years?*"

These 17 submissions defined the discussion space for the workshop and served as the basis for group dialogues and the development of a forward-looking research agenda; they were complemented by in-session deliberation and post-event reflections rather than intended to

Fig. 2. Participants interacting during the workshop.

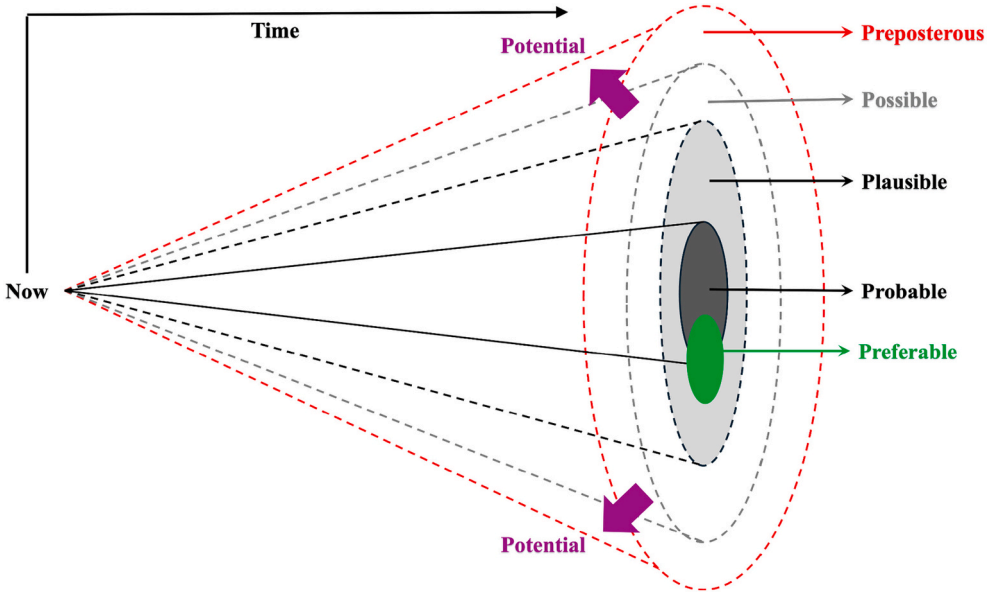

Fig. 1. Futures cone model illustrating potential trajectories for cycling safety research.

be exhaustive. Expected outcomes included fostering international collaboration and producing a strategic paper to guide cycling safety research. Our hypothesis was that integrating diverse perspectives and speculative methodologies may enrich the workshop and help identify key priorities and innovative approaches for advancing the field.

3.2. Participants

A total of 31 experts, including researchers, practitioners, and policymakers, participated in the workshop. These individuals brought expertise from diverse fields, including transportation safety, urban planning, public health, and environmental policy. Given the size of the group, participants were divided into four subgroups, each tasked with analyzing the abstracts compiled in the 'book of abstracts' (see Appendix I) and collaboratively developing a research agenda. Their findings were then discussed and refined in a plenary session with all attendees.

The workshop included representatives from 16 institutions across 8 countries, encompassing a broad mix of academic institutions, government agencies, and industry organizations. Academic participants contributed research expertise and theoretical perspectives, while government representatives provided policy and regulatory insights. Industry professionals added practical and technological viewpoints, ensuring that real-world applications were considered alongside research and policy discussions. This multidisciplinary, international mix enabled a broad exchange of knowledge. At the same time, participants acknowledged the limited representation of clinical and medical professionals and identified this as a priority for future collaboration—particularly given the growing diversity of bicycle types and other micromobility devices sharing road space. They noted that clinical specialists are often less involved in transport safety research because their work typically focuses on treatment and rehabilitation rather than prevention, yet their expertise could provide valuable insights into injury mechanisms, recovery trajectories, and the broader health impacts of cycling crashes.

3.3. Procedure

The workshop followed a structured five-phase procedure designed to engage participants in collaborative envisioning and planning (see Fig. 3). The methodology integrated speculative and structured approaches to generate a forward-looking and actionable research agenda for cycling safety. Each phase was strategically designed to build upon the previous, ensuring a comprehensive exploration of future challenges and opportunities.

Phase 1 - Future Reflections and Analysis: Participants began by reviewing pre-submitted abstracts, which outlined potential challenges, opportunities, and directions for cycling safety research. Using color-coded *post-its* (yellow for problems and pink for opportunities), participants engaged in identifying recurring themes and key gaps in current knowledge. This phase established a foundation for critical reflection and provided a shared understanding of the current and emerging research landscape.

Phase 2 - Prioritization of Visionary Ideas: In this phase, participants individually reviewed the submitted abstracts and selected those they deemed the most visionary or impactful for the future of cycling safety. Following these individual evaluations, group discussions were conducted to collectively justify and debate the selections, fostering a critical examination of the ideas.

The process was guided by the futures cone framework, encouraging participants to assess the plausibility, probability, and preferability of each idea. Emphasis was placed on identifying innovative concepts that aligned with long-term objectives and addressed pressing challenges. The prioritization exercise culminated in the identification of key focal areas to guide the subsequent phases, ensuring a clear trajectory of actionable research priorities.

Phase 3 - Complementing Future Visions: Building upon the prioritized ideas, participants collaboratively explored potential gaps or overlooked perspectives to refine the research framework. Using the above-described futures' cone as a lens, discussions were expanded to consider plausible scenarios that had not been fully addressed in the abstracts, including mixed-fleet dynamics (e-bikes, cargo bikes, e-scooters, mobility scooters) and context-specific constraints in different urban and rural settings. The goal was to broaden the spectrum of plausible futures and surface critical risks and opportunities. This exercise ensured the inclusion of diverse viewpoints and alternative trajectories, broadening the spectrum of considered futures and identifying critical opportunities or risks that might otherwise have been excluded. The refined framework aimed to ensure that the envisioned research agenda was comprehensive, inclusive, and aligned with the complex and evolving landscape of cycling safety.

Phase 4 - Designing Future Studies: Participants transitioned to designing concise research questions and methodologies to address the challenges and opportunities identified in the previous phases. Each study proposal was articulated in a single sentence and documented on orange post-its to ensure clarity and focus. These proposals bridged speculative explorations with actionable strategies, creating a clear link between visionary ideas and practical implementation.

Examples of proposed studies included leveraging AI-driven traffic monitoring to enhance cycling safety and equity and exploring policy adaptations for sustainable urban planning. To visualize and situate these proposed trajectories, participants revisited the futures cone to map the pathways of their ideas, identifying the most plausible scenarios and their potential impact. This exercise helped integrate forward-looking aspirations with grounded, actionable strategies, ensuring a cohesive and impactful research agenda, and is illustrated in Fig. 4.

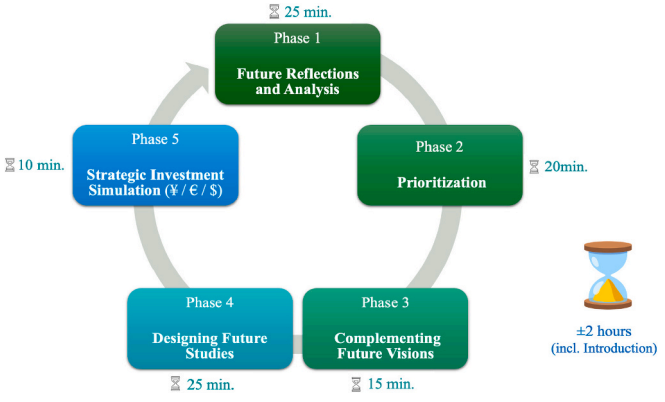

Fig. 3. Workshop structure (subsequent phases).

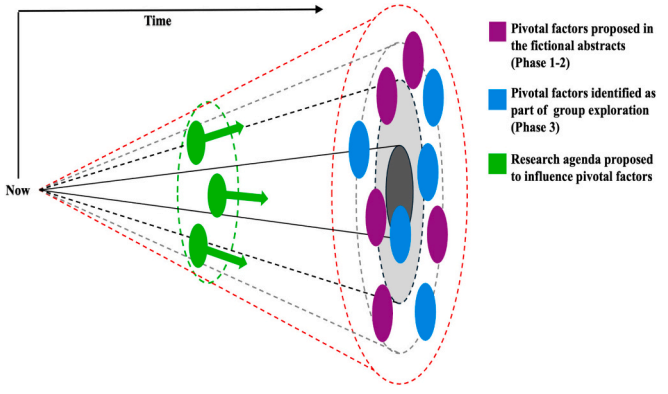

Fig. 4. Deployment of future cones in the workshop for mapping research priorities.

Phase 5 - Strategic Investment Simulation: To simulate research resource allocation, participants engaged in a funding exercise. Each participant received three tokens, valued at €1 million each, to distribute across the proposed studies. Justifications for each allocation were recorded on green post-its, prompting focused discussion of priorities, trade-offs, and how resources align with both visionary aims and practical goals. As an outcome, this phase highlighted the role of strategic decision-making and its implications for the futures participants seek to achieve.

The workshop concluded with a synthesis of findings, in which participants reviewed the proposed studies and their alignment with the overarching goals of cycling safety research. The outcomes were organized into a strategic publication framework to guide global research efforts over the next two decades. Combining speculative methodologies with structured frameworks produced a research agenda that is both innovative and pragmatic, and that addresses the complexities of future cycling safety challenges.

3.4. Data collection and analysis

The data collected during the workshop provided a rich qualitative foundation for analysis, encompassing multiple sources that captured the collaborative and interactive nature of the event. Photographic evidence was systematically gathered throughout the sessions, documenting the color-coded post-it notes that participants used to register key insights, visionary ideas, and proposed research questions. These visual artifacts were organized by workshop phase so that the progression of ideas –from initial prioritization through the formulation of actionable strategies– could be traced over time. The color-coding scheme enabled a clear differentiation between prioritized concepts, complementary visions, and proposed studies, which facilitated orderly compilation and later analysis.

In addition to the visual record, participants were encouraged to consistently document their discussions and outputs on post-it notes during all phases of the workshop. These written contributions captured a broad span of content, including innovative ideas, perceived gaps in the research landscape, and concrete research questions. To contextualize these written records, group discussions were audio-recorded throughout the event. The recordings offered a dynamic account of exchanges among participants, preserving both the reasoning behind specific proposals and the points of consensus or divergence that arose in real time. Transcriptions of these recordings were then produced and analyzed alongside the written sources to ensure that meaning, intent, and rationale were not lost when moving from discussion to documentation.

Further enriching the dataset, eight participants provided additional reflections by email after the workshop. These post-event contributions supplied individual perspectives that complemented the collective deliberations and occasionally elaborated on ideas that had been raised only briefly during the sessions. Through integrating these reflections with the workshop materials, the analysis benefited from a broader view of participant viewpoints and from clarifications that helped reduce interpretive gaps. For the purposes of analysis, all sources (i.e., photographs, written notes, transcripts, and post-event reflections) were compiled into a single, phase-indexed corpus, allowing cross-checking of references and consistent retrieval of related items across phases and themes.

The data analysis was conducted by Prof. O. Oviedo-Trespalacios and Prof. S. A. Useche, using a thematic analysis approach to identify recurring patterns, key ideas, and priorities emerging from the workshop discussions. This process involved systematic familiarization with the complete corpus, followed by inductive generation of initial codes directly from the raw material. These codes were then reviewed and grouped into candidate themes reflecting the main areas discussed in the workshop (i.e., societal, policy, infrastructure, vehicle, and user-related dimensions) while maintaining explicit links between themes and their underlying evidence. Throughout this stage, constant comparison across sources and phases was used to check consistency and to avoid over-representing isolated comments or under-representing minority viewpoints that were nevertheless salient for future research.

The broader group of participants contributed to refining the analysis by providing feedback on preliminary findings circulated after the workshop. Their comments were used to adjust theme boundaries, clarify labels, and confirm that the synthesis fairly represented both areas of agreement and legitimate differences in emphasis. This iterative and participatory step strengthened the relevance and credibility of the thematic structure by aligning it with the multidisciplinary character of the group, which yielded a coherent thematic framework that provides a grounded basis for advancing cycling safety research and for linking speculative exploration with strategies that can be further developed, tested, and evaluated in practice.

4. Results and discussion

4.1. Synthesis of the fictional abstracts

As aforementioned, as part of the workshop, participants submitted open-content abstracts addressing the question "*What research would you be doing in 20 years?*". The complete set of these speculative abstracts is summarized in Table 1, with full-length versions provided in Appendix I. These contributions employed forward-looking and imaginative approaches to cycling safety research, offering diverse perspectives on potential future developments in the field.

Methodologically, the abstracts were designed to align with the workshop's goal of fostering innovative thinking and identifying strategic research trajectories. Given the diverse academic and professional backgrounds of the participants, each abstract emphasized different themes, methods, challenges, and research priorities, addressing a series of topics considered as "key issues" for the next two decades of cycling safety research among the contributing authors.

For instance, one prominent theme, present in 47% of the abstracts (8 out of 17), was the integration of advanced technologies into cycling safety. These contributions explored innovations such as connected devices, eXtended Reality (XR), and AI-driven predictive systems as essential tools for shaping the future of cycling safety. Many abstracts emphasized the potential of these technologies to enhance cyclist protection, monitor behaviors, and mitigate emerging risks. However, they also raised critical concerns, including accessibility challenges, ecological validity, and ethical dilemmas – particularly the need for equitable and inclusive safety solutions that remain underdeveloped.

Another major focus was infrastructure and urban planning, highlighted in 29% of the abstracts (5 out of 17). These contributions explored innovations such as minimalist infrastructure designs, multimodal transport hubs, and adaptive urban spaces. Rather than treating infrastructure as an isolated element, these abstracts emphasized its interdependence with behavioral and societal factors. Many participants remarked the need to mitigate existing disparities while anticipating future shifts in urban mobility. As one abstract (Abstract 13) put it,

Table 1
Detailed summary of the research abstracts incorporated.

No.	Abstract Title	Keywords	Description	Methods	Challenges and constraints	Implications for Future Cycling Safety Research
1	*Cycling safety, technology, and mobility in 20 years*	Road safety; aging population; tech integration; active/passive safety	Explores future safety measures, focusing on technology, aging populations, and cost-benefit approaches for cycling improvements.	Cost-benefit analysis, ergonomic interface development	Aging population, urban segmentation, technological challenges	Focus on aging population needs, development of ergonomic technologies, and integration of connected infrastructure for real-time safety monitoring.
2	*The Future of Bicycling Safety: A Review of Selected Reviews*	Crash risk; countermeasures; safety tech; infrastructure gaps	Reviews past trends to predict future safety interventions, emphasizing countermeasures, data quality, and technological evaluation.	Literature review, data quality analysis	Technological over-hype, inconsistent data availability	Encourage rigorous evaluation of technologies and focus on implementing effective, evidence-based safety measures at intersections and urban settings.
3	*The opportunities and challenges of using eXtended Reality for data collection and study of cyclist behavior*	XR; data collection; cyclist behavior; experimental fidelity	Highlights XR's potential for cost-effective, controlled cyclist behavior studies and its limitations in ecological validity.	Virtual Reality (VR), data collection simulation	Ecological validity, simulator fidelity	Use XR for safe, cost-effective data collection on cyclist behavior in dangerous or futuristic scenarios, while addressing challenges of fidelity and ecological validity.
4	*Future Perspectives in Cycling Safety Research: A Multidisciplinary Research Agenda*	IoT; urban design; policy adaptation; autonomous vehicles	Proposes multidisciplinary approaches using IoT, urban design, and autonomous vehicle integration for improved cycling safety.	IoT sensors, cooperative safety systems, behavioral studies	Autonomous vehicle integration, risk-taking behaviors	Focus on integrating IoT and autonomous systems with cycling safety, and conduct behavioral research to address risk-taking behaviors and enhance policy frameworks.
5	*Incorporating Abstract Spatio-Temporal Shapes into a Semantic City Model for Urban Cycling - First Ideas on Design and Application*	Semantic modeling; visibility; infrastructure safety; data mining	Proposes semantic modeling to enrich urban cycling safety using data-driven simulations and visibility analysis.	Microsimulations, spatial modeling	Visibility constraints, insufficient infrastructure design data	Develop semantic models and microsimulations to optimize urban cycling safety infrastructure, incorporating visibility and sensor-based insights.
6	*Non-destructive testing and inspection methods for bicycles in service: toward enhanced safety*	Durability testing; bicycle components; non-destructive methods	Advocates for non-destructive testing to assess bicycles' condition and prevent accidents due to product deterioration.	Non-destructive testing methods, strength test linkage	Lack of regular testing, aging bicycles	Establish regular non-destructive testing standards for bicycles, linking results to lifespan estimations to reduce accident risks due to mechanical failures.
7	*Future cycling infrastructure and autonomous systems: meeting the needs of diverse bicycle types and populations*	Infrastructure; autonomous systems; senior-friendly bicycles	Addresses infrastructure needs for diverse bicycle types and autonomous systems, focusing on safety and inclusivity.	Sensor technology development, safety optimization	Diverse user needs, climate resilience	Invest in inclusive infrastructure that accommodates diverse bicycle types, autonomous systems, and climate resilience. Enhance sensor technologies for safety.
8	*Advancements and standardization in bicycle brake testing: addressing durability and performance for electrically assisted cycles*	Brake standards; EPACs; safety tech; ABS	Discusses standards and advancements in brake systems, emphasizing the safety of electrically assisted bicycles.	Durability testing, standardization research	Brake performance in adverse conditions	Develop and standardize advanced braking systems, including ABS for electrically assisted bicycles, to enhance safety in diverse conditions.
9	*The Last Ride: Vision Zero's Struggle with Human-Powered Bicycles in an Automated World*	Vision Zero; human agency; automated vehicles; policy tensions	Critiques Vision Zero's rigidity in balancing technological automation and human autonomy in cycling safety.	Policy analysis, advocacy discourse	Tension between safety and freedom, societal resistance	Explore inclusive policies that balance Vision Zero goals with preserving the autonomy and health benefits of cycling.
10	*Bicycle traffic control innovations at intersections: adapting for safety in Japan and beyond*	Intersection safety; traffic control; signal optimization; legal frameworks	Investigates traffic signal optimization and its role in reducing intersection accidents for cyclists.	Traffic simulation, international comparison	Non-compliance with signals, evolving traffic light designs	Optimize traffic signal systems for cyclist safety, integrating automated vehicle interactions and context-specific legal frameworks.
11	*Cycling as a social movement: balancing freedom, safety, and environmental sustainability*	Freedom; minimalism; environmental sustainability; policy gaps	Examines the cultural aspects of cycling, focusing on freedom, environmentalism, and minimalist infrastructure needs.	Policy critique, cultural analysis	Over-restrictive infrastructure regulations	Focus on minimalist infrastructure solutions and cultural shifts to promote cycling as a form of self-expression and environmental stewardship.
12	*Standardization for safe bicycle use: toward mandatory education and clear regulations*	User safety education; legal frameworks; autonomous cycling	Explores the need for user education, standardization, and awareness of traffic laws for safer cycling.	Standardization development, educational program design	User ignorance, lack of consistent safety education	Develop educational programs and legal frameworks that ensure safe and informed bicycle usage while addressing new forms of mobility (e.g., mopeds).
13	*Exploring Multidimensional Challenges and Forward-Thinking Approaches in Cycling Safety Research*	Smart wearables; e-bikes; urban sustainability; safety regulations	Examines smart wearables and e-bikes, addressing safety concerns, regulations, and urban mobility integration.	Technological assessment, regulatory framework	Cognitive distractions, inconsistent regulations	Regulate and design technologies that prioritize safety and sustainability, minimizing cognitive distractions and integrating e-bikes into urban transport systems.
14	*Integrating Ambient Intelligence and Social Systems for Universal Safe Cycling: A Vision for 2044*	AI; predictive safety; aging population; smart cycling communities	Envisions predictive safety paradigms using AI and community-driven networks for future cycling environments.	AI-driven infrastructure, ethical frameworks	Privacy concerns, ethical AI implementation	Focus on predictive safety systems, aging-friendly designs, and ethical considerations for integrating ambient intelligence into cycling environments.

(*continued on next page*)

Table 1 (*continued*)

No.	Abstract Title	Keywords	Description	Methods	Challenges and constraints	Implications for Future Cycling Safety Research
15	*All roads lead to Rome (and Rome remains user-based safety): our potential 2044 directions in cycling safety research*	User focus; behavior ergonomics; gradual evolution	Emphasizes the enduring role of user behavior in ensuring cycling safety and gradual adoption of technology.	Behavioral ergonomics research, longitudinal analysis	Income-related gaps, equitable tech access	Prioritize behavioral ergonomics and iterative advancements in safety technologies, while ensuring equitable access to safety-enhancing features.
16	*Conflict models to predict the risks and benefits of cycling and automated driving co-existence.*	Conflict prediction; cyclist behavior; simulation modeling	Investigates cyclist and automated vehicle interactions through conflict prediction and modeling.	Sub-microscopic traffic simulations, conflict analysis	Insufficient cyclist representation in models	Develop robust simulation models to predict and mitigate conflicts between automated vehicles and cyclists in mixed traffic environments.
17	*How to Implement the E-Bike City?*	E-bike cities; micromobility; environmental impact; infrastructure gaps	Advocates for transitioning urban spaces toward active mode-friendly infrastructure and policies, emphasizing environmental benefits while maintaining accessibility for everyone.	Micromobility data collection, user-focused studies	Technological pitfalls, privacy concerns in sensor data	Promote infrastructure and policies for active modes and micromobility integration, balancing sustainability and user needs while addressing technological and data-privacy challenges.

infrastructure must work "*with the imperative of safety, ensuring a sustainable and efficient cycling infrastructure for all*". Key challenges included improving infrastructure-user connectivity, reducing cyclist risks, enhancing urban resilience, and leveraging technological advancements to optimize safety.

Regarding practical issues, a fundamental challenge in transitioning to sustainable mobility is reallocating space from motorized modes –often polluting and unsafe– to active transport, particularly cycling. The concept of an '*E*-Bike City' (see Abstract 17) exemplifies the need for systemic changes in urban space distribution, prioritizing cycling and micromobility over private car use. While research can refine implementation strategies, the core principle remains clear: cities must rapidly adopt policies and infrastructure that support active mobility by redistributing road space, ensuring safe, accessible, and efficient environments for cyclists.

The human and societal dimensions of cycling safety also emerged as a central theme, with 43% of abstracts (6 out of 17) addressing cultural attitudes, behavioral ergonomics, and social dynamics. Notably, "*Cycling as a Social Movement*" (Abstract 11), which won the best abstract distinction, emphasized the crucial role of human behavior and collective action in shaping cycling environments. It highlighted the interplay between cycling, social justice, and equity, advocating for a balance between technological and infrastructural advancements and human-centered considerations. This abstract also addressed contemporary shifts in cycling motivation, suggesting that as societies move toward "*an era of VR, surveillance, and self-driving vehicles, cycling may become more attractive to people seeking freedom, self-expression, and environmental action*".

Other abstracts explored user-related concerns, including demographic trends, social change, and the acceptance of politically endorsed technological and safety frameworks. For example, Abstract 9 cautioned against excessive reliance on automation, noting that "*many cyclists and citizens resist these measures, viewing cycling as a vital form of exercise, recreation, and personal freedom that cannot be replaced by automation*". Other abstracts examined the dynamic nature of cycling patterns, exploring how extreme events influence riding behavior (see Abstract 7) and how demographic evolution will create diverse needs, risks, and opportunities in future cycling safety research (see Abstract 15).

Finally, 33% of the abstracts focused on addressing gaps in data collection and methodological approaches. These contributions proposed innovative methods such as non-destructive testing for bicycles, conflict modeling between cyclists and automated vehicles, and AI-driven data analytics. Many of these abstracts emphasized the importance of strengthening the empirical foundations of cycling safety research. Specifically, they called for the development of advanced simulation models, improved sensor-based detection systems, and refined risk assessment frameworks to enhance policy and infrastructure planning. While coming from diverse fields such as social sciences, public health, and engineering, they share a common goal: integrating multiple disciplinary perspectives to develop comprehensive research methods and practices, aiming to generate more reliable data and actionable insights to guide future interventions.

4.2. Challenges and opportunities in the future of bicycle road safety research

In general terms, the workshop discussions identified a set of key factors shaping cycling safety, categorized into five domains (See Fig. 5): society, policy, infrastructure, vehicles, and users. There are both headwinds and tailwinds in these areas: alongside issues such as anti-bike sentiment or uneven data, participants also noted growing public support, recent policy commitments, and investment in protected networks and safer designs.

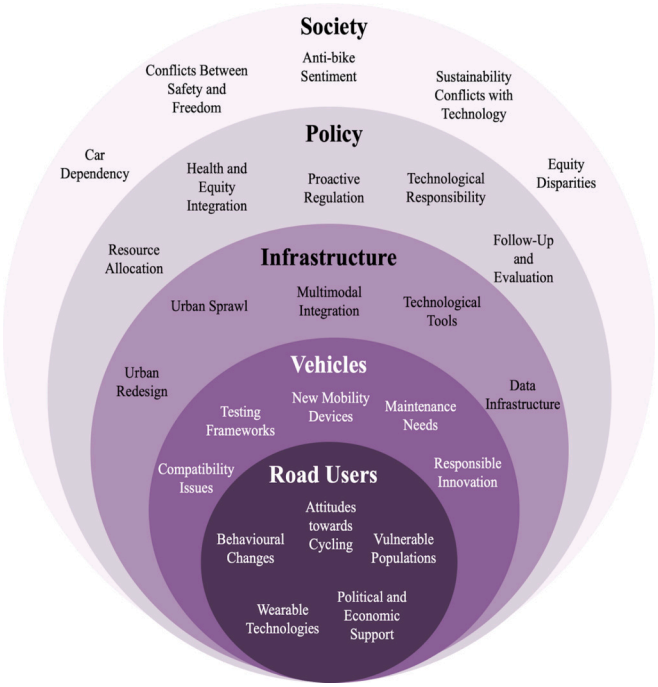

Fig. 5. Summary of key factors identified in the workshop.

To keep the analysis grounded, insights from the verbal discussions were triangulated with the pre-workshop speculative abstracts and the written outputs (e.g., color-coded post-its), allowing us to check emphases and retain differences where they existed. This multi-source synthesis reflects the interdependence of factors affecting cycling safety and shows that each domain presents barriers and levers for strategic action. The following subsections summarize the challenges and opportunities raised by participants, noting contextual differences where relevant.

4.2.1. Society

The societal dimension of cycling safety reflects entrenched cultural norms, value trade-offs, and systemic inequities that shape transportation systems. Participating experts uniformly anticipated that cycling –and its social relevance– will continue to grow worldwide over the next 20 years. A first issue highlighted in the workshop was car dependency and its social expectations. Cars are often treated as a default feature of modern life, which limits the ability to envision futures where active mobility becomes the norm. During the discussion of fictional abstracts, participants noted with some surprise that none of the authors explored a transport system without cars. While interest in car-related harms and safety impacts is growing [34], this omission highlights the depth of car reliance in prevailing imaginaries. By contrast, bicycles appeared consistently in participants' envisioned futures, pointing to their role in sustainable and more equitable transport.

Participants discussed how prevailing social attitudes toward risk and mobility continue to shape cycling safety outcomes. Several referred to what they termed a culture of "safetyism" to describe risk framings that portray cycling as inherently hazardous and that, in their view, shift responsibility for protection from systems to individual riders (see Abstract 11). They noted that such framings may discourage cycling uptake under certain conditions, potentially weakening the well-known "safety-in-numbers" effect, whereby higher participation correlates with lower per-cyclist crash risk. They also observed that these dynamics may exacerbate inequities when compliance with protective requirements (e.g., helmets, insurance, or visibility gear) places disproportionate burdens on lower-income users. Taken together, these observations align with evidence that strongly individualized safety narratives and restrictive policy measures can, in some contexts, reduce participation and thereby alter overall safety and health outcomes [32,33].

Within this broader context, participants reflected on recurring value tensions regarding how safety goals are pursued relative to mobility, personal freedom, and wider societal priorities. Vision Zero emerged in several speculative abstracts and subsequent discussions as a reference point for exploring these tensions. During the workshop, the abstract notion of "safety-at-all-costs" was used as a heuristic to prompt debate about potential extremes in safety governance, rather than as a position attributed to mainstream road safety frameworks. Participants emphasized that neither Vision Zero nor the Safe System approach is premised on restricting mobility; both rest on an ethical commitment to minimize, and where possible eliminate, fatalities and serious injuries while enabling everyday travel. Accordingly, the discussion centered on how different implementation pathways balance harm reduction with accessibility, usability, and equity in practice.

This debate also brought forward multiple ethical perspectives, such as sustainability, distributive justice, and the dignity of risk, which inform transport governance in pluralistic societies. Participants stressed that effective harm reduction should prioritize systemic interventions at the source of danger (including speed management, junction protection, forgiving infrastructure, and safer heavy-vehicle operations), rather than shifting responsibility onto cyclists. Several participants pointed to the Safe System approach as a unifying framework capable of operationalizing these principles, while also noting that technology-centric safety solutions, although promising, must be assessed critically for resource demands, accessibility, and potential distributional inequities.

In parallel with these value debates, participants also addressed the persistence of anti-bike sentiment and aggression toward cyclists, particularly in car-dominated environments. In such contexts, cyclists are often perceived as obstacles or nuisances, leading to behaviors such as close-passing, verbal harassment, and deliberate intimidation [34]. These hostilities were interpreted as manifestations of deeper cultural norms that privilege motorized travel and speed over equity and coexistence in public space. Participants noted that addressing these attitudes requires more than technical countermeasures; genuine progress in cycling safety depends on broader cultural change that repositions cycling as a legitimate, respected, and desirable mode of everyday transport.

Equity concerns were another central thread. Cross-country disparities in infrastructure and safety policy create uneven risks, often to the disadvantage of lower-resourced settings. There is a lack of studies in jurisdictions with the highest mortality rates, such as low- and middle-income countries (LMICs) [35]. In these contexts, data scarcity (i.e., limited measurement of exposure and behaviors, underreporting of crashes and near-misses, and restricted access to open, comparable datasets) acts as a major barrier to diagnosis and evaluation [2,36]. Constraints in research infrastructure and technological capacity compound the problem, an issue echoed in Abstract 15: "*Will the access to these 'safety increasing' features be still determined by income-related gaps?*". At a practical level, these gaps call for cautious interpretation of existing evidence and point to the need to invest in basic data systems alongside interventions.

Within societies, behavioral and exposure differences also shape cycling safety and deserve explicit attention [37]. Participants emphasized that vulnerable groups –including older adults, children, and individuals with disabilities– often face compounded challenges arising from physical, perceptual, and infrastructural barriers. These differences highlight the need for targeted research and inclusive design interventions. For aging populations in particular, participants recommended practical adjustments such as smoother pavement, improved lighting, and more accessible bike parking to sustain safe participation. These points resonate with speculative Abstracts 1, 14, and 15, which highlighted the importance of designing for "aging societ[ies], where cycling remains an essential form of mobility and recreation" (Abstract

14).

4.2.2. Policy

Policy plays a critical role in shaping the safety and inclusivity of transportation systems, yet current frameworks often perpetuate systemic inequities. Participants noted that transport policies tend to prioritize motorized vehicles, allocating substantial resources to car-specific infrastructure such as highways and urban parking facilities [37], or to over-rely on visionary commitments that are difficult to translate into practice ("*Zero accidentality will probably still be a work in progress*"; Abstract 1). In contrast, cycling infrastructure –while essential– is often underfunded, resulting in fragmented or unsafe cycling networks ("*It would be beneficial for policymakers to consider increasing investment in cycling and the associated infrastructure*"; Abstract 7). This imbalance discourages cycling and increases safety risks. Future research should focus on quantifying the long-term societal costs of car-centric policies, investigating effective policy instruments that can rebalance investment priorities, and developing tools to measure the real impact of policy commitments on cycling safety.

Moreover, the workshop discussions stressed the need for transport policy to adopt a more integrated approach that aligns with public health, sustainability, and equity goals. Transport systems have major public-health impacts – positive (through active mobility) and negative (via air pollution and road trauma) [34,38]. Yet policies rarely account for these broader effects. To address these gaps, participants consistently highlighted the need for research to develop empirically grounded, context-sensitive frameworks to evaluate the indirect public-health benefits of cycling infrastructure; to examine how transport policies can be integrated with climate and health objectives; and to analyze case studies of effective cross-sector collaboration in policymaking.

Participants also emphasized the need for agile, adaptive policy frameworks that can respond to rapid technological change. Connected and automated vehicles (CAVs), for instance, are reshaping mobility, and their adoption has often outpaced the development of corresponding regulations. This normative lag creates safety vulnerabilities for cyclists, as interactions between traditional road users and automated systems remain unpredictable. Recent studies suggest that, despite advances in automation, the burden of ensuring safety often remains with vulnerable road users, such as cyclists and pedestrians [16]. CAV systems may still rely on their caution and adaptability –particularly in complex or low-visibility conditions– leaving these users exposed to residual crash risks [15,39]. Further work is needed to measure these safety gaps, develop cyclist-inclusive automation standards, and align emerging CAV policies with the protection of vulnerable road users.

The discussions also highlighted the dangers of *technopositivism* – the over-reliance on technology as a universal solution. While innovations like CAVs and smart traffic systems offer significant potential, they often overlook the human-centered and context-specific challenges of transportation [15]. This approach risks exacerbating inequities, particularly for marginalized populations who may lack access to advanced technologies or live in areas where these solutions are impractical. For example, rural communities and low-income urban neighborhoods may struggle to adopt high-tech solutions due to cost or infrastructure limitations. Research should investigate the unintended consequences of transport technology adoption, evaluate accessibility barriers to emerging mobility solutions, and propose regulatory frameworks that ensure new technologies serve all populations equitably [2,40].

Participants advocated for policies that prioritize human-centered, context-sensitive solutions. Rather than relying solely on technology, transport policies should prioritize innovations that promote sustainability and inclusivity. This requires collaboration across sectors –transport, public health, urban planning, and technology development– to ensure that policies address the diverse needs of all road users. However, for such collaboration to be effective, knowledge gaps must first be addressed. Finally, workshop participants emphasized stronger coordination across sectors and levels of government, and policymaking that reflects real user experience. Building on these insights, future research should develop methods to systematically embed user perspectives in policy design, implementation, and evaluation; examine mechanisms to align governance structures and data-sharing practices; and produce evidence-based guidance for policymakers working at the intersection of safety, equity, and emerging technology.

4.2.3. Infrastructure

Infrastructure is the backbone of cycling safety, with strong potential to reduce risk and support active mobility. Participants emphasized urban redesigns that prioritize cyclist safety and create equitable space for all users. Examples such as Amsterdam and Copenhagen illustrate how comprehensive cycling networks, integrated with broader urban planning, can make cycling safer, more accessible, and more viable. These cases support the view that design improvements reduce conflicts with motorized traffic and help foster a sustained culture of active mobility [41,42]. However, participants warned that without substantial changes, current inequities may persist [43], reproducing today's vulnerabilities. Innovation in design and management was therefore framed as a necessary step. Participants called for a shift beyond traditional painted lanes, favoring creative, connected facilities that reduce risk and improve continuity.

Urban sprawl was identified as a barrier to cycling networks, as it often favors car travel and complicates implementation. Participants pointed to the need for infrastructure that adapts to changing travel patterns shaped by energy costs, climate action, and population growth. Compact-city models with integrated bicycle hubs were highlighted as a means to reduce car dependency and promote active mobility. According to participants, such hubs can offer secure parking and seamless connections to public transport, thereby improving accessibility for a wide range of users. Similarly, the workshop also stressed the need for moving beyond isolated bike lanes to create continuous infrastructure that integrates cycling with public transit and walking, enabling smooth transitions between modes of transport that may increase its perceived attractiveness, convenience, potential multi-modal commuting shifts, and daily life integration.

Data –reliable, comparable, and decision-useful– was also a central focus of the workshop, and the discussion exposed clear gaps. In line with Abstract 3 ("*the collection of accurate data on cyclist behavior*") and Abstract 17 ("*more data is needed to support the transition*"), participants noted that the absence of reliable, open, and context-rich datasets limits evaluation and policy design, particularly for infrastructure planning. Overall, the workshop findings in this regard converge on a clear priority: accurate behavior data is the precondition for credible evaluation, monitoring, and targeting of cycling safety measures. In this view, the sentiment of Abstract 3 remains a critical and consequential theme for the next phase of cycling safety research and practice.

Despite growing attention to cycling data, many existing datasets remain incomplete or inconsistently structured, limiting their usefulness for analysis and real-world application. Gaps are wider for new technologies and emerging vehicle types, leaving decision-makers without timely evidence on specific risks and opportunities. In response, participants called for more robust, standardized frameworks for collection and sharing, emphasizing openness and accessibility to support collaboration across disciplines and stakeholders. In addition, integrating cycling-specific data within broader transportation systems was viewed as necessary to enable multimodal planning that addresses cyclists' needs in practice, especially in LMICs where scarcity is most acute [2].

In parallel with stronger data frameworks, discussions considered the potential of emerging analytical resources to support design and evaluation. Simulation software, digital twins, and semantic modeling were stressed as suitable tools to test and refine layouts with the aim of improving safety and efficiency for cyclists; for example, digital twins can simulate traffic and assess interventions in controlled environments, while semantic models help structure and analyze complex networks. Notably, these tools become more informative as underlying datasets

improve, creating a feedback loop between data quality and design evaluation.

Regarding immersive technologies, participants pointed to the growing research use of Virtual Reality (VR) and Augmented Reality (AR) to study cyclist behavior and infrastructure performance. These tools allow low-risk experiments where variables such as surface conditions, traffic density, and user interactions can be systematically varied. In particular, VR has been used to examine how cyclists perceive and react to different environments, while AR can overlay real-time safety-relevant information onto physical spaces. At a practical level, these methods help prototype designs before field deployment and can complement naturalistic data when safety or feasibility is an issue.

Moreover, Abstract 3 highlights that VR and AR are "*increasingly applied to study cyclist behavior*", helping to address data gaps by offering high experimental control, lower risk, improved accuracy in behavioral data collection, and flexible testing of design variants. In turn, when paired with better data-sharing systems and integrated analytics, these tools can support closer alignment between infrastructure, policy, and safety goals. Further work should assess how they scale to policy processes, ensure sound data governance and ethics, and inform real-world planning.

4.2.4. Vehicles

In this section, *vehicles* refers to both motor vehicles and bicycles; where points apply to only one of these, we state it explicitly. The future of vehicles –motorized and non-motorized– will shape cycling safety and transport dynamics. Participants highlighted the pace of automation and connectivity, from automated cars (in 20 years, roads may be "dominated by self-driving vehicles"; Abstract 9) to connected bicycles. These developments hold promise for safety and efficiency but also raise compatibility and equity questions. For example, several participants noted that conventional bicycles risk being marginalized in systems designed primarily around smart, connected platforms, which could amplify inequities and exclude some users.

The growing complexity of vehicles –including bicycles– introduces significant safety challenges as advanced technologies become integral to their operation. Workshop participants expressed concerns over issues such as brake system maintenance and the adequacy of current testing and regulatory frameworks. For example, existing safety protocols may not fully address the interactions between cyclists and automated vehicles in mixed-use environments, where accurately detecting and responding to cyclists remains a critical challenge [44].

Workshop discussions and recent literature, such as the work by Sharif et al. [45] stress the need for proactive, forward-thinking safety evaluation systems to address emerging risks from technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain. While these innovations offer groundbreaking solutions, they also create vulnerabilities related to continuous updates, resource management, and potential operational failures. These challenges are similar to those seen in transport systems, where the increasing complexity of vehicle technologies heightens the likelihood of system faults. As forecasted changes –such as alterations in traffic light control methods noted in Abstract 10– come into view, comprehensive strategies are needed to support safety, functionality, and resilience in increasingly interconnected mobility systems.

Beyond motor-vehicle measures, participants emphasized bicycle-centric safety. Priorities included braking performance (e.g., wet-weather stopping distance, and resistance to brake fade) and assessment of whether ABS on EPACs can reduce loss-of-control events; component and design standards validated under adverse conditions and in real-world trials; visibility and conspicuity (lighting performance, reflectivity, placement); and e-bike system integrity (battery/thermal safety, power–speed compliance, and tamper resistance). Stability and handling for cargo bikes and child-carrying configurations (geometry, load distribution, trailer coupling) were cited as areas where laboratory protocols should be linked to field testing. Participants also called for standardized, non-destructive testing and lifecycle-based inspection protocols, and for linking component-failure data with crash and hospital records to inform evidence-based standards. These measures were framed as complements –not substitutes– to motor-vehicle actions (e.g., safer heavy-vehicle operations) and to infrastructure design.

Another key concern is the emergence of new types of road users as vehicles evolve. Micromobility devices such as e-scooters and novel hybrid vehicles are already changing traffic systems, and additional types of road users may appear in the future. This evolving diversity necessitates robust tools and frameworks to assess their behaviors, risks, and interactions with established users like cyclists. Participants proposed predictive modeling and adaptive regulatory strategies to anticipate and manage mixed-fleet conditions, and stressed the need to align these measures with existing infrastructure so that new and traditional users can operate safely in the same space.

Finally, participants discussed responsible innovation in vehicle design. By consensus, they recommended adopting a Responsible Innovation (RI) framework to guide industry and public stakeholders in the development and evaluation of safety technologies (e.g., advanced braking systems, smart helmets, AI-driven collision avoidance). The RI approach calls for designing with societal needs, safety, equity, and environmental sustainability in view; engaging diverse users early; conducting rigorous testing; and anticipating unintended effects before wide deployment. Applied to both motor-vehicle and bicycle technologies, this approach can address critical safety and equity concerns while building public trust as vehicle systems continue to evolve.

4.2.5. Road users

Road users are a dynamic and integral component of cycling safety, representing a key element in shaping the future research agenda, and this was consistently highlighted in both group discussions and pre-workshop abstracts. Cycling, as an inherently human-centered activity, resists full automation, making the behavior, attitudes, and interactions of users central to any discussion of road safety.

Participants emphasized that the adoption of new safety technologies is likely to drive changes in user behavior, some of which could introduce unforeseen risks. For instance, users may develop over-reliance on collision-avoidance systems or other automated features, leading to complacency and reduced vigilance. Misuse or exploitation of these systems –for example, by intentionally testing the limits of automated responses– was also flagged as a potential risk, highlighting the need for ongoing behavioral research to anticipate and mitigate such challenges. Accordingly, written information sources such as the workshop Abstract 15 highlighted the relevance of public trust and responsible technological usage ("*another intriguing implication is that people will probably increasingly rely on technology, posing the need to advance research on its positive issues, especially to avoid seeing it as a threat*").

Moreover, psychosocial matters, especially individual behaviors and attitudes toward cycling, were mentioned as other key factors in shaping road safety and active mobility uptake. In many jurisdictions, hostility and aggression toward cyclists create unsafe environments, driven by misperceptions of cyclists as obstacles or frustrations about sharing road space. Participants highlighted how these behaviors discourage individuals from cycling, reducing safety and undermining larger societal efforts to normalize active mobility. A recurring discussion was the role of perceived inconvenience or lack of safety in deterring people from choosing bicycles as a mode of transport. For example, potential cyclists may avoid riding due to fears of crashes, inadequate infrastructure, or concerns about interactions with motorists. Addressing these behaviors requires interventions that target individual decision-making and behavioral patterns, fostering a sense of shared responsibility among all road users.

To influence individual behaviors, participants stressed the importance of awareness-building initiatives and targeted education programs, as well as looking at "*how cycling safety issues might differ for those*

riding for feelings of freedom and self-expression" (Abstract 11). Examples include campaigns that highlight the personal and societal benefits of cycling –such as improved health, reduced traffic congestion, and environmental sustainability– as well as training programs designed to improve interactions between drivers and cyclists. These efforts could also leverage the "safety-in-numbers" effect, where a higher presence of cyclists on the road correlates with fewer risks per individual. Research into behavioral economics and psychology was identified as a promising avenue to explore strategies that motivate people to cycle more, such as financial incentives, gamified cycling programs, or community engagement activities, which could help establish cycling as a safer, more accessible, and attractive choice for individuals.

The needs of vulnerable populations were also identified as a critical area for research and innovation. Older adults, people with disabilities, and others with unique challenges in cycling safety require tailored solutions to ensure inclusivity, both in the present and future ("*in 20 years, improving cycling safety will likely remain critical, especially given the continued challenges of road safety for cyclists and other vulnerable road users*"; Abstract 1). Regarding users' future technological trends, wearables such as smart helmets or connected devices were noted as promising developments, as they could provide personalized safety alerts, helping these individuals navigate urban environments more confidently.

While still limited, these technologies represent a significant opportunity to enhance connectivity between users and broader safety systems, fostering a more integrated and equitable transport ecosystem. Furthermore, participants emphasized that research should not only focus on technological interventions but also explore how to address the barriers faced by these groups, such as inaccessible infrastructure or discriminatory road-use practices.

Additionally, the workshop highlighted socially driven changes and the challenges faced by people who work on the road by bicycle, such as delivery riders. These cyclists contend not only with the inherent vulnerability of riding in traffic but also with job-related demands (including tight schedules and heavy loads) that can exacerbate safety risks [26]. According to Abstract 13, addressing the needs of these groups requires a holistic approach that considers both their occupational demands and the broader cycling safety ecosystem, as well as legal frameworks still under development across several domains, some of which "*will likely focus on standardizing specifications, enhancing safety protocols, and promoting sustainability*".

Finally, participants stressed the need to anticipate the emergence of new road users, such as individuals using innovative forms of personal mobility devices (e.g., e-scooters) or new autonomous vehicles, whose behaviors and interactions with cyclists remain underexplored. Proactive tools and methodologies to study these emerging interactions, as well as adaptive frameworks for rapidly incorporating findings into policy and practice, will be critical. Alongside this, calls were made for a greater emphasis on RI frameworks that hold industries accountable for the safety implications of their products. For example, vehicle manufacturers and tech companies involved in automated and connected systems should prioritize cyclist safety in their designs and collaborate with researchers and policymakers to ensure responsible deployment, an action possibly allowing industries to play an active role in creating safer, more user-friendly and equitable transportation ecosystems.

4.3. Research agenda

Building on the key factors identified earlier, the next phase of the workshop asked participants to design targeted studies that address challenges and opportunities across the five domains: society, policy, infrastructure, vehicles, and users. The aim was to translate those dimensions into actionable research themes while avoiding paths that would reproduce current problems. Through collaborative discussion, the group assembled an agenda that balances near-term priorities with longer-term studies, keeping both practicality and foresight in view.

The resulting agenda integrates three overarching concerns: technological advancements, infrastructure improvements, and human-centered approaches. Behavioral and societal research was a central focus, especially on how to make cycling safe and attractive for all and how to bring perceived and objective safety closer together. In parallel, the agenda highlights emerging technologies, including AI-enabled safety tools and predictive risk modeling for vehicle interactions, to strengthen protection for cyclists, support network design, and anticipate conflicts among road users.

Infrastructure priorities were likewise central. Participants emphasized the development of international standards for bicycle-infrastructure safety and the redesign of urban space to create cycling-friendly cities. This includes rethinking spatial allocation with a view to shifting space from motorized traffic toward active modes. Addressing infrastructure gaps was framed as both a technical and a policy challenge, requiring coordinated action across sectors.

Data availability and methodological capacity were highlighted as core enablers of evidence-based decisions. The agenda calls for stronger data-collection frameworks, including behavior, exposure, and near-miss systems, and for the use of AI and IoT monitoring where appropriate. It also prioritizes work on ethics and privacy in mobility data so that digital tools are implemented responsibly and maintain user trust. Particular attention is given to uneven data in low- and middle-income settings, where comparability and openness remain limited.

Within this broader program, participants discussed how prevailing social attitudes toward risk and mobility continue to shape cycling safety outcomes. Several referred to what they termed a culture of "safetyism" to describe risk framings that portray cycling as inherently hazardous and that, in their view, shift responsibility for protection from systems to individual riders. They noted that such framings may discourage cycling uptake in some contexts, which could weaken the "safety-in-numbers" effect and exacerbate inequities when compliance requirements place disproportionate burdens on lower-income users. In this agenda, the role of research is to examine these dynamics empirically rather than to take a position: measure impacts on participation and crash risk, test communication and implementation approaches that avoid burden-shifting and evaluate distributional effects.

Related to this discussion, participants reflected on value tensions concerning how safety goals are pursued relative to mobility, personal freedom, and wider societal priorities. Vision Zero appeared as a reference point for exploring these tensions, while the Safe System was discussed as the operational frame used in practice. Participants emphasized that neither framework is about restricting mobility. Both are grounded in the ethical commitment to minimize, and where possible eliminate, fatalities and serious injuries while enabling everyday travel. Accordingly, the debate centered on how implementation pathways balance harm reduction with accessibility, usability, and equity. For the research agenda, the task is to produce decision-ready evidence on impacts, to compare options that reduce harm at the source without discouraging routine use, and to assess distributional consequences across settings.

Equity remains a cross-cutting priority. The agenda includes studies on socioeconomic disparities in access and safety, with attention to low- and middle-income contexts. Research on cost-effective infrastructure solutions, scalable policy frameworks, and inclusive technology development is needed so that cycling remains a viable option across diverse populations and street environments.

To bridge speculative and actionable work, the agenda incorporates methodological innovations. Extended Reality can support behavior and safety studies under controlled conditions, allowing tests that are difficult or risky to perform in the field, from complex junction layouts to future street configurations. Non-destructive testing and real-world trials for bicycle safety technologies are also encouraged to advance standardization for emerging micromobility solutions. For vehicle-side measures, participants noted the value of linking component-failure information with crash and hospital records to inform evidence-based

Table 2
Proposed research agenda.

#	Research Focus	Problem	Methods Suggested	Rationale	Priority
Domain: Society					
1	Making Cycling Attractive for All	Lack of understanding about societal barriers and incentives for cycling adoption.	Behavioral research, participatory methods, and AI-based analyses	Enhances equity and accessibility while supporting active mobility goals.	High
2	Addressing Socioeconomic Inequities in Cycling Safety	Marginalized communities face greater barriers to safe cycling environments.	Equity-focused policy modeling, stakeholder engagement	Promotes inclusivity and addresses disparities in cycling infrastructure and safety measures.	High
Domain: Policy					
3	Balancing Safety and Freedom in Policy	Safety-focused policies, like Vision Zero, may inadvertently restrict freedoms and reduce cycling's appeal.	Policy discourse analysis, participatory policymaking	Encourages a balanced approach that safeguards cyclists without sacrificing mobility autonomy.	Medium
4	Ethical and Privacy Issues in Cycling Data Usage	Emerging technologies pose privacy risks and ethical dilemmas, particularly in sensitive mobility data collection and usage.	Ethical frameworks, blockchain for data security	Safeguards user privacy while enabling critical research and policy applications.	Medium
5	Transitioning Developing Nations to Sustainable Mobility	Limited resources and systemic barriers prevent leapfrogging directly to active mobility systems.	Pilot studies, cost-benefit analyses, and policy modeling	Enables sustainable and equitable mobility transitions while avoiding car-centric development pathways.	High
Domain: Infrastructure					
6	Developing Standards for Bicycle Infrastructure Safety	Fragmented and insufficient infrastructure that fails to address diverse user needs and safety requirements.	International workshops, participatory urban design methods	Establishes global standards and fosters collaboration among stakeholders to enhance safety infrastructure.	High
7	Exploring Synergies in Multimodality	Disjointed connections between cycling and other transport modes reduce overall mobility efficiency.	Multimodal transport simulations, urban planning frameworks	Improves transport system integration, benefiting diverse users and reducing car dependency.	Medium
8	Enhanced Data Collection for Cycling Safety	Lack of robust, reliable, and privacy-preserving data on cyclist behavior and infrastructure performance.	AI and IoT-based data collection, smartphone tracking	Provides evidence-based insights to inform policy, planning, and technology development.	Medium
9	Urban Redesigns for Compact, Cycling-Friendly Cities	Sprawling urban designs favor cars and make cycling networks difficult to implement. Space must be reallocated in dense urban areas to build safe infrastructure.	Participatory urban design, infrastructure cost-benefit analyses	Encourages active mobility while addressing spatial and resource constraints.	High
Domain: Vehicles					
10	Risk Prediction for Emerging Vehicle Interactions	Limited understanding of risks posed by automated vehicles and other emerging mobility technologies to cyclists.	Conflict modeling, sub-microscopic traffic simulations	Anticipates and mitigates risks in mixed mobility environments.	High
11	Testing and Standardizing Bicycle Safety Technologies	Inconsistent and inadequate evaluation of new bicycle technologies like smart wearables and advanced braking systems.	Non-destructive testing, real-world trials	Ensures the safety and reliability of emerging technologies in varied contexts.	Medium
12	AI-Driven Safety Solutions for Cyclists	Current AI systems inadequately detect and accommodate cyclists, creating safety risks.	Simulation studies, AI testing, and predictive modeling	Promotes safer integration of cyclists into increasingly automated transport ecosystems.	High
Domain: Road Users					
13	Understanding Perceived vs. Objective Safety	Misalignment between perceived safety (e.g., fear of traffic) and objective safety data.	Psychosocial research, focus groups, and big data analytics	Aligns user perceptions with actual safety outcomes to increase cycling adoption and satisfaction.	Medium
14	Psychological and Behavioral Interventions for Cycling Adoption	Limited understanding of psychosocial factors influencing cycling behavior and risk-taking.	Behavioral ergonomics studies, educational campaigns	Encourages safer and more widespread cycling through targeted behavioral interventions.	Medium
15	Leveraging Extended Reality (XR) for Behavior and Safety Studies	Limited ability to study cyclist behavior in high-risk or futuristic scenarios.	XR-based controlled experiments	Provides cost-effective and controlled environments to study cyclist behavior and infrastructure performance under various conditions.	Medium

standards.

The aforementioned prioritization of themes suggests a broad consensus on critical directions. While behavioral research and AI integration were viewed as foundations with influence across multiple areas, the agenda keeps infrastructure, policy, and user-focused studies at its core to deliver a comprehensive and durable approach to cycling safety. It also underlines the need to adapt priorities to diverse contexts so that solutions remain technically sound as well as socially and economically inclusive.

Taken together, the agenda offers a structured roadmap for the coming decades. Beyond academic work, it emphasizes the translation of findings into practice through collaboration with policymakers, industry, and urban planners. Pilot programs, real-world testbeds, and participatory implementation models will be important to ensure that research insights lead to tangible improvements in cycling safety and accessibility. Table 2 presents a condensed overview of the focus areas, the problems they address, the proposed methods, and their rationale, and is intended to guide coordinated action among researchers, practitioners, and decision-makers.

5. Limitations

Although the workshop brought together a broad, multidisciplinary group of experts from several countries and sectors, and used participatory and futures-oriented methods to elicit and prioritize proposals, there are limitations that should be acknowledged.

First, the agenda was developed in a single international workshop with a purposive sample. Although the group was diverse, the resulting priorities reflect the perspectives and experience of those who took part, the centrality of participants' memory throughout the session, and a different expert constellation could reasonably have emphasized other themes [46,47]. Self-selection and professional background may also have influenced which problems showed most urgent.

Second, health and clinical viewpoints were comparatively under-

represented, which may have reduced the weight given to injury biomechanics, trauma care, and rehabilitation. Future iterations should engage these communities more directly so that severity, treatment, and recovery considerations inform priority setting alongside exposure, behavior, and infrastructure.

Third, the agenda is global in outlook, but its application is context sensitive. Institutional capacity, governance arrangements, legal frameworks, crash profiles, and infrastructure maturity vary across regions and will shape feasibility and timelines. In addition, data constraints, particularly in low- and middle-income countries, limit comparability and should be addressed alongside intervention work.

Finally, the speculative methods used here are intended to explore plausible and preferable futures rather than to forecast specific developments. For that reason, proposals should be treated as agenda-setting directions that require empirical testing in pilots and testbeds, standardization where appropriate, and periodic revision as social and technological conditions evolve.

6. Conclusions

This paper presents a forward-looking research agenda for cycling safety, developed through a participatory workshop at the International Cycling Safety Conference (ICSC) 2024. Bringing together multidisciplinary researchers, policymakers, practitioners, and industry representatives, the workshop provided a setting to exchange perspectives, apply speculative methods, and identify priorities that can guide the next steps in cycling safety research.

The findings highlight the need to address systemic social factors such as car dependency, anti-bike sentiment, and inequities in safety, alongside technical challenges including data gaps, infrastructure design, and vehicle integration. Participants also emphasized balancing safety goals with the convenience and appeal of everyday cycling, so that implementation pathways do not unintentionally discourage use.

Key research themes included making cycling safer and more attractive for all, fostering multimodal integration, and leveraging emerging technologies such as AI, wearables, and Extended Reality (XR) for safety studies. The identified priorities reflect the interconnected nature of the societal, policy, infrastructure, vehicle, and user domains, and they point to solutions that require coordinated work across disciplines and sectors.

This agenda advances the field and supports the value of participatory approaches for complex mobility problems. It can be strengthened by engaging a broader and more diverse set of stakeholders than the present workshop could include, and by prioritizing equity, innovation, and collaboration when shaping safer and more sustainable transport systems.

CRediT authorship contribution statement

Oscar Oviedo-Trespalacios: Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft. **Francisco Alonso:** Visualization, Methodology, Investigation, Conceptualization, Writing – original draft. **Heike Bunte:** Validation, Methodology, Investigation, Writing – original draft. **Yan Feng:** Validation, Methodology, Investigation, Writing – original draft. **Angela Francke:** Validation, Methodology, Investigation, Writing – original draft. **Cara J. Hamann:** Validation, Methodology, Investigation, Writing – original draft. **Stephanie Jansson:** Validation, Methodology, Investigation, Writing – original draft. **Andreas Keler:** Validation, Methodology, Investigation, Writing – original draft. **Masato Kitano:** Validation, Methodology, Investigation, Writing – original draft. **Christoph M. Konrad:** Validation, Methodology, Investigation, Writing – original draft. **Michael J. Kuzel:** Validation, Methodology, Investigation, Writing – original draft. **Claudia Leschik:** Validation, Methodology, Investigation, Writing – original draft. **Manfred Neun:** Validation, Methodology, Investigation, Writing – original draft. **Masayoshi Okubo:** Validation, Methodology, Investigation, Writing – original draft. **Elisabeth Rubie:** Validation, Methodology, Investigation, Writing – original draft. **Nicolas Saunier:** Validation, Methodology, Investigation, Writing – original draft. **Ichiro Sugitani:** Validation, Methodology, Investigation, Writing – original draft. **Nur S.A. Sukor:** Validation, Methodology, Investigation, Writing – original draft. **Hayato Tomisu:** Validation, Methodology, Investigation, Writing – original draft. **Axel Thieulin:** Validation, Methodology, Investigation, Writing – original draft. **Divera Twisk:** Validation, Methodology, Investigation, Writing – original draft. **Pathiraja A.S. Udayanga:** Validation, Methodology, Investigation, Writing – original draft. **Teun Uijtdewilligen:** Validation, Methodology, Investigation, Writing – original draft. **Sergio A. Useche:** Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft.

Ethical approval

The thematic proposal, protocol, and guidelines for data collection, custody, and management for this workshop were reviewed and approved by the ethics committee of the Research Institute on Traffic and Road Safety (INTRAS) at the University of Valencia (Spain) prior to submitting it for consideration to the ICSC organizing committee. The procedure number, which received favorable approval from the consulted institutional body, was IRBHE004140524.

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Declaration of competing interest

The authors declare that there are no conflicts of interest or controversies regarding the contents of this paper. The views, interpretations, and conclusions expressed herein do not necessarily reflect those of the institutions where the authors are affiliated or the organizations that provided financial support for their participation in the conference.

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Appendix A. Supplementary data

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