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Research Trends in Road Safety (2013-2023): A Bibliometric Review Using Science Mapping Techniques on Human and Technological Factors

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ABSTRACT

Introduction: Road safety remains a pressing global public health issue, marked by rising rates of traffic-related accidents, injuries, and fatalities. While various interventions have been implemented, there is still limited understanding of how human factors, trust in automated systems, and hazard perception influence safety outcomes in both autonomous and semi-autonomous driving contexts. This study aims to explore research trends and knowledge gaps in road safety using a bibliometric approach, focusing on the intersection between human behavioral factors and emerging intelligent transport technologies.

Methods: This study employs a bibliometric research design to analyze the scholarly literature on road safety and campaign-related studies, covering the period from 2013 to 2023 and using Scopus as the primary database.

Results: By applying science mapping techniques specifically bibliographic coupling and co-word analysis, a total of 581 peer-reviewed journal articles were examined. From these, 114 highly cited publications were identified and grouped into five thematic clusters based on bibliographic coupling and four keywords-based domains from co-words analysis. The results underscore the growing role of Advanced Driver Assistance Systems (ADAS), Connected Intelligent Transport Systems (C-ITS), and artificial intelligence (AI)-based risk prediction in reducing traffic incidents. Key areas of concern include behavioral adaptation, trust in automation, and situational awareness. Recommendations include enhancing regulatory frameworks, reinforcing helmet and speed limit compliance, and incorporating AI-powered predictive models and real-time monitoring systems into urban mobility planning. Additionally, the study emphasizes shifting from traditional media to targeted digital road safety campaigns through social media and mobile applications.

Conclusion: The findings underscore the importance of integrating AI-powered monitoring systems, enforcing data-informed traffic regulations, and implementing targeted behavioral campaigns to reduce accident risks. These strategies should be designed with adaptive models that account for how road users respond to risk and safety interventions. Future research should build interdisciplinary models that merge cognitive psychology, risk perception metrics, and intelligent transport technologies to guide data-driven safety innovations, providing valuable insights for urban planners, policymakers, and traffic safety educators.

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INTRODUCTION

Road safety remains a critical global public health concern, with traffic accidents, injuries, and fatalities continuing to rise worldwide. Recent data estimate that approximately 1.35 million people die each year due to road accidents, with 93% of these deaths occurring in low- and middle-income countries (1,2). This situation calls for strengthened global cooperation among governments, international agencies, and communities (3). Tackling this issue demands the adoption of technology-based solutions supported by evidence-informed public policies. Technological advances such as real-time vehicle-to-infrastructure communication and enhanced driver alert systems have contributed to improved safety (4). In parallel, regulatory measures including mandatory helmet use and speed control enforcement have effectively reduced crash rates (5). Education programs, like those implemented in Iran, further demonstrate the role of public awareness in mitigating road risks.

Various risk factors influence traffic accidents, including unsafe driving behavior, substandard road infrastructure, and inadequate enforcement of regulations. Distractions, speeding, and mobile phone use are frequent causes of accidents,(6–9) while poor signage and environmental hazards worsen conditions (10,11). Studies suggest that a holistic approach combining infrastructure improvements and safety education is effective in addressing these (3,12). Global and regional statistics underline the urgency of reform, especially in countries such as India and Brazil where road deaths are prevalent among youth (3,4). Disparities between urban and rural areas also reveal heightened fatality rates in underserved regions due to weaker infrastructure and policy enforcement (5,6,13).

The introduction of autonomous vehicles (AVs) offers potential to reduce certain crash types, but also introduces challenges regarding human-machine interaction (7,10). Seasonal and environmental variables further compound road safety risks (11). Vulnerable populations such as young drivers, pedestrians, and motorcyclists face elevated risks. These intersections between emerging technologies and persistent human factors highlight the need for integrative methods such as bibliometric analysis, which can track conceptual and empirical developments across time. Risky driving behaviors, infrastructure gaps, and limited awareness continue to endanger these groups (14–17). Targeted educational and behavioral interventions are essential (18).

Despite progress in Advanced Driver Assistance Systems (ADAS) and Connected Intelligent Transport Systems (C-ITS), low user trust and limited understanding hinder their effectiveness (19,20). Furthermore, the disconnection between behavioral insights and technological adoption models constrains their impact (5,21). As such, bibliometric science mapping techniques are uniquely positioned to uncover how these behavioral and technological discourses evolve and overlap in the scholarly literature. Digital campaigns for road safety have yet to show consistent behavioral impact, (22) necessitating more robust and theory-informed messaging strategies (23).

To address these complexities, this study employs bibliometric and science mapping methods to identify influential themes, gaps, and research trajectories in the field (24). Specifically, the article aims to map and synthesize road safety research using bibliometric analysis, providing a structured overview of scholarly developments. This includes the use of bibliographic coupling and co-word analysis to identify thematic convergence and divergence across disciplines. Behavioral and technological data integration provides a clearer understanding of safety determinants and policy needs (5,25).

Furthermore, understanding risky behaviors, such as speeding and mobile phone use, is essential for designing more effective safety policies (6). Improving road safety demands data-driven, adaptive frameworks that incorporate AI-powered risk prediction, behavioral metrics, and proactive policy reform (19).

This review systematically maps road safety research trends using bibliometric tools, with a focus on behavior, technology, and regulatory strategies. By organizing the literature into subthemes-behavioral risk, technological adoption, and policy innovation-the study contributes to improved readability and stakeholder relevance. The study offers practical insights to enhance future interventions, especially for at-risk populations such as young drivers, AV users, and pedestrians.

METHOD

Research Type

Bibliometric Approach

The bibliometric approach is a quantitative method that examines bibliographic databases through science mapping techniques (26). Compared to meta-analysis or systematic reviews, bibliometric analysis allows for the

evaluation of larger datasets and reduces subjectivity by minimizing selection bias (27). Unlike co-citation analysis or keyword burst detection, which emphasize historical influence and temporal spikes, this study prioritizes structural mapping through bibliographic coupling and co-word analysis to capture both thematic continuity and conceptual emergence. It enables comprehensive insight into the structural and intellectual landscape of a specific research domain (28).

Bibliometric analysis comprises two primary components: performance analysis and science mapping (29). The former assesses research contributions based on publication output and citation impact, while the latter explores connections among research elements to understand the structural composition of a field (26,30). This choice was made to identify both intellectual foundations and current thematic trajectories in road safety literature. This study applies bibliographic coupling and co-word analysis to achieve its research objectives, as described below:

Bibliographic coupling – This method investigates contemporary and emerging developments in a research domain (26). It operates on the principle that publications citing the same references are likely to address related topics (31). The strength of this connection, known as bibliographic coupling, offers insight into the ongoing research landscape (32).

Co-word analysis – This method identifies conceptual connections by analyzing co-occurring words within document titles, keywords, or abstracts (28). It assumes that groups of keywords signify thematic structures, with their co-occurrence reflecting conceptual similarities (33). Frequently occurring keywords exert greater influence on a research field than those with low occurrences. By examining these associations, researchers can identify emerging topics and outline future research directions (26).

Research design and data collection procedure

This study employs a bibliometric research design to analyze the scholarly literature on road safety and campaign-related studies. A structured search query was formulated to retrieve relevant publications, using a combination of keywords associated with road safety, traffic safety, driving safety, campaigns, awareness programs, and social marketing. The search was conducted in Scopus, a widely recognized, high-quality academic database known for its extensive coverage of peer-reviewed literature across multiple disciplines. Scopus contains more than 21,100 journals and has been widely utilized for bibliometric analyses due to its comprehensive indexing and metadata accuracy (34,35). The inclusion period for the data spans from 2013 to 2023, and only English-language publications were considered to ensure accessibility and consistency.

The search query employed was: ("road safety" OR "traffic safety" OR "driving safety") AND ("campaign" OR "awareness program" OR "social marketing"). This query was applied to search within titles, abstracts, and keywords, ensuring that only studies explicitly related to road safety campaigns were included. To maintain a focus on high-quality research, only journal articles were considered, as they undergo rigorous peer review. Other document types, such as books, book chapters, conference proceedings, editorials, and reports, were excluded from the dataset. The exclusion rationale was based on the lack of peer review rigor and metadata standardization typically associated with these alternative document types. A total of 581 journal articles were retrieved from the Scopus database based on this search query. These articles were then processed and analyzed using VOSviewer 1.6.20 and Biblioshiny (a Bibliometrix R package) to conduct a science mapping analysis. Table 1 presents the breakdown of the search query, outlining the keywords and their justifications for inclusion in this study.

Table 1. Search String in Scopus Database

No	Keywords	Justification
1	"road safety" OR "traffic safety" OR "driving safety"	Identifies literature related to safety measures, policies, and research on preventing road accidents.
2	"campaign" OR "awareness program" OR "social marketing"	Focuses on public awareness efforts, behavioral change initiatives, and promotional activities designed to improve road safety.

The selected articles were subsequently analyzed to explore publication trends, thematic clusters, co-authorship patterns, and gaps in road safety research.

RESULTS AND DISCUSSION

Bibliographic Coupling

The initial step in this analysis involves determining an appropriate citation threshold to ensure a reliable and accurate network visualization. Among the 581 documents examined, 114 met the threshold of 20 citations, selected after comparative threshold testing to balance representativeness and clarity. Setting the threshold requires careful consideration a value that is too high may exclude relevant clusters, while a value that is too low can result in excessive clustering, leading to redundancy (36,37).

Table 2 displays the top 10 publications ranked by citation count, with the three most-cited works being Huang et al. (2017) with 291 citations, Engelmann (2016) with 216 citations, and Li G (2022) with 165 citations (38–47).

Table 2. Top 10 Publications ranked by citation count

No	Document	Citations	Total Link Strength
1	Huang (2017)	291	1
2	Engelmann (2016)	216	0
3	Li (2022)	165	1
4	Şimşekoğlu (2015)	148	0
5	Yu (2017)	127	0
6	Macqueen (2015)	109	0
7	Vaiana (2014)	101	0
8	Dogan (2017)	100	4
9	Liu (2022)	100	0
10	Golestan (2016)	96	4

Source: Researchers' finding

Figure 1 illustrates a network visualization of bibliographic coupling, revealing five thematic clusters. These clusters are labeled based on an inductive interpretation, which involves revisiting representative articles within each cluster and synthesizing themes and research streams.

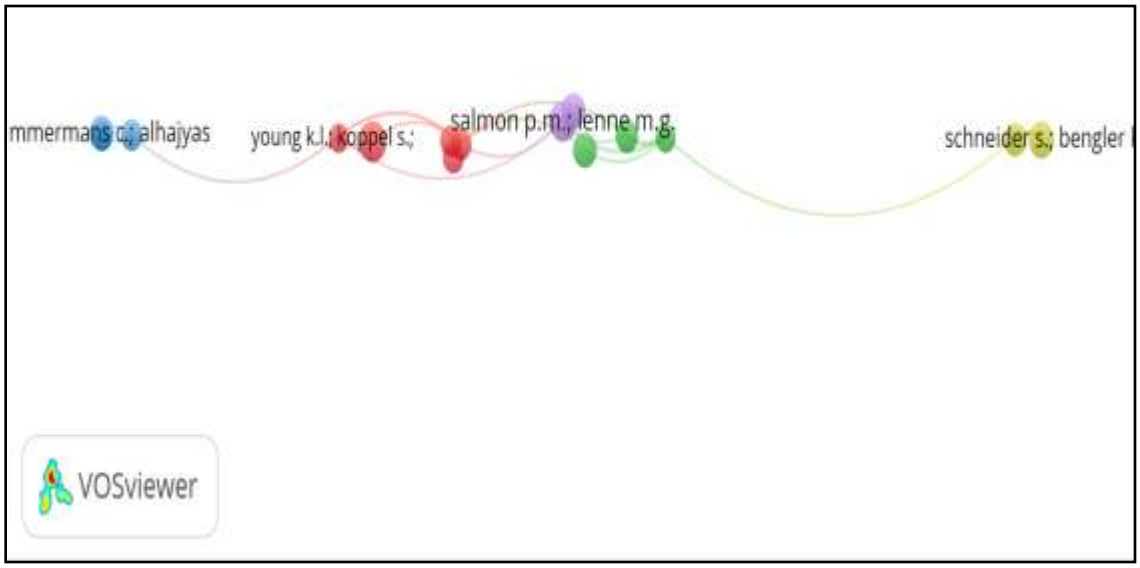

Figure 1. Network visualization of bibliographic coupling of Road Safety Research Trends
Source: Researchers' finding

Cluster one (red) is categorized as "Driver Cognition, Situation Awareness, and Distraction in Road Safety." This cluster reflects a growing scholarly focus on understanding the cognitive mechanisms underpinning driver behavior, particularly in response to in-vehicle technologies and external distractions. Olaverri-Monreal et al. (2014) investigated drivers' preferences for the design of Driver Information Systems (DIS) and Advanced Driver Assistance Systems (ADAS) through a card-sorting experiment. They analyzed drivers' performance and gaze behavior based on their preferred in-vehicle information placement, utilizing gaze location and speed metrics. The results indicated that drivers could access information within the time limits recommended by NHTSA guidelines. Interestingly, participants' preferences for DIS and ADAS layouts closely mirrored available market options, though they did not consider mobile applications and social media essential for vehicles (48). As technological integration progressed, research shifted toward age-specific cognitive patterns, as seen in Bridie Scott-Parker et al. (2020) examined drivers' situation awareness (SA), revealing that all participants could identify immediate driving hazards, such as vehicles ahead. However, the structure of SA varied by age group. Understanding these differences is crucial for improving road safety interventions, enhancing young drivers' learning experiences, refining instructional approaches for middle-aged drivers, and optimizing safety strategies for older drivers (49). Ortiz et al. (2018) examined the impact of texting while driving, revealing significant performance impairments across all age groups, with older drivers being the most affected (50). Compared to standard driving conditions, older drivers showed a 14% increase in the standard deviation of lane position (SDLP) under normal conditions and a 29% increase while texting. The likelihood of collisions also increased by 8.3% among young adults, 25.0% among adults, 80.5% among middle-aged adults, and 134.5% among older drivers. The study recommends integrating nonstandard vision tests into driver licensing exams to help older drivers implement compensatory safety measures while promoting awareness of risky behaviors among younger drivers. Gregoriades and Sutcliffe (2018) measured drivers' SA using the SAES in a Cave Automatic Virtual Environment (CAVE) (51). Their findings indicated that an information-rich radar-style display improved SA and driving performance compared to a minimal arrow hazard indicator and a control design lacking a head-up display (HUD). Over the past decade, studies in this cluster demonstrate a clear conceptual shift from interface usability and general cognitive models toward age-specific risk profiling and immersive cognitive modeling. Bibliometric signals (e.g., citation bursts post-2015) indicate growing scholarly attention to cognitive load, distraction, and adaptive interfaces. This evolution reflects a move toward context-sensitive frameworks and empirically grounded, personalized interventions that inform the advancement of intelligent transport systems.

Cluster two (green) is categorized as "Cognitive and Behavioral Factors in Road Safety: Automation, Hazard Perception, and Human Interaction." Fisher et al. (2016) emphasize the importance of considering human factors in the development of intelligent vehicles, as overlooking human behavior may pose safety risks. Their study examines challenges associated with Level 2 and Level 3 automation, as defined by the National Highway Traffic Safety Administration (NHTSA) (52). At Level 2 automation, the driver is no longer required to actively control the vehicle's position and speed but must still maintain situational awareness. Additionally, voice-activated systems intended to support drivers may instead introduce cognitive distractions. At Level 3 automation, the driver is mostly disengaged but must remain ready to take over control when necessary. Prolonged disengagement may result in a decline in critical driving skills, while abrupt transitions in control pose additional safety risks. To address these concerns, researchers have proposed mitigation strategies based on experimental studies and insights from human factors research in both surface transportation and aviation. Vansteenkiste et al. (2016) designed and evaluated a hazard perception test for bicyclists, focusing on visual behavior, environmental awareness, and risk perception among both adults and children (approximately 8 years old) (53). Their findings suggest that children may have difficulty interpreting crucial traffic information quickly. Future research should refine hazard perception assessments to enhance their accuracy in evaluating bicyclist safety. Pammer et al. (2018) found that approximately 90% of drivers, regardless of experience level, detected high-threat objects near the roadside (54). Their findings suggest that expertise enables drivers to filter and prioritize relevant hazards more effectively, a skill developed through structured training rather than experience alone. The study underscores the importance of enhancing not only driver awareness but also the ability to differentiate between relevant and irrelevant stimuli to improve road safety.

Cluster 3 (blue) is titled "Technological Risk Mitigation and Traffic Safety Interventions". Timmermans et al. (2019) conducted time series analyses, revealing an increasing trend in road traffic crashes (RTCs) resulting in severe injuries, while fatal RTCs have shown a slight decline (55). The study also found that different severity levels

of RTCs are linked to distinct causes. Both drivers and pedestrians involved in severe or fatal crashes are impacted by seasonal weather variations, with the highest risks occurring in winter and autumn. Based on these insights, the study suggests implementing targeted traffic safety measures to better protect road users during these high-risk seasons. Ali et al. (2019) identified a short-run uni-directional causal relationship between road traffic fatalities (RTF) and several economic and environmental factors (56).Their findings indicate that GDP growth influences RTF in Asia, Europe, and America, while increased health expenditures contribute to a reduction in RTF, particularly in upper-middle-income countries (UMICs). Additionally, rainfall is associated with higher RTF rates in Asia and America, whereas greater population density appears to enhance road safety. The study recommends that governments enforce stricter traffic laws, allocate more funding to health expenditures, incorporate traffic safety education into school curricula, and raise public awareness about the dangers of road crashes. Celaya-Padilla et al. (2019) introduced a convolutional neural network (CNN)-based deep learning approach to detect distracted drivers using mobile phones (57). By utilizing a ceiling-mounted wide-angle camera, the CNN, built on the Inception V3 deep neural network, was trained on 85,401 images, achieving an AUC of 0.86 in blind testing and a sensitivity of 0.97. This technology can be integrated into smart infotainment systems to improve driver awareness, encourage safer driving behaviors, and reduce accident rates.

Cluster 4 (yellow) is categorized as "Pedestrian Safety, Hazard Perception, and Methodological Approaches in Road Research." Schneider and Bengler (2020) organized their findings based on key factors, including the research question, technical setup, experimental task, and participant sample. Their study evaluates the current state of research while establishing a foundation for future investigations. It aims to enhance awareness of existing challenges, refine data interpretation, and guide pedestrian research toward producing reliable and generalizable insights. These efforts ultimately seek to improve pedestrian mobility, comfort, and safety (58). Meir and Gilad (2020) examined pedestrian hazard perception (HP) and found that experienced adults consistently rated images with a partially obstructed field of view as more hazardous. Additionally, they considered vehicles near crossing sites and complex traffic scenarios, including roundabouts, to be riskier than T-junctions. The findings indicate that young pedestrians may rely more on visual cues when assessing crossing safety. The results showed that participants aged 9–13 displayed less decisive responses compared to experienced adults and 7–8-year-olds. Regardless of age, most participants prioritized approaching vehicles and pedestrian crossings over road configurations. The study discusses the implications of these findings for road safety interventions (59).

Cluster 5 (purple) is titled "Enhancing Road Safety Through Situation Awareness, Risk Prevention, and Policy Intervention." Pervez (2021) identified several factors that are positively correlated with motorcycle fatalities, including the summer season, weekends, nighttime, elderly riders, heavy vehicles, and single-vehicle collisions (60). In contrast, the presence of pillion passengers and motorcycle-to-motorcycle crashes show a negative association with fatalities. In Pakistan, the likelihood of fatal injuries rises during morning hours, among young riders, and when female pillion passengers' clothing becomes entangled in the wheel. Therefore, potential counter measures for improving motorcycle safety include stricter law enforcement to reduce risky behaviors and speeding, the introduction of dedicated motorcycle lanes, and educational programs for female pillion passengers. These insights help raise awareness of motorcycle safety and offer practical recommendations for policymakers seeking to improve road safety in Pakistan and other developing countries with similar traffic conditions. Salmon et al. (2014) examined differences in road users' situation awareness (SA) and found that while structural variations exist, the actual content of SA, including road user schemata and environmental interactions, differs (61). Further analysis suggests that while these variations are generally compatible on arterial roads, shopping areas, and roundabouts, they may cause conflicts at intersections. The study highlights the critical role of incompatible SA in collisions between different road users, particularly between drivers and motorcyclists. These findings support proposed interventions aimed at improving SA compatibility and behavioral alignment among road users, ultimately reducing accident risks. A summary of the bibliographic coupling analysis is provided in Table 3.

Table 3. Bibliographic Coupling Analysis

Cluster no (color)	Cluster label	Number of publications	Representative publication
1 (red)	Driver Cognition, Situation Awareness, and Distraction in Road Safety	5	Andreas Gregoriades & Alistair Sutcliffe (2018) (51); Ortiz C. et al. (2018) (50); Bridie Scott-Parker et al. (2020) (49); Cristina Olaverri-Monreal et al. (2014) (48)
2 (green)	Cognitive and Behavioral Factors in Road Safety: Automation, Hazard Perception, and Human Interaction	3	Kristen Pammer et al. (2018) (54).; Pieter Vansteenkiste et al. (2016) (53); Donald L. Fisher et al. (2016) (52)
3 (blue)	Road Traffic Safety: Influencing Factors, Risk Mitigation, and Technological Interventions	3	Chantal Timmermans et al. (2019) (55); Qamar Ali et al. (2019) (56); José María Celaya-Padilla et al. (2019) (57)
4 (yellow)	Pedestrian Safety, Hazard Perception, and Methodological Approaches in Road Research	2	Sonja Schneider and Bengler (2020) (58); Anat Meir and Gilad (2020) (59)
5 (purple)	Enhancing Road Safety Through Situation Awareness, Risk Prevention, and Policy Intervention	2	Amjad Pervez (2021) (60); Paul M. Salmon et al. (2014) (61)

Co-Word Analysis

From the 3.957 keywords, the co-word analysis identified 13 keywords that met the 55-occurrence threshold, selected in line with established literature standards to optimize thematic network coherence. Similar to bibliographic coupling, the citation threshold was determined through multiple trials on the minimum threshold until a robust network visualization was achieved. The top 15 keywords in the co-word analysis are presented in Table 4. The highest co-occurring words include “road safety” (160 occurrences), “motor transportation” (142 occurrences), and “road and streets” (99 occurrences).

Table 4. Top 15 Keywords

No	Keyword	Occurrences	Total Link Strength
1	Road Safety	160	418
2	Motor Transportation	142	595
3	Roads and Streets	99	491
4	Accident Prevention	65	297
5	Traffic Safety	65	164
6	Traffic Accident	49	335
7	Accidents, Traffic	46	331

8	Accidents	45	182
9	Vehicles	44	192
10	Automobile Drivers	37	157
11	Automobile Driving	35	283
12	Car Driving	35	283
13	Highway Accidents	33	176
14	Situation Awareness	33	123
15	Prevention And Control	32	238

Source: Researchers' finding

Figure 2 presents the network structure derived from the co-word analysis, illustrating four clusters, each corresponding to a distinct thematic area. These clusters were labeled based on a qualitative analysis of representative keywords with brief reflections on overlap and differences with bibliographic coupling clusters.

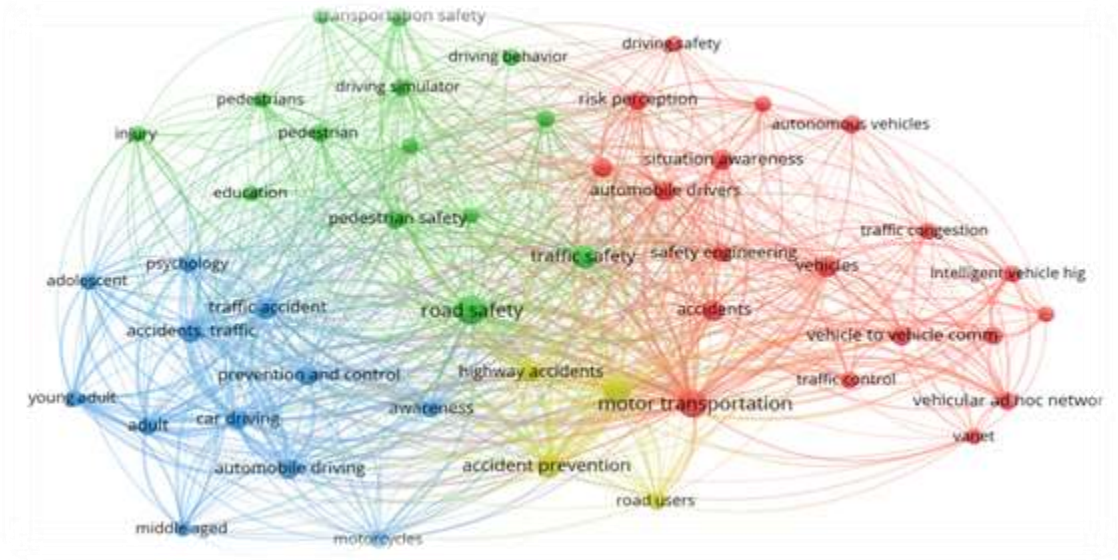

Figure 2. Network visualization of co-word analysis Road Safety Research Trends
Source: Researchers' finding

Cluster One is categorized as Driving Safety, Risk Perception, and Vehicle Communication, reflecting overlap between behavioral and technological dimensions in Modern Transportation. Zhongxiang Feng et al. (2024) found that autonomous vehicles (AVs) influence pedestrian crossing decisions (62). Specifically, as vehicle speed increases and distance to pedestrians decreases, individuals are more likely to refrain from crossing. Scenario analysis revealed that middle-aged pedestrians and those with high-risk perception tend to be more cautious when making crossing decisions, whereas pedestrians with greater trust in AVs are more inclined to cross. These findings contribute to the advancement of urban intelligent transportation systems by enhancing the understanding of pedestrian decision-making at the intersection of social and technological factors. Lim and Rajivan (2023) found that drivers expect vehicles to provide malfunction detection, troubleshooting guidance, and log data (63). Additionally, when drivers perceive a threat as urgent, they tend to rely on instincts rather than fully processing the situation in its early stages. To address this, the study proposes a 'Driver Response Phase' framework, offering design implications for future

vehicle systems to support user responses to security risks. Sayed et al. (2022) identified failure to maintain a safe following distance as a primary cause of crashes (64). Using negative binomial models, the study predicted crash frequency based on factors such as age, driving experience, personality traits, and behavior. The findings suggest that integrating the Driver Behavior Questionnaire (DBQ) with risk perception scenarios can improve the assessment of driver characteristics and crash risk. Proposed countermeasures include traffic management policies, awareness campaigns on driving etiquette, regulated driving hours, and specialized training programs for novice drivers. Măirean et al. (2022) risky driving behavior is negatively associated with optimism bias but positively linked to the illusion of control (65). Additionally, risk perception negatively correlates with risky behavior and mediates the relationship between optimism bias, illusion of control, and risky driving. These findings have practical implications for traffic safety interventions. Linheng Li et al. (2020) proposed a novel methodology for risk perception and warning strategies in connected and autonomous vehicle (CAV) environments. The study developed a dynamic safety potential field model to describe spatial driving risks, integrating multiple traffic variables. A Potential Field Indicator (PFI) was introduced as a new risk metric, demonstrating superior accuracy in assessing driving risk across different vehicle motion states compared to existing indicators. Simulations using SUMO software validated the model's effectiveness in accident prevention, highlighting its potential for integration into strategic decision-making for driver assistance systems in CAV environments (40).

Cluster Two is categorized as Enhancing Road Safety Through Education, Driving Behavior, and Pedestrian Protection. Poliak (2023) analyzed road users' perceptions of safety innovations, focusing on front braking lights, using contingency tables, chi-square tests, non-parametric tests, and Cramer's V (66). The findings indicate that a significant percentage of road users feel safer with a front braking light in various situations, including crossing traffic involving vehicles and pedestrians (71%), pedestrian crossings (74%), left turns (63.4%), and navigating multi-vehicle traffic (62.5%). While employment type had no significant impact on perceptions, individuals with higher driving mileage held a more positive view of front braking lights at pedestrian crossings. Perello-March (2023) explored the connection between prefrontal cortical hemoglobin oxygenation levels, perceived risk, and traffic complexity in automated driving (67). The study found that as traffic complexity increases, drivers, still perceive moderate risk. This perception is supported by a significant rise in blood oxygenation levels, particularly in hazardous scenarios. Linlin Jing (2022) examined the relationship between risk preference, risk perception, and risky driving behaviors (68). The results indicate that risk perception is a stronger predictor of risky driving behaviors than risk preference, with gender and age influencing this interaction. Notably, risk perception has a greater predictive effect on females than males and is more pronounced among drivers with 1–3 years of experience. These findings suggest that interventions should address all stages of the causal chain to enhance road safety. Cong Zhao et al. (2023) evaluated the accuracy of millimeter-wave (MMW) radar in traffic risk assessment and early warning systems (69). While MMW radar provides real-time position and velocity data for dynamic risk analysis, hardware limitations introduce vehicle positioning errors, potentially leading to misinterpretations of vehicle motion and interaction. The study examined factors influencing radar positioning accuracy, including installation height, sampling frequency, vehicle location, posture, and size, and validated findings through simulated experiments. The study proposed a general guideline for radar data processing in traffic risk assessment and early warning systems.

Cluster Three is categorized as Traffic Accident Prevention and Awareness in Young and Adult Drivers. Albatayneh (2024) conducted a survey examining trends in driver behavior, revealing widespread non-compliance with speed limits and seatbelt use, along with frequent mobile phone usage while driving (70). A key finding was that drivers aged 18–19 made up the majority of respondents who had experienced one or two accidents. The study also indicated that social media was perceived as the most effective platform for traffic awareness campaigns, whereas television was considered the least effective. These insights highlight the need for comprehensive traffic safety education, particularly for young drivers. The study recommends integrating Traffic Awareness as a mandatory university module to encourage responsible driving habits and reduce traffic-related incidents in academic settings. Jae-Hong Lee (2024) investigated the impact of smartphone use on novice drivers' visual attention and driving performance through a simulation involving 45 participants (71). Drivers completed four tasks: hand-held calls, hands-free (Bluetooth) calls, texting, and driving without smartphone use. Eye-tracking data revealed significant variations in eye blink duration, fixation frequency, saccadic eye movement, and fixation duration. Performance metrics indicated heightened risks, including speeding, lane departures, road edge excursions, and collisions. Notably,

texting posed the greatest risk, even though drivers attempted to compensate by reducing speed. These findings emphasize the need for interventions aimed at shifting novice drivers' attitudes toward traffic safety. Bedru (2021) surveyed 403 motorcycle riders and found that only 12.4% wore helmets (72). Key factors influencing helmet use included holding a valid license [AOR 3.51], driving distances over 10 km [AOR 2.53], prior accident experience [AOR 2.71], more than ten years of riding experience [AOR 2.98], and a higher perceived accident risk [AOR 3.10]. The study underscores the urgent need for behavior-focused interventions, including awareness campaigns and mandatory helmet regulations. Dalton et al. (2020) conducted a five-day study with 364 participants to evaluate the effectiveness of digital road safety signage.(22) While participants on intervention days were more likely to rank 'Look out for cyclists' as important (OR 1.20), this result was not statistically significant ($p = 0.355$). Additionally, there was no significant difference in awareness between those who had seen the campaign image and those who had not ($p = 0.778$). The study concludes that short-term digital signage is ineffective for increasing public awareness, highlighting the need for further research on long-term exposure to safety messaging.

Cluster Four is categorized as Streets and Highway Safety Measures. Lawton (2024) found that drivers were more likely to stop when traveling straight than when making a left turn, with left-turning vehicles stopping more frequently than right-turning ones (73). Additionally, single-unit trucks and tro-tros exhibited a higher likelihood of stopping compared to other vehicle types. Driver compliance increased in areas with channelization, intersection lighting, or speed humps, as well as at four-approach junctions compared to three-approach junctions. These findings suggest that safety behaviors serve as a guideline for safety professionals in selecting effective interventions and estimating their economic impact in low- and middle-income countries (LMICs) like Ghana. The study recommends for Ghanaian road safety agencies to enhance public awareness and reduce road crash fatalities. Aleksa et al. (2024) examined the impact of Advanced Driver Assistance Systems (ADAS) on crash reduction in Austria (74). Among ADAS technologies, warning and braking-related systems showed the greatest potential, with projections indicating they could prevent up to 8,700 crashes and 70 fatalities by 2040. The Intelligent Speed Assistance system could lead to an 8% reduction in crashes, while the Turning Assistant for heavy goods vehicles had the lowest crash reduction impact but remained significant due to the severity of truck-related accidents. To maximize ADAS benefits, driver education should include training on proper usage, benefits, and limitations. Burger et al. (2024) found that a mobile application improved driver safety perception, particularly when offering hazard notifications (75). Notifications that appeared at the top of the screen with auditory cues were the most effective. The study supports the integration of C-ITS functionalities into mobile applications to supplement older vehicle technologies, reduce accidents, and enhance overall traffic safety. Khan and Das (2024) explored the Safe System Approach (SSA) as a strategy for building a more resilient transportation system (76). SSA enhances road safety through system design, behavior modification, and targeted measures for vulnerable users. Within the Safe Vehicles component, SSA encourages continuous safety improvements, rigorous testing, and regulatory advancements among manufacturers. The Safe Speeds element aligns speed limits with human safety thresholds while integrating community involvement for context-specific solutions. SSA also strengthens Safe Roads by incorporating innovative countermeasures and forgiving road designs. In Post-Crash Care, SSA promotes collaboration between emergency services, medical professionals, and the justice system, ensuring a standardized and integrated accident response. These findings contribute to global road safety efforts and inform strategies for improving transportation systems.

Table 5. Summary of co-word analysis Road Safety Research Trends

Cluster no (color)	Cluster label	Number of keywords	Representative Keywords
1 (red)	Driving Safety, Risk Perception, and Vehicle Communication in Modern Transportation	19	Motor Transportation, Automobile drivers, situation awareness, risk perception, vehicles, accidents, vehicle to vehicle comm, driving safety, autonomous vehicles, traffic congestion

2 (green)	Enhancing Road Safety Through Education, Driving Behavior, and Pedestrian Protection	14	road safety, traffic safety, pedestrian safety, driving simulator, driving behavior, pedestrians, education, injury
3 (blue)	Traffic Accident Prevention and Awareness in Young and Adult Drivers	12	accidents, traffic, traffic accident, prevention and control, car driving, automobile driving, young adult, adult, adolescent, motorcycles, awareness, psychology
4 (yellow)	Streets and Highway Safety Measures	4	Roads and streets, accident prevention, highway accidents, road users

While both bibliographic coupling and co-word analysis uncover significant thematic clusters in road safety research, they offer complementary yet distinct perspectives. Bibliographic coupling emphasizes the intellectual and citation-based structure of the field by identifying clusters based on shared references, revealing how contemporary studies are intellectually linked, such as themes on automation, trust, and risk mitigation technologies. In contrast, co-word analysis captures the conceptual and semantic organization by analyzing the frequency and co-occurrence of keywords, exposing dominant topics such as driving behavior, injury prevention, and vehicle communication. Interestingly, both techniques highlight overlapping concerns, such as risk perception and automation, yet diverge in their granularity: coupling reveals deeper authorial and methodological lineages, whereas co-word analysis surfaces emerging and policy-relevant terminologies. This divergence enriches the understanding of road safety discourse by illuminating both structural depth and conceptual breadth within the literature.

Study Implications

Theoretical implications

The findings of this study contribute to theoretical perspectives on risk perception, vehicle automation, and behavioral interventions. Bibliographic coupling and co-word analysis reveal overlapping and distinct patterns across clusters underlining how human and technological themes intersect in traffic safety. Theoretical implications emerge from identifying key drivers of risky behaviors, including distraction, hazard perception, automation level, and traffic complexity (52,54).

Implication for human behavior. Key drivers of risky behavior such as distraction, hazard perception, and attentional limitations support established cognitive theories, including *Situation Awareness (SA)* and *risk perception* models. These findings support existing cognitive theories on situation awareness and risk perception in driving which suggest that a driver's ability to detect hazards depends on experience, attentional capacity, and environmental complexity (77,78). However, gaps in adapting these theories to automated environments merit future exploration.

Implications for Automation and Technology. Studies clustered under automation and Intelligent Transport Systems (ITS) (40,57) expands theoretical perspectives on how AI-based decision-making tools influence driver behavior. Research on ADAS effectiveness (74), and hazard warning systems (75), reinforces the Technology Acceptance Model (TAM) demonstrating that driver compliance with safety technologies depends on perceived ease of use, trust, and awareness (79). Potential contradictions, such as trust leading to over-reliance and reduced hazard sensitivity, highlight theoretical tensions.

Implication for public health and policy. Research on pedestrian safety and behavioral interventions (56) contributes to public health and transportation theories, emphasizing the need for integrated, multi-disciplinary approaches to traffic risk reduction (59,61). Classic bibliometric frameworks such as Small's co-citation theory and Slovic's risk perception model, although not dominant in this corpus, offer potential historical grounding for future studies. These findings are consistent with those of Setyowati et al. (2025), who underscore the significance of adopting a comprehensive and integrated strategy in reducing global traffics and fatalities (80). This convergence reinforces the case for multitheoretical frameworks.

Managerial Implications

The study suggests that policy interventions should focus on high-risk groups, such as young and novice drivers, motorcyclists, and pedestrians (70,72). These findings not only align with but also advance earlier policy reviews that often addressed behavioral and technological factors separately. By explicitly integrating both dimensions, this study highlights gaps in previous frameworks and provides a more comprehensive basis for targeted interventions—especially in areas such as young driver safety and AV user behavior. The integration of ADAS and ITS technologies into vehicle systems (74), highlights the need for enhanced driver training programs to ensure users understand and correctly utilize these safety features. Automotive manufacturers should develop user-friendly driver assistance tools while addressing concerns about automation over-reliance and reduced hazard perception (52). For urban planners, the results support infrastructure improvements, such as better lighting, pedestrian crossings, speed humps, and intelligent traffic signals, which influence driver compliance and pedestrian safety (73). Additionally, data from intelligent transport monitoring systems, including MMW radar and AI-powered road safety assessments, should be incorporated into predictive analytics models to enhance accident prevention efforts (69). Education campaigns should shift towards social media-based awareness programs, with stronger long-term exposure planning given prior failures of short-term interventions as findings suggest that digital platforms are more effective than traditional television broadcasts in influencing road safety behaviors (70). Moreover, mobile applications with real-time hazard warnings especially in low- and middle-income countries (LMIC) context, (75) can enhance situational awareness, reducing crash risks.

CONCLUSION

This study employs bibliometric analysis to map key trends in road safety research, focusing on the intersections of human factors, automation, and public policy. By applying bibliographic coupling and co-word analysis on 581 Scopus-indexed articles published between 2013 and 2023, it identifies five thematic clusters and four keyword-based domains, revealing evolving priorities in the field. The findings underscore the importance of integrating AI-powered monitoring systems, enforcing data-informed traffic regulations, and implementing targeted behavioral campaigns to reduce accident risks. These strategies should be designed with adaptive models that account for how road users respond to risk and safety interventions.

Theoretically, the study enhances existing road safety frameworks by incorporating risk perception, trust in automation, and behavioral adaptation. It also opens discourse on theoretical gaps, particularly concerning contradictions between automation trust and hazard vigilance, and between short-term awareness and long-term behavior change. Future theoretical models should reflect how both drivers and pedestrians adjust their behaviors based on their experiences and perceptions of safety technologies. From a policy perspective, the research calls for stricter enforcement, AI-based surveillance, and digitally driven public safety campaigns. For urban planners, the recommendations include smart infrastructure investments, real-time hazard alerts, and driver education programs that foster safer road user behavior.

Overall, the study contributes a multi-dimensional approach to road safety, combining insights from technology, behavior, and planning, and provides an evidence-based foundation for future research and policy development. It concludes with a call to action for researchers, policymakers, and urban designers to adopt bibliometric insights as a strategic tool for shaping data-informed, context-sensitive road safety policies, especially in low- and middle-income countries.

AUTHOR'S CONTRIBUTION STATEMENT

Conceptualization, Methodology, writing-original draft, writing-review. Author 1; Conceptualization, Methodology, data collection, writing-review & editing. Author 2; Conceptualization, data collection and writing-review, and submit the journal. Author 3; Conceptualization, draft writing- review & editing. Author 4.

CONFLICTS OF INTEREST

The author hereby certifies that this research is free from conflicts of interest. The author has no financial or personal affiliations with any organizations that would compromise the integrity and objectivity of this study.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

The authors affirm that during the preparation of this work the authors used ChatGPT in order to assist in generating preliminary drafts of writing and refining the clarity of the text. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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