Journal of Railway Transportation and Technology
Vol. 4 No. 1 (2025) 17-34
eSSN: 2830-6880

Railway safety research: Mapping trends, strategic clusters, and future pathways

Sameh Fuqaha[1]

[1]Department of Civil Engineering, Postgraduate Studies, Universitas Muhammadiyah Yogyakarta, Yogyakarta 55183, Indonesia.

Article Info

Article history:

Received 2025-04-12
Revised 2025-04-23
Accepted 2025-04-23

Keywords:

Railway safety
Human reliability
Predictive maintenance
Cybersecurity
Infrastructure resilience

ABSTRACT

This study presents a comprehensive bibliometric analysis of railway safety research from 2019 to 2024, offering critical insights into the thematic evolution, intellectual structure, and future pathways in this vital domain. By analyzing 445 peer-reviewed articles retrieved from leading academic databases, the study identifies major research clusters centered around risk assessment, human factors, and AI-enabled infrastructure monitoring. The findings reveal a significant shift toward intelligent safety systems, with deep learning, predictive maintenance, and human reliability modeling emerging as dominant themes. China, the United Kingdom, and India are identified as leading contributors, with strong international collaboration driving innovation in the field. Despite notable progress, the analysis uncovers persistent gaps—particularly in cybersecurity resilience, cognitive integration in risk assessment, infrastructure adaptation to climate risks, and localization technologies for autonomous train systems. Future research directions are proposed to address these gaps, including multi-sensor fusion for train positioning, AI-based decision-making frameworks for autonomous operations, and integration of human factors into machine learning-based safety evaluations.

Corresponding Author:

Sameh Fuqaha
Department of Civil Engineering, Postgraduate Studies, Universitas Muhammadiyah Yogyakarta, Yogyakarta 55183, Indonesia. Email: sameh.h.psc24@mail.umy.ac.id

1. INTRODUCTION (10 PT)

Railway transportation plays a vital role in ensuring the efficient movement of people and goods across regions and countries. However, its complex technical systems and operational dependencies make it vulnerable to a wide range of safety risks [1]. Unlike other transport modes, where individual vehicles operate independently, railway systems are highly interconnected, meaning that a single error—such as a mechanical failure, signal fault, or dispatching mistake—can affect the entire network [2] In recent years, these risks have expanded to include modern concerns such as cybersecurity threats targeting signaling systems and communication platforms [3]

Maintaining railway safety involves more than just technology—it also requires well-trained personnel, effective management systems, and environmental controls. Research has emphasized that the quality of management practices significantly influences urban and high-speed rail safety [4]. Safety Management Systems (SMS) are considered essential tools for reducing accident risks, and they include key components such as accident investigation, emergency response plans, and education and training programs [5], [6].

Given the complexity of railway operations, it is increasingly important to track the evolution of research trends and identify underexplored topics that can contribute to long-term system improvements. Traditional literature reviews, while useful, often lack efficiency and scalability, especially as the volume of scientific publications grows rapidly [7]. In this context, bibliometric analysis has emerged as a powerful tool that enables researchers to quantitatively examine large datasets, detect publication patterns, identify thematic structures, and assess the influence of authors, journals, and countries [8].

A wide range of studies has explored railway safety from different angles. For example, human factors have been analyzed as key contributors to accidents and operational failures [9], while bibliometric research has addressed transportation network vulnerability under natural hazards [10]. Other works have investigated technological and policy-driven safety efforts, such as interlocking systems at rail stations [11], safety management practices in China's high-speed rail [12], and regulatory approaches in Canada [13]. Studies have also highlighted specific risk points like highway-railway crossings [14] and cybersecurity in rail systems [15].

In addition, recent literature has focused on specialized safety areas. These include nondestructive testing for infrastructure flaw [16], photonic sensors—such as fiber Bragg gratings—for real-time structural monitoring [17]. real-time condition monitoring in freight systems [18], and safety management during train operations [19]. Other reviews have discussed scheduling and maintenance planning [20], sanding system reliability [21], and the integration of deep learning into safety strategies [22]. However, while these studies provide valuable insights, they tend to be fragmented. There is still a lack of comprehensive overviews that connect different research streams and offer a strategic classification of safety-related topics in the railway domain. Shi et al (2024) emphasized multi-sensor systems for intrusion detection in high-speed rail, showing how sensor fusion can improve performance in challenging environments [23]. From a socio-economic angle, Hromádka et al (2023) evaluated the benefits of improved safety and reliability through cost-benefit analysis, which helps inform investment decisions in infrastructure projects [24]. Omino (2020) highlighted human-centered safety strategies like training, education, and system redesign [25].

2. METHDOLOGY

A bibliometric analysis was employed in this study to explore and visualize the current state of research on railway safety, identify thematic trends, classify strategic focus areas, and propose future research pathways. Bibliometric analysis, a computer-assisted scientific review method, has proven effective for systematically mapping and quantifying research landscapes across various domains [26], [27]. This approach enables the identification of influential authors, institutions, and countries, as well as the detection of emerging themes and research gaps within the railway safety domain.

Two main algorithms are commonly used in constructing bibliometric networks: full counting and fractional counting. While both methods are valid, full counting is generally preferred due to its simplicity and ease of interpretation. Fractional counting, though more intricate, is useful in scenarios requiring precise weight distribution across contributions.

To implement the bibliometric analysis, this study utilized two established tools: VOSviewer, a widely recognized software for visualizing bibliometric networks, and the bibliometrix package in R software [28]. These tools were applied to generate co-authorship, keyword co-occurrence, and citation networks. In these networks, nodes represent research entities—such as articles, authors, institutions, journals, or keywords—while links indicate relationships among them, such as collaborations or thematic similarities. The methodological framework of this study consists of the following steps: (1) data collection from a comprehensive academic database, (2) performance analysis of key bibliometric indicators, (3) network analysis and visualization, and (4) interpretation of the results to inform future directions in railway safety research.

2.1 Scope of the Study

At this stage, relevant scientific studies were examined to explore existing work on railway safety. The main question guiding this review was: "What current trends, advanced developments, and strategic efforts are shaping railway safety, and how can these be organized to guide future research directions?"

2.2 Defining Search Resources

The selection of appropriate databases is critical for ensuring comprehensive and high-quality bibliometric results. For this study on railway safety research, Scopus was utilized. It is the most extensive and reputable scientific databases that offer complementary coverage across a broad spectrum of disciplines [29].

2.3 Boolean Operator-Based Search

To conduct a comprehensive literature review on railway safety, a structured Boolean search strategy was employed. This approach enabled the identification of relevant studies by combining key terms associated with railway safety and its strategic dimensions. The search was organized into two primary Boolean groups to refine the results and ensure the inclusion of multidisciplinary perspectives.

The first Boolean group focused on the core topic of railway safety. Keywords in this group included terms such as "railway safety," "railroad safety," "rail transport safety," "train safety," "railway accident prevention," and "railway risk management." These terms were chosen to capture a wide range of studies focused on both general safety practices and specific accident mitigation strategies within the railway sector.

The second Boolean group was designed to capture broader concepts and emerging themes relevant to the strategic development of railway safety. This group included keywords such as "risk assessment," "safety management systems," "human factors," "accident analysis," "technological innovation," "predictive maintenance," "resilience," "smart transportation," "sustainable transport," and "rail infrastructure monitoring." In total, over 60 keywords were selected for this group, encompassing technical, operational, environmental, and policy-related dimensions of railway safety.

By combining these two Boolean groups, the search strategy ensured the retrieval of publications that not only address the technical aspects of railway safety but also reflect the evolving strategic classifications and future research directions within the field. This method allowed for a focused and systematic review of the most relevant and impactful contributions in railway safety research.

Using the predefined set of keywords related to railway safety, search queries were carried out in Scopus. The initial search results yielded a total of 353 documents from Scopus. These documents included a broad range of publications across various disciplines connected to the topic of railway safety.

2.4 Filtering Search Results

To ensure that only the most relevant and high-quality studies were included in the analysis, a series of filtering criteria were applied to the initial search results. First, only documents published in journals were considered, as these are peer-reviewed and typically reflect higher academic rigor. Second, the selection was limited to articles and reviews, excluding editorials, conference papers, and other non-research materials. Third, the language filter was set to English to maintain consistency and ensure interpretability. All publications—regardless of their year of publication—were retained to capture the complete evolution of research on railway safety, from its early stages to the most recent advancements. This filtering process helped refine the dataset for a comprehensive and unbiased bibliometric analysis.

Not all data collected from the database is directly related to the research topic. Therefore, a filtering process was applied to remove irrelevant references. This process used three main criteria: source type (limited to journals), document type (only articles and reviews), and language (English only). To ensure a complete overview, publications from the earliest available year were included in the analysis.

2.5 Merging, Deduplicating Results and Review

Search results from both databases were merged using the method described by Echchakoui [30], which allows for systematic integration and deduplication using R software. After removing duplicates, the final dataset consisted of 326 unique and relevant documents.

The refined dataset was subjected to bibliometric analysis. This process, being data-driven and automated, reduces subjective bias and enhances the objectivity and reproducibility of the findings. Relationships among key entities were visualized, and thematic clusters were identified based on co-occurrence and citation patterns.

2.6 Research Framework

An overview of the methodology is illustrated in Figure 1, while Figure 2 presents the conceptual framework guiding this study.

3. PRIMARY FOCUS OF PREVIOUS REVIEWS, IDENTIFIED GAPS, AND RESEARCH QUESTIONS

Table 1 presents a summary of key review articles on railway safety research published between 2019 and 2024. It outlines their thematic scope, methodological approaches, and contributions to both operational efficiency and environmental sustainability within the railway sector. An examination of prior literature reveals a noticeable lack of comprehensive studies that map the evolution of railway safety research while also providing a structured and strategic classification of existing approaches. Although various studies have explored individual elements such as accident mitigation, risk evaluation, and infrastructure resilience, few offer an integrated perspective that consolidates these aspects into a unified analytical framework.

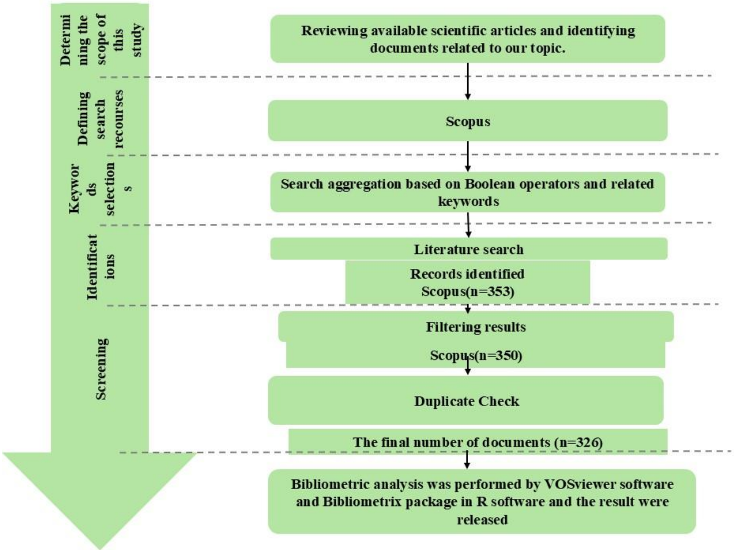

Figure 1. Research steps

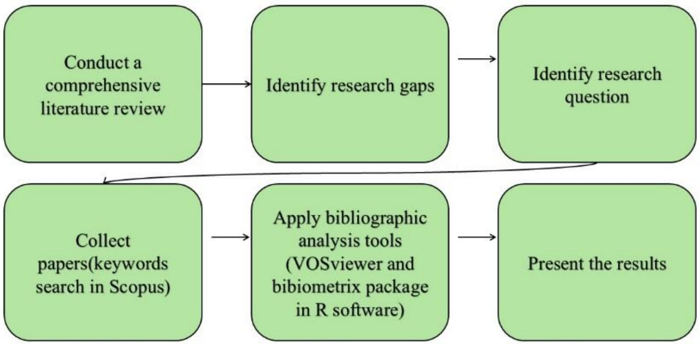

Figure 2. Study's framework.

Table 1 - Overview of Review Papers on Railway Safety

Ref	Year	Scope	The primary areas of discussion
[22]	2022	Deep learning applications	• Review deep learning for infrastructure, operations, and station safety • Highlight models for fault detection and automation • Discuss vision-based and sensor-based diagnostics
[23]	2024	Multi-sensor intrusion detection	• Review sensor fusion for perimeter intrusion • Emphasize real-time detection and system accuracy • Present fusion frameworks and robustness strategies
[76]	2021	Vehicle safety technology	• Overview of crashworthiness and ride comfort • Assess vehicle control systems and stability • Focus on safe vehicle dynamics for passengers
[25]	2020	Human-centered railway systems	• Highlight human factors in railway systems • Discuss behavior-based safety interventions • Promote human-science approaches for error reduction
[17]	2023	Photonic sensors for safety	• Survey of photonic sensors like FBG • Explore real-time structural monitoring • Examine advanced safety and security applications

[24]	2023	Cost-benefit analysis of safety	• Evaluate socio-economic benefits of safety • Apply cost-benefit analysis in infrastructure • Support policy decisions through quantitative insights
[77]	2024	Perimeter detection in railways	• Survey intrusion detection technologies • Discuss sensor modalities and AI models • Address gaps in surveillance and monitoring systems
[16]	2022	Nondestructive testing	• Review NDT for rail flaw detection • Include ultrasonic, electromagnetic, and AI tools • Propose improvements for inspection efficiency

To fill this research gap, the present study is guided by a central research question: What are the emerging trends, strategic classifications, and future research directions in the field of railway safety? To facilitate a more focused investigation, this primary question is broken down into four specific sub-questions:

RQ1: How has railway safety research evolved over time, and what is its current landscape?
RQ2: Which countries, institutions, journals, and authors are leading and shaping the field?
RQ3: What are the most cited and influential publications in this domain?
RQ4: What are the key themes and future-oriented topics that are driving research in railway safety?
To maintain a coherent and organized structure, the remainder of the paper is arranged as follows:
Section 4 delivers a bibliometric analysis that addresses the research questions.
Section 5 explores future research pathways by identifying emerging areas and strategic opportunities in railway safety.
Section 6 provides the conclusion, summarizing key findings.

4. DOCUMENT ANALYSIS

4.1 Trend

Analyzing the trend of research publications provides insights into the development and progression of a specific topic. It highlights the academic interest over time, showing whether a field is advancing or regressing [26]. Fig. 3 illustrates the annual and cumulative publication trends for railway safety research from 2019 to 2024, highlighting the substantial growth in academic contributions to this critical field. Based on the dataset, annual publications increased steadily from 2019 through 2021, reflecting rising scholarly attention. While the number of annual publications remained relatively stable from 2022 to 2024, the cumulative trend, represented by the dashed line, shows a sharp and consistent rise—culminating in an overall growth of 674.1% over the six-year period.

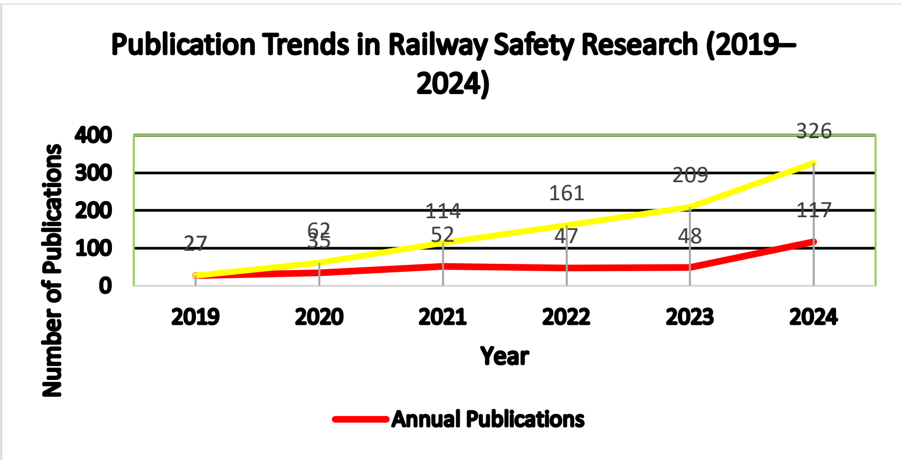

Figure 3. Trends in research and developments in Railway safety (2019–2024)

This trend underscores the growing prioritization of railway safety in research, particularly in response to increasing global transportation demands, technological modernization, and public safety concerns. The leveling-off of annual publications in recent years may suggest a shift toward deeper exploration and refinement of existing methods and technologies, rather than a decline in interest. The marked rise in cumulative publications reflects the expanding scope of railway safety research, encompassing themes such as artificial intelligence applications, condition monitoring, human factors, risk assessment, and infrastructure resilience. This growth has been driven by interdisciplinary collaboration among experts in civil engineering, computer science, transportation planning, and systems engineering.

4.2 State of research

Identifying the key contributors to railway safety research is essential for understanding global research efforts and innovation trends in this critical domain. As visualized in Figure 4, China dominates the field with 45.6% of all publications, followed by India with 13.9%, South Korea (7.5%), the United Kingdom (6.7%), and the United States (6.3%). Other notable contributors include France, Poland, Italy, Canada, and Taiwan, all of which have actively published in the area of railway safety between 2019 and 2024.

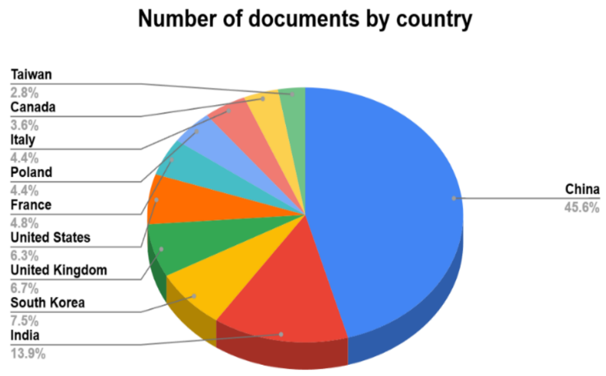

Figure 4. Documents by Country in railway safety.

In terms of citation impact, Figure 5 shows that China again leads with 49.2% of total citations, demonstrating not only quantity but also the high relevance and influence of its research outputs. The United Kingdom ranks second with 14.5%, followed by Australia (10.5%) and Poland (7.0%). These countries reflect consistent contributions to impactful and high-quality research, particularly in domains such as predictive maintenance, safety performance assessment, and smart railway infrastructure. The collaborative landscape of global research is depicted in Figure 6, which illustrates the co-authorship network between countries. China, as the central node, demonstrates strong collaborative ties with India, the United Kingdom, the United States, and several European and Asian countries. The dense interconnections reveal a globally integrated research environment where technological advancements, policy frameworks, and academic insights are collectively shaping railway safety strategies.

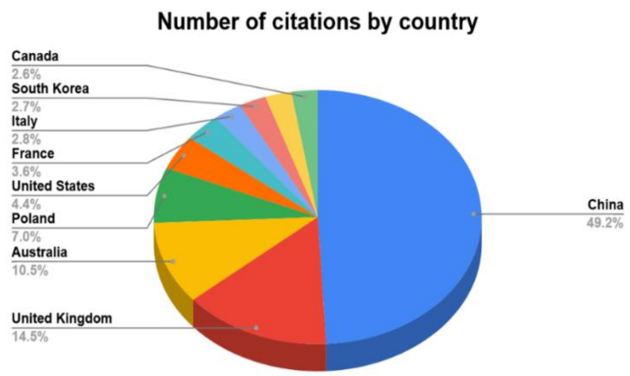

Figure 5. Citations by Country in railway safety

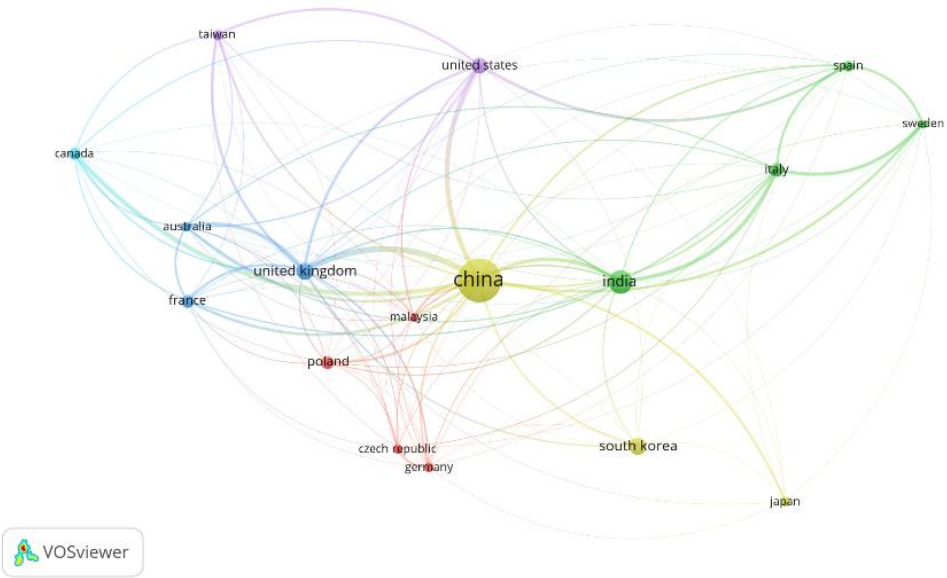

Figure 6. Global Collaboration Network in railway safety research

Based on Table 2, China has produced 115 documents with 910 citations, with an average publication year of 2022.5, indicating sustained and recent research momentum. India follows with 35 documents and 48 citations, showing its growing academic presence, particularly in recent years (average year: 2023.6). The United Kingdom, United States, and South Korea also contribute significantly, both in terms of publication volume and citation impact. Countries like Australia (5 documents, 195 citations), Poland (11 documents, 130 citations), and France (12 documents, 66 citations) further reflect the diversity of global participation in railway safety research. Notably, Canada's performance (9 documents, 48 citations) and Italy's contributions (11 documents, 52 citations) underscore their ongoing investment in transport safety and innovation.

Table 2 - Key Contributions by Country in railway safety.

Country	Documents	Citations	Avg_Pub_Year
China	115	910	2022.5
United Kingdom	17	269	2021.7
Australia	5	195	2021
Poland	11	130	2021.2
United States	16	82	2022.4
France	12	66	2021.4
Italy	11	52	2021.6
South Korea	19	50	2021.7
India	35	48	2023.6
Canada	9	48	2022.1

This global distribution in Figure 6 confirms the interdisciplinary nature of railway safety research, driven by institutions and scholars from multiple regions. These contributions reflect a mix of foundational studies and emerging research themes that continue to evolve through international collaboration and innovation.

The analysis of the most active organizations, as presented in Table 3, reveals the significant contributions of leading institutions in the field of railway safety research. Among them, several universities and research institutions stand out for their repeated engagement in scholarly output. These organizations play a pivotal role in shaping the research landscape, contributing foundational knowledge, technological advancements, and interdisciplinary approaches to safety in rail transportation. Their involvement underscores a deep institutional commitment to enhancing rail infrastructure, operational reliability, and public safety.

Table 3 - Leading Organizations in Railway Safety Research

Organization	Articles
State Key Laboratory of Rail Traffic Control and Safety	7
School of Traffic and Transportation	6
School of Electronic and Information Engineering	5
School of Civil Engineering	5
China Academy of Railway Sciences	4
Birmingham Centre for Railway Research and Education	4
University of Texas Rio Grande Valley	3
Lanzhou Jiaotong University	3
School of Transportation and Logistics	3
Institute of Computing Technologies	3

The contributions of individual researchers are equally notable, as highlighted in Table 4. Leading scholars such as Li X. and Wang Y., each with 10 publications, emerge as prominent figures in the field. Researchers like Zhang H. (9 publications), Zhang Z. and Jia L. (7 publications each) also reflect sustained efforts and thought leadership. These individuals contribute to a wide array of topics including sensor technologies, risk assessment frameworks, human factors, and intelligent railway systems. Their research not only advances theoretical understanding but also influences real-world practices and policies across international rail systems.

Table 4 -Top Authors in Railway Safety Research

Author	Publications
Li X.	10
Wang Y.	10
Zhang H.	9
Zhang Z.	7
Jia L.	7
Liu J.	7
Kaewunruen S.	6
Liu C.	6
Tarawneh C.	6
Li J.	6

A global perspective on the research landscape is provided by the earlier country-level analysis. As shown in Figure 7, countries such as China (115 documents, avg. year 2022.5), India (35 documents, avg. year 2023.6), and South Korea (19 documents, avg. year 2021.7) demonstrate strong recent activity in railway safety research. Meanwhile, nations like the United Kingdom and United States also maintain a significant presence, reflecting a long-term commitment to safety, innovation, and performance in rail systems. This global distribution reveals not only centers of emerging excellence but also ongoing regional investments in transport infrastructure and safety technologies.

These findings collectively underscore the collaborative and competitive dynamics of the railway safety research field. The consistent contributions of key organizations and scholars, along with the growing involvement of diverse countries, reflect a shared recognition of rail safety as a critical global challenge. This convergence of expertise, resources, and innovation continues to drive the development of smarter, safer, and more sustainable railway systems worldwide.

4.3 Citation Analysis of Literature

An essential consideration for researchers in the railway safety domain is identifying the most impactful publications that have significantly contributed to academic advancement. Citation analysis offers valuable insight into the foundational studies, major breakthroughs, and emerging research directions within the field. Highly cited publications often serve as cornerstones, shaping discourse and guiding future innovations. This analysis addresses Research Question 3 (RQ-3) by highlighting influential articles and their relative contributions to railway safety research. Table 5 presents the most cited publications from the dataset, showcasing major advancements in areas such as onboard condition monitoring, statistical safety assessment, pattern recognition using optical fiber sensors, and ergonomic evaluations for accident prevention.

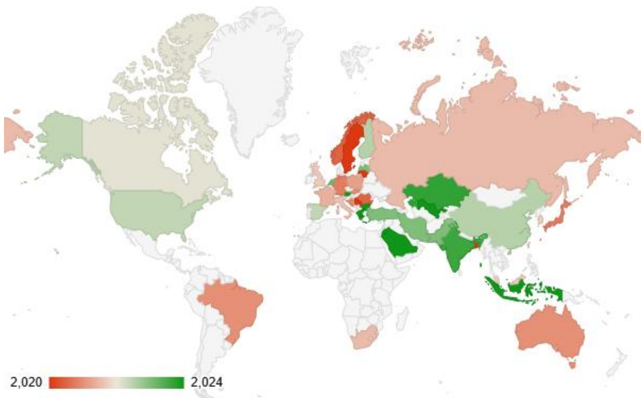

Figure 7. Average Publication Year by Country in railway safety research.

Table 5 - Highly Cited Publications in railway safety research

Ref	Title	Authors	Year	Total Citations	Source
[18]	Onboard Condition Monitoring Sensors, Systems and Techniques for Freight Railway Vehicles: A Review	Bernal E.; Spiryagin M.; Cole C.	2019	154	IEEE Sensors Journal
[78]	A statistical study of railway safety in China and Japan	Cao Y.; An Y.; Su S.; Xie G.; Sun Y.	2022	89	Accident Analysis and Prevention
[79]	Pattern Recognition for Distributed Optical Fiber Vibration Sensing: A Review	Li J.; Wang Y.; Wang P.; Bai Q.; Gao Y.; Zhang H.; Jin B.	2021	80	IEEE Sensors Journal
[51]	A hybrid human and organisational analysis method for railway accidents based on STAMP-HFACS and human information processing	Li C.; Tang T.; Chatzimichailidou M.M.; Jun G.T.; Waterson P.	2019	76	Applied Ergonomics
[80]	Using text mining to establish knowledge graph from accident/incident reports in risk assessment	Liu C.; Yang S.	2022	64	Expert Systems with Applications
[81]	A Lightweight Framework for Obstacle Detection in the Railway Image Based on Fast Region Proposal and Improved YOLO-Tiny Network	Guan L.; Jia L.; Xie Z.; Yin C.	2022	58	IEEE Transactions on Instrumentation and Measurement
[82]	The fundamental approach of the digital twin application in railway turnouts with innovative monitoring of weather conditions	Kampczyk A.; DybeÅ, K.	2021	57	Sensors
[83]	Practical multi-class event classification approach for distributed vibration sensing using deep dual path network	Wang Z.; Zheng H.; Li L.; Liang J.; Wang X.; Lu B.; Ye Q.; Qu R.; Cai H.	2019	57	Optics Express
[36]	A Deep Learning Approach towards Railway Safety Risk Assessment	Alawad H.; Kaewunruen S.; An M.	2020	55	IEEE Access
[35]	Learning from Accidents: Machine Learning for Safety at Railway Stations	Alawad H.; Kaewunruen S.; An M.	2020	52	IEEE Access

Leading the citation count is the publication titled *"Onboard Condition Monitoring Sensors, Systems and Techniques: A Review"* by Bernal et al., with 154 citations, reflecting its foundational contribution to monitoring freight train systems. Another highly influential study, *"A Statistical Study of Railway Safety in China Based on Bayesian Network and Accimap"* by Cao et al, has received 89 citations, indicating its significance in safety modeling and analysis. Other notable works include "Pattern Recognition for Distributed Optical Fiber Sensors in Railway Applications" by Li et al. with 80 citations, and "A Hybrid Human and Organizational Analysis Method for Railway Accidents" by Li et al. with 76 citations, both of which underscore the integration of sensor technology and human factors in rail safety systems. The study by Liu and Yang, "Using Text Mining to Establish Knowledge Graph for Railway Accident Prevention", with 64 citations, reflects emerging applications of AI and data mining in railway risk assessment.

Fig. 8 illustrates the trends of articles published in the five most productive journals in railway safety research between 2019 and 2024. Visualization highlights fluctuating contributions across journals while showcasing their pivotal role in disseminating research.

Among these, IEEE Access and the Journal of the Korean Society for Railway have consistently published relevant work, with steady output over the years. The Sensors journal also shows noticeable peaks, particularly in 2021 and 2024, reflecting its appeal for works involving smart monitoring and sensor-based railway systems. Lecture Notes in Electrical Engineering exhibit a sharp rise in 2022 and 2024, underscoring its role in documenting interdisciplinary work that combines railway safety with electrical and computing technologies. Meanwhile, the Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit continues to serve as a key outlet for traditional engineering contributions related to rail operations and transit infrastructure.

Collectively, these journals play a critical role in fostering scholarly communication, bridging disciplines, and promoting innovation in the global railway safety research ecosystem. Their evolving publication trends also reflect the dynamic interplay between technology, safety policy, and infrastructure management in modern railway systems.

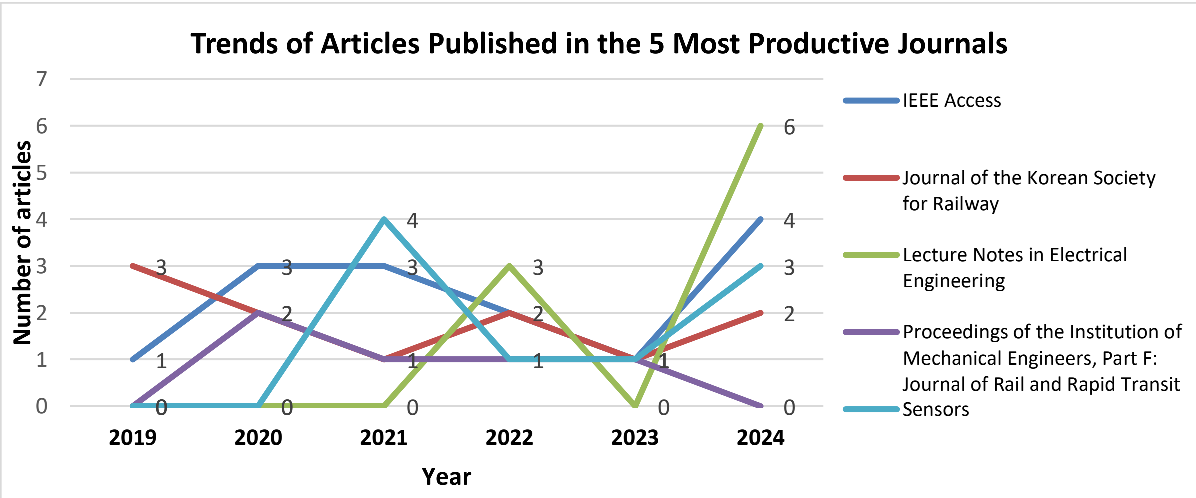

Figure 8. Trends of Articles Published in the 5 Most Productive Journals (2019–2024)

4.4 Categorizing of the keywords

The keyword co-occurrence network generated using VOS viewer reveals three prominent clusters, each representing a significant thematic domain within the railway safety research landscape as in figure 9. The clustering reflects keyword proximity and co-usage based on actual articles in the dataset. The dominant keywords—railway safety, deep learning, machine learning, object detection, and risk assessment—are each central to the thematic structure of the research.

4.4.1 Cluster 1: Risk Assessment and Safety Performance Evaluation

Studies in this cluster focus on safety performance evaluation, risk modeling, and the development of proactive safety frameworks in railway operations. Quantitative and semi-quantitative approaches have been proposed for evaluating railway safety. For example, Braband and Schabe [31] applied statistical risk analysis using the Cox regression model to quantify accident likelihood, offering a foundation for structured, data-driven safety indicators. Similarly, Braband and Schäbe [32] developed a semi-formal approach to evaluate incident likelihood using both statistical probabilities and expert insights.

Semi-quantitative assessments have gained prominence in recent years due to their practical applicability in railway settings. Appoh and Yunusa-Kaltungo [33] introduced a dynamic hybrid model for comprehensive risk assessment, combining numerical indicators with expert knowledge to evaluate system safety in real time. Likewise, Boussif et al. [34] assessed operational risks in remote control and supervision systems through an integrated qualitative-quantitative approach.

Efforts to improve risk factor identification have also been observed through AI and data mining techniques. For instance, Alawad et al. [35] proposed two machine learning frameworks: one for learning from historical railway accidents to derive predictive insights, and another for developing a deep learning safety index capable of ranking risks and flagging hazards proactively [36]. In addition, Khalid et al. [37] introduced event tree analysis to address multi-stage accident progression and better simulate the chain of failures, a critical advancement in modeling low-frequency, high-impact events. Chang et al. [38] proposed a hybrid belief rule base for assessing railway system risk, accounting for both regional variability and data uncertainty in infrastructure reliability.

The challenge of integrating human and organizational variables in technical assessments was addressed by Li et al. [39], used computer vision to detect early warning signs in track component wear, and by Catelani et al. [40], applied FMECA (Failure Mode, Effects, and Criticality Analysis) to railway safety-critical systems, enabling structured evaluations of potential points of failure. From a system-wide perspective, Bulakh et al. [41] discussed the relationship between railway risk systems and organizational safety performance, offering insight into how institutional design influences accident prevention frameworks. Finally, Cheng [42] analyzed railway safety climate from an organizational angle, highlighting the importance of leadership engagement, procedural clarity, and workforce training in shaping safety culture.

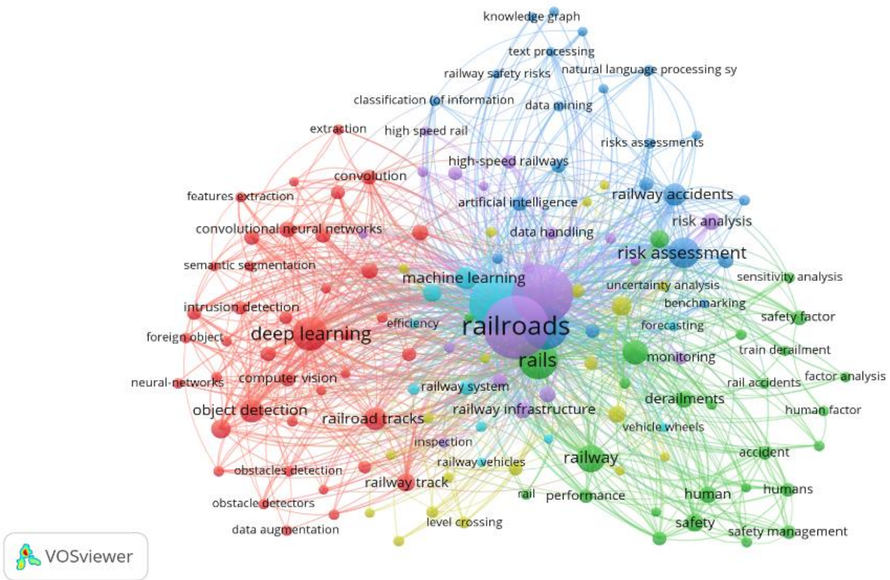

Figure 9. Co-Occurrence Network of Keywords

3.3.2. Cluster 2: Human Factors and Operational Safety

This cluster centers on keywords such as human, human factor, safety management, accident, and operator behavior, emphasizing the vital role of human performance in railway safety systems. The studies grouped in this category explore both the psychological and organizational dimensions of accident causation and prevention in rail environments.

A major strand of research focuses on how Human Reliability Assessment (HRA) frameworks and performance-shaping factors influence accident risk. For example, Gawlak [43] conducted a dedicated assessment of human factors in railway operations, proposing metrics for evaluating how human behavior affects safety outcomes under stress or workload. Complementing this, Nowakowski et al. [43] analyzed the role of driver perception and behavior during critical signal transitions, linking reaction time to error probability.

Organizational safety culture and its role in shaping operator performance have been widely discussed. Kecklund et al. [45] presented an integrated framework that combines technological, human, and organizational interactions, arguing for a systems-based perspective on railway safety culture and accountability. Similarly, Lefsrud et al. [13] advocated for performance-based regulation, allowing greater adaptability to human-system interactions across Canadian rail networks.

The psychological and cognitive aspects of human factors have been addressed by several studies. Hadj-Mabrouk [46] examined the cognitive workload and attention distribution of train drivers, proposing design improvements in user interfaces to enhance decision-making in time-constrained environments. In addition, Mizukami [25] and Omino [47] contributed a broad discussion on human science and behavior, reflecting a continued interest in sociotechnical integration . Some papers directly link human reliability to technological advances. Lloyd-Roberts et al. [48] emphasized the concept of human-in-the-loop AI, promoting systems where automation complements rather than replaces human oversight. Meanwhile, Jeon et al. [49] proposed an augmented reality-based inspection framework where human operators are guided by smart glasses to perform high-accuracy diagnostics.

Accident investigations and institutional preparedness have also been examined. Esmaeeli et al. [50] critically reviewed train derailments in Canada, using root-cause analysis to understand how organizational decisions and human errors contribute to systemic vulnerabilities. Li et al. [51] offered a hybrid human-organizational framework to analyze accident causes across various operational levels, from individual mistakes to policy deficiencies.

In addressing human limitations, Narasimha Swamy et al. [52] and Muhammed Nor et al. [53] provided insight into human fatigue, scheduling, and role clarity, reinforcing the need for continuous workforce training and ergonomic improvements. Lastly, Cooper et al. [54] introduced the use of Bayesian Belief Networks (BBNs) to model human error pathways, highlighting how probabilistic models can capture the uncertainty and variability inherent in human behavior. Together, these studies reveal a shift in railway safety research—from traditional fault attribution toward systemic, behavior-sensitive, and technology-aware approaches that place the human element at the center of safety strategies.

3.3.3 *Cluster 3: Infrastructure Control, Deep Learning, and Condition Monitoring*

This cluster is defined by high-frequency keywords such as deep learning, machine learning, computer vision, object detection, and monitoring systems—indicating the rapid digital transformation of railway safety research through intelligent infrastructure and AI-based technologies.

Several studies focus on fault detection, track condition monitoring, and real-time predictive maintenance. For example, Bernal et al. [18] reviewed onboard condition monitoring systems for freight trains, emphasizing the role of vibration and acoustic sensors in tracking mechanical health and identifying failure patterns in advance.

Alawad et al. [55] contributed two pivotal studies. The first proposed a framework for learning from historical railway accidents using machine learning classifiers to support predictive safety strategies. The second developed a deep learning-based safety index to proactively assess infrastructure vulnerabilities and rank safety priorities across railway systems [35].

The application of computer vision for object detection is a recurring theme. Cao et al. [56] designed an AI-based railway intrusion detection system using machine vision and image processing techniques, significantly reducing false alarm rates in security surveillance. To further enhance visibility in difficult conditions, Cao et al. [57] also introduced a method for haze removal in railway monitoring images, improving clarity and precision in optical inspections.

Arumugam et al. [58] applied deep learning architectures to detect potential accident risks by analyzing real-time sensor data, showcasing a fusion of environmental sensing and neural network modeling for safety prediction. Similarly, Alif et al. [59] performed a comparative study of various convolutional network models including CNN, CCT, and Swin Transformer for bolt detection and anomaly classification, highlighting the advantages of newer architectures for infrastructure diagnostics. Duan et al. [60] developed a backpropagation neural network model for railway accident risk prediction based on historical and environmental data, further expanding the toolkit for predictive analytics in operational planning. Another advanced model from Ding and Chen [61] utilized wavelet-based neural networks for track structure health assessment, capturing dynamic changes and micro-defects in real-time. Chiu [62] addressed the automation of regulatory inspection planning through an AI-driven framework, optimizing the deployment of inspection crews and sensor placement using historical performance trends and machine learning algorithms.

In terms of rail-object interaction and foreign object recognition, Ding et al. [63] created a multi-scale CNN framework for detecting object intrusion across rail boundaries, providing real-time alerts with high accuracy. These advancements are key for preventing collisions and service interruptions in urban and high-speed lines. Finally, Consilvio et al. [64] demonstrated a strain monitoring system that allows for the real-time detection of stress and deformation in rail tracks, ensuring preventive action before infrastructure failures occur. Collectively, these studies highlight a clear transition from manual and reactive maintenance strategies to smart, automated, and real-time safety control systems. The integration of deep learning, sensor fusion, and predictive intelligence offers scalable solutions for enhancing both the operational integrity and safety assurance of railway infrastructure.

4. FUTURE RESEARCH PATHWAYS IN RAILWAY SAFETY

Drawing upon the bibliometric insights and thematic classifications identified in this study, several underexplored and emerging areas in railway safety research have been brought to light. These areas not only reflect current technological and operational transitions but also align with the increasing demand for more resilient, intelligent, and human-centered railway systems. As rail transport systems face evolving safety challenges, it is imperative that future research strategically addresses these knowledge gaps.

One promising area is the advancement of predictive maintenance across diverse rail networks. Recent studies have highlighted the effectiveness of AI-based predictive maintenance in prolonging the lifecycle of critical components and reducing unexpected downtimes [65], [66]. However, these solutions often lack scalability and adaptability across different infrastructural and geographical contexts, especially in low-resource environments. Moreover, human reliability remains insufficiently integrated into these models. Future research should aim to incorporate operator behaviors and human error probabilities to develop more comprehensive and context-sensitive predictive maintenance frameworks.

Another critical frontier is the integration of AI-augmented safety systems with robust cybersecurity mechanisms. Artificial intelligence has facilitated the development of intelligent decision-support tools and advanced human-machine interfaces in train operations. Despite growing adoption, studies indicate ongoing vulnerabilities within cyber-physical systems, particularly regarding signaling networks and train control communication [3], [67], [68].To address these threats, there is a pressing need for standardized cybersecurity frameworks that include real-time intrusion detection, system hardening protocols, and resilience evaluation under adversarial conditions.

In addition, there is a need to rethink how human factors are embedded in risk evaluation frameworks. While human error remains a predominant contributor to rail accidents, existing semi-quantitative models often rely on oversimplified indicators such as education level or years of experience. This narrow view neglects more complex cognitive and psychological influences. Future frameworks should integrate variables like fatigue, stress levels, and risk perception. The development of multidimensional Human Reliability Assessment (HRA) models—especially those enhanced by AI and machine learning—could yield deeper insights into safety-critical human behaviours [9], [69].

The increasing occurrence of climate-induced disasters underscores the urgent need for infrastructure that is resilient to natural hazards. While several studies have proposed vulnerability assessment tool [70], [71], few have translated these into actionable design guidelines or incorporated them into routine engineering practice. Future research should explore how real-time structural health monitoring can be integrated with disaster preparedness and rapid recovery frameworks. Such efforts would enable railway systems to quickly adapt to, and recover from, disruptions caused by extreme environmental events.

Train localization also remains a foundational aspect of railway safety. The shift toward virtual balises using GNSS-based localization systems within the European Rail Traffic Management System (ERTMS) represents a significant leap forward in cost-effectiveness and automation. However, these systems face critical challenges, including cyber risks and operational failure in GNSS-denied areas such as tunnels or dense urban environments [72], [73], [74]. Future advancements should explore multi-sensor fusion technologies, combining GNSS with inertial navigation systems, visual odometry, and other complementary tools to enhance accuracy, reliability, and operational continuity.

Lastly, enabling full autonomy in train operations presents both a technical and ethical challenge. Autonomous trains must exhibit real-time situational awareness, dynamic decision-making capabilities, and seamless interaction with mixed traffic environments [75]. While technologies for obstacle detection and automated scheduling are progressing, there remains a critical need to define operational boundaries for autonomous systems. Future studies should develop AI-driven fail-safe mechanisms, decision validation models, and frameworks for human override in high-risk scenarios. These initiatives are essential for ensuring safety, accountability, and public trust in next-generation rail operations.

6. CONCLUSION

This study has undertaken a comprehensive bibliometric analysis of railway safety research spanning the years 2019 to 2024, with the aim of mapping the intellectual structure, thematic evolution, and strategic directions within this increasingly critical domain. By systematically analyzing 326 high-quality publications sourced from Scopus and employing robust visualization tools such as VOSviewer and bibliometrix-R, the research offers a data-driven understanding of the field's progression, key contributors, influential works, and emerging focal points.

The findings reveal a substantial growth in scholarly activity over the past six years, driven by the global imperative to enhance the safety, reliability, and sustainability of rail transport systems. China has emerged as the most prolific and impactful contributor, followed by other major players including the United Kingdom, India, South Korea, and the United States. The international co-authorship networks further demonstrate the global nature of railway safety research, with interdisciplinary collaborations playing a vital role in shaping the discourse.

Through co-occurrence and cluster analysis, three dominant research streams were identified: (1) risk assessment and safety performance evaluation, (2) human factors and operational safety, and (3) infrastructure monitoring and AI-driven control systems. Collectively, these clusters reflect a paradigmatic shift from traditional safety assessments to intelligent, technology-enabled, and human-centered approaches. Studies within these themes have contributed valuable insights into predictive maintenance, human error modeling, cyber-physical system security, and sensor-integrated safety monitoring.

Despite these advancements, the analysis also highlights several underexplored areas requiring further inquiry. These include the need for more nuanced integration of human behavior in safety risk modeling, standardized frameworks for cybersecurity in autonomous systems, and resilient infrastructure designs capable of withstanding natural hazards. Moreover, with the advent of autonomous trains and smart rail networks, future research must address complex challenges related to situational awareness, ethical decision-making, and multi-sensor fusion technologies.

Ultimately, this study fills a critical gap in literature by offering a structured, quantitative overview of the field's development and identifying strategic classifications that can inform future research directions. The insights presented herein are intended to guide academics, industry practitioners, and policymakers in developing holistic, adaptive, and forward-looking safety strategies. As global transportation systems face increasing demands and evolving threats, the role of railway safety research will be paramount in ensuring the resilience, efficiency, and security of rail mobility in the decades to come.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Universitas Muhammadiyah Yogyakarta (UMY) for the continuous support provided throughout the course of this research. This work would not have been possible without the academic resources, institutional facilities, and collaborative environment offered by UMY.

REFERENCE

[1] C. Sun, W. Zhang, H. Wang, and P. Sun, "A Review of Research on the Security of Train Control Networks," in *2024 6th International Conference on System Reliability and Safety Engineering, SRSE 2024*, 2024, pp. 459–463. doi: 10.1109/SRSE63568.2024.10772416.

[2] Z. Chen *et al.*, "Developing CBTC system safety requirement hierarchy through STPA methodology," *Heliyon*, vol. 10, no. 11, 2024, doi: 10.1016/j.heliyon.2024.e31776.

[3] Z. Wang and X. Liu, "Cyber security of railway cyber-physical system (CPS) – A risk management methodology," *Communications in Transportation Research*, vol. 2, 2022, doi: 10.1016/j.commtr.2022.100078.

[4] L. Dong and X. Liu, "Research on Risk Evaluation Index System of City Regional Railway Operation Safety Based on SEM," in *ICCREM 2020: Intelligent Construction and Sustainable Buildings - Proceedings of the International Conference on Construction and Real Estate Management 2020*, 2020, pp. 155–162. doi: 10.1061/9780784483237.018.

[5] O. Bal, "Formation and management of safety culture in the railway industry: best practices and strategies," *Collection of scientific works of the State University of Infrastructure and Technologies series "Transport Systems and Technologies,"* no. 42, 2023, doi: 10.32703/2617-9059-2023-42-6.

[6] K. J. Lee, M. J. Kim, S. Y. Jang, B. D. Song, and M. S. Bang, "Analysis of Railway Accident Status and Perception of Railway Safety Management Workers for Improvement of Railway Safety Management System," *Journal of the Korean Society for Railway*, vol. 25, no. 1, pp. 71–80, 2022, doi: 10.7782/JKSR.2022.25.1.71.

[7] N. Makhija, S. M. Satapathy, and A. K. Dwivedi, "A systematic review and bibliometric analysis of community detection methodologies in dynamic networks," 2021. doi: 10.1504/IJBIS.2021.118631.

[8] W. M. Lim and S. Kumar, "Guidelines for interpreting the results of bibliometric analysis: A sensemaking approach," *Global Business and Organizational Excellence*, vol. 43, no. 2, 2024, doi: 10.1002/joe.22229.

[9] L. Ciani, G. Guidi, and G. Patrizi, "Human reliability in railway engineering: Literature review and bibliometric analysis of the last two decades," 2022. doi: 10.1016/j.ssci.2022.105755.

[10] S. A. Hassan, H. A. Amlan, N. E. Alias, M. A. Ab-Kadir, and N. S. A. Sukor, "Vulnerability of road transportation networks under natural hazards: A bibliometric analysis and review," *International Journal of Disaster Risk Reduction*, vol. 83, 2022, doi: 10.1016/j.ijdrr.2022.103393.

[11] F. Bădău, "RAILWAY INTERLOCKINGS – A REVIEW OF THE CURRENT STATE OF RAILWAY SAFETY TECHNOLOGY IN EUROPE," *Promet - Traffic and Transportation*, vol. 34, no. 3, 2022, doi: 10.7307/PTT.V34I3.3992.

[12] C. Lu and C. Cai, "Overview on safety management and maintenance of high-speed railway in China," 2020. doi: 10.1016/j.trgeo.2020.100397.

[13] L. Lefsrud, R. Macciotta, and A. Nkoro, "Performance-based regulations for safety management systems in the canadian railway industry: An analytical discussion," 2020. doi: 10.1139/cjce-2018-0513.

[14] B. Dezhkam and S. M. Eslami, "A review of methods for highway-railway crossings safety management process," *International Electronic Journal of Mathematics Education*, vol. 12, no. 3, 2021, doi: 10.29333/iejme/632.

[15] R. Kour, A. Patwardhan, A. Thaduri, and R. Karim, "A review on cybersecurity in railways," *Proc Inst Mech Eng F J Rail Rapid Transit*, vol. 237, no. 1, 2023, doi: 10.1177/09544097221089389.

[16] W. Gong, M. F. Akbar, G. N. Jawad, M. F. P. Mohamed, and M. N. A. Wahab, "Nondestructive Testing Technologies for Rail Inspection: A Review," 2022. doi: 10.3390/coatings12111790.

[17] A. Minardo *et al.*, "Innovative Photonic Sensors for Safety and Security, Part I: Fundamentals, Infrastructural and Ground Transportations," *Sensors*, vol. 23, no. 5, 2023, doi: 10.3390/s23052558.

[18] E. Bernal, M. Spiryagin, and C. Cole, "Onboard Condition Monitoring Sensors, Systems and Techniques for Freight Railway Vehicles: A Review," 2019. doi: 10.1109/JSEN.2018.2875160.

[19] L. Marques, S. Moro, and P. Ramos, "Literature Review on Problem Models and Solution Approaches for Managing Real-Time Passenger Train Operations: The Perspective of Train Operating Companies," in *Transportation Research Record*, vol. 2677, no. 1, 2023. doi: 10.1177/03611981221104810.

[20] M. Sedghi, O. Kauppila, B. Bergquist, E. Vanhatalo, and M. Kulahci, "A taxonomy of railway track maintenance planning and scheduling: A review and research trends," 2021. doi: 10.1016/j.ress.2021.107827.

[21] W. A. Skipper, A. Chalisey, and R. Lewis, "A review of railway sanding system research: Wheel/rail isolation, damage, and particle application," 2020. doi: 10.1177/0954409719851634.

[22] K. Oh *et al.*, "A Review of Deep Learning Applications for Railway Safety," 2022. doi: 10.3390/app122010572.

[23] T. Shi *et al.*, "A Survey on Multi-Sensor Fusion Perimeter Intrusion Detection in High-Speed Railways," *Sensors*, vol. 24, no. 17, 2024, doi: 10.3390/s24175463.

[24] V. Hromádka, J. Korytárová, E. Vítková, H. Seelmann, and T. Funk, "Benefits of Increased Railway Safety and Reliability and their Evaluation," *Tehnicki Glasnik*, vol. 17, no. 3, pp. 424–431, 2023, doi: 10.31803/tg-20221208095644.

[25] K. Omino, "Recent topics on human science for railways," *Quarterly Report of RTRI (Railway Technical Research Institute)*, vol. 61, no. 4, pp. 244–248, 2020, doi: 10.2219/RTRIQR.61.4_244.

[26] R. Taherkhani and M. Aziminezhad, "Human-building interaction: A bibliometric review," 2023. doi: 10.1016/j.buildenv.2023.110493.

[27] M. Aziminezhad and R. Taherkhani, "BIM for deconstruction: A review and bibliometric analysis," 2023. doi: 10.1016/j.jobe.2023.106683.

[28] T. Rahman, M. Zudhy Irawan, A. Noor Tajudin, M. Rizka Fahmi Amrozi, and I. Widyatmoko, "Knowledge mapping of cool pavement technologies for urban heat island Mitigation: A Systematic bibliometric analysis," 2023. doi: 10.1016/j.enbuild.2023.113133.

[29] J. F. Burnham, "Scopus database: A review," 2006. doi: 10.1186/1742-5581-3-1.

[30] S. Echchakoui, "Why and how to merge Scopus and Web of Science during bibliometric analysis: the case of sales force literature from 1912 to 2019," *Journal of Marketing Analytics*, vol. 8, no. 3, 2020, doi: 10.1057/s41270-020-00081-9.

[31] J. Braband and H. Schabe, "Application of the Cox Regression Model for analysis of Railway Safety Performance," in *Proceedings of the 31st European Safety and Reliability Conference, ESREL 2021*, C. B., C. M., B. D., and B. C., Eds., Siemens Mobility GmbH, Ackerstr. 22, Braunschweig, 38126, Germany: Research Publishing, Singapore, 2021, pp. 564–569. doi: 10.3850/978-981-18-2016-8_009-cd.

[32] J. Braband and H. Schäbe, "A semi-formal approach towards likelihood evaluation in cybersecurity risk assessment," in *Proceedings of the 29th European Safety and Reliability Conference, ESREL 2019*, B. M. and Z. E., Eds., Siemens Mobility GmbH, Braunschweig, Germany: Research Publishing Services, 2020, pp. 3943–3948. doi: 10.3850/978-981-11-2724-3_0230-cd.

[33] F. Appoh and A. Yunusa-Kaltungo, “Dynamic Hybrid Model for Comprehensive Risk Assessment: A Case Study of Train Derailment Due to Coupler Failure,” *IEEE Access*, vol. 10, pp. 24587–24600, 2022, doi: 10.1109/ACCESS.2022.3155494.

[34] A. Boussif, A. Tonk, J. Beugin, and S. Collart Dutilleul, “Operational risk assessment of railway remote driving system,” *Safety and Reliability*, vol. 42, no. 2–3, pp. 143–164, 2023, doi: 10.1080/09617353.2023.2226965.

[35] H. Alawad, S. Kaewunruen, and M. An, “Learning from Accidents: Machine Learning for Safety at Railway Stations,” *IEEE Access*, vol. 8, pp. 633–648, 2020, doi: 10.1109/ACCESS.2019.2962072.

[36] H. Alawad, S. Kaewunruen, and M. An, “A Deep Learning Approach towards Railway Safety Risk Assessment,” *IEEE Access*, vol. 8, pp. 102811–102832, 2020, doi: 10.1109/ACCESS.2020.2997946.

[37] N. I. M. Khalid, N. F. N. Najdi, N. F. K. Adlee, M. Misiran, and H. Sapiri, “Assessing railway accident risk through event tree analysis,” in *AIP Conference Proceedings*, I. H., Y. A.M., A. N., and Z. J., Eds., School of Quantitative Sciences, Universiti Utara Malaysia, UUM Sintok, Kedah, 06010, Malaysia: American Institute of Physics Inc., 2019. doi: 10.1063/1.5121060.

[38] L. Chang *et al.*, “Hybrid belief rule base for regional railway safety assessment with data and knowledge under uncertainty,” *Inf Sci (N Y)*, vol. 518, pp. 376–395, 2020, doi: 10.1016/j.ins.2019.12.035.

[39] Z.-N. Li, W. Liu, L.-J. Han, and S.-Q. Yin, “Research on track invasion foreign object detection system and method based on two-dimensional LiDAR,” *Guangdianzi Jiguang/Journal of Optoelectronics Laser*, vol. 31, no. 3, pp. 262–268, 2020, doi: 10.16136/j.joel.2020.03.0096.

[40] M. Catelani, L. Ciani, D. Galar, G. Guidi, S. Matucci, and G. Patrizi, “FMECA Assessment for Railway Safety-Critical Systems Investigating a New Risk Threshold Method,” *IEEE Access*, vol. 9, pp. 86243–86253, 2021, doi: 10.1109/ACCESS.2021.3088948.

[41] M. Bulakh, A. Okorokov, and D. Baranovskyi, “Risk System and Railway Safety,” in *IOP Conference Series: Earth and Environmental Science*, S. D.B., Ed., The Faculty of Mechanics and Technology, Rzeszow University of Technology, Kwiatkowski str. 4, Stalowa Wola, 37-450, Poland: IOP Publishing Ltd, 2021. doi: 10.1088/1755-1315/666/4/042074.

[42] Y.-H. Cheng, “Railway safety climate: a study on organizational development,” *International Journal of Occupational Safety and Ergonomics*, vol. 25, no. 2, pp. 200–216, 2019, doi: 10.1080/10803548.2017.1361591.

[43] K. Gawlak, “Analysis and assessment of the human factor as a cause of occurrence of selected railway accidents and incidents,” *Open Engineering*, vol. 13, no. 1, 2023, doi: 10.1515/eng-2022-0398.

[44] W. Nowakowski, T. Ciszewski, and Z. Łukasik, “Analysis of the impact of human factors on the occurrence of rail accidents,” in *Transport Means - Proceedings of the International Conference*, Kazimierz Pulaski University of Technology and Humanities in Radom, Malczewskiego 29, Radom, 26-600, Poland: Kauno Technologijos Universitetas, 2020, pp. 437–441. [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85100135300&partnerID=40&md5=59f0db45f5e92a24b773514fc54bee36

[45] L. Kecklund, J. Skriver, S. Petterson, and M. Lavin, “Integrating Humans, Technology and Organization (HTO) in European Railway Safety Management Systems,” in *Advances in Intelligent Systems and Computing*, B. S., A. T., F. Y., T. R., and A. S., Eds., MTO Safety AB, PO Box 171 07, Stockholm, 104 62, Sweden: Springer Verlag, 2019, pp. 337–343. doi: 10.1007/978-3-319-96080-7_39.

[46] H. Hadj-Mabrouk, “Human factors affecting railway safety: Approach for considering human errors in investigations,” in *Handbook of Research on Decision Sciences and Applications in the Transportation Sector*, University Gustave Eiffel, France: IGI Global, 2021, pp. 92–123. doi: 10.4018/978-1-7998-8040-0.ch004.

[47] N. Mizukami, “Recent Topics on Human Science for Railways,” *Quarterly Report of RTRI (Railway Technical Research Institute)*, vol. 63, no. 4, pp. 234–237, 2022, doi: 10.2219/RTRIQR.63.4_234.

[48] B. Lloyd-Roberts, P. James, M. Edwards, S. Robinson, and T. Werner, “Improving Railway Safety: Human-in-the-loop Invariant Finding,” in *Conference on Human Factors in Computing Systems - Proceedings*, Computer Science, Swansea University, Swansea, United Kingdom: Association for Computing Machinery, 2023. doi: 10.1145/3544549.3573853.

[49] H. Jeon, Y. Yu, B. Ko, S. Kim, and B. Koo, “Augmented reality-based safety inspection framework for safety management in railway bridge and tunnel projects,” *Journal of the Korean Society for Railway*, vol. 24, no. 7, pp. 590–607, 2021, doi: 10.7782/JKSR.2021.24.7.590.

[50] N. Esmaeeli, F. Sattari, L. Lefsrud, and R. Macciotta, “Critical Analysis of Train Derailments in Canada through Process Safety Techniques and Insights into Enhanced Safety Management Systems,” in *Transportation Research Record*, vol. 2676, no. 4, Department of Chemical and Materials Engineering,

University of Alberta, Edmonton, AB, Canada: SAGE Publications Ltd, 2022, pp. 603–625. doi: 10.1177/03611981211062893.

[51] C. Li, T. Tang, M. M. Chatzimichailidou, G. T. Jun, and P. Waterson, "A hybrid human and organisational analysis method for railway accidents based on STAMP-HFACS and human information processing," *Appl Ergon*, vol. 79, pp. 122–142, 2019, doi: 10.1016/j.apergo.2018.12.011.

[52] S. Narasimha Swamy, S. Kushaal, S. Kumar, R. Aithal, and M. N. Vijayalakshmi, "Enhancing Railway Safety Through Human Activity Recognition," in *8th IEEE International Conference on Computational System and Information Technology for Sustainable Solutions, CSITSS 2024*, Rv College of Engineering, Department of Aiml, Bengaluru, India: Institute of Electrical and Electronics Engineers Inc., 2024. doi: 10.1109/CSITSS64042.2024.10816793.

[53] M. A. Muhammed Nor *et al.*, "'Role of Human Factor for the Implementation of the "Vision Zero" Concept in Railway Transport: An Overview,'" in *AIP Conference Proceedings*, R. D., K. K., M. Z., and N. R.M., Eds., Faculty of Mechanical and Automotive Engineering, Universiti Malaysia Pahang, Pahang, Pekan, 26600, Malaysia: American Institute of Physics, 2024. doi: 10.1063/5.0189251.

[54] A. Cooper, F. Mazzeo, P. Waterson, M. S. Young, and D. Louis, "The use of Bayesian Belief Networks (BBNs) to probe deeper into railway safety management systems – Two studies from Great Britain and Italy," *Appl Ergon*, vol. 109, 2023, doi: 10.1016/j.apergo.2023.103968.

[55] H. Alawad, S. Kaewunruen, and A. Min, "Utilizing Big Data for Enhancing Passenger Safety in Railway Stations," in *IOP Conference Series: Materials Science and Engineering*, Y. I., M. M., D. M., U. 8215/1 University of Zilina Zilina, D. A.M., T. D., and N. D., Eds., Birmingham Centre for Railway Research and Education, University of Birmingham, Birmingham, B15 2TT, United Kingdom: Institute of Physics Publishing, 2019. doi: 10.1088/1757-899X/603/5/052031.

[56] Z. Cao *et al.*, "Railway Intrusion Detection Based on Machine Vision: A Survey, Challenges, and Perspectives," *IEEE Transactions on Intelligent Transportation Systems*, vol. 25, no. 7, pp. 6427–6448, 2024, doi: 10.1109/TITS.2024.3412170.

[57] Z. Cao *et al.*, "Haze Removal of Railway Monitoring Images Using Multi-Scale Residual Network," *IEEE Transactions on Intelligent Transportation Systems*, vol. 22, no. 12, pp. 7460–7473, 2021, doi: 10.1109/TITS.2020.3003129.

[58] M. Arumugam, G. Arun, and C. Dhanapal, "Detection of Railway Accident Risk Using Deep Learning Approach," in *2024 OPJU International Technology Conference on Smart Computing for Innovation and Advancement in Industry 4.0, OTCON 2024*, Kongu Engineering College, Department of CT-PG, Perundurai, India: Institute of Electrical and Electronics Engineers Inc., 2024. doi: 10.1109/OTCON60325.2024.10687379.

[59] M. A. R. Alif, M. Hussain, G. Tucker, and S. Iwnicki, "BoltVision: A Comparative Analysis of CNN, CCT, and ViT in Achieving High Accuracy for Missing Bolt Classification in Train Components," *Machines*, vol. 12, no. 2, 2024, doi: 10.3390/machines12020093.

[60] J. Duan, T. Bai, B. Lv, H. Zong, and H. Fu, "Lightweight Detection of Fasteners with YOLOv8 Combined with ShuffleNetV2," in *Lecture Notes in Electrical Engineering*, Y. J., Y. D., J. L., Q. Y., L. Z., and D. L., Eds., School of Mechanical-Electronic and Vehicle Engineering, Engineering and Architecture, Beijing University of Civil, Beijing, 100044, China: Springer Science and Business Media Deutschland GmbH, 2024, pp. 480–489. doi: 10.1007/978-981-99-9315-4_46.

[61] Y. Ding and D.-R. Chen, "Wavelet-based neural network model for track stiffness signal detection," *Int J Wavelets Multiresolut Inf Process*, vol. 22, no. 3, 2024, doi: 10.1142/S021969132350056X.

[62] C. M. Y. Chiu, "AI-Driven railway regulator inspection planning system: enhancing railway safety inspection prioritisation and incident management," *HKIE Transactions Hong Kong Institution of Engineers*, vol. 31, no. 4, pp. 1–7, 2024, doi: 10.33430/V31N4THIE-2024-0012.

[63] M. Ding, G. Yu, and X. Wang, "Construction of safety culture for heavy haul railway during 14th Five-Year plan period," *China Safety Science Journal*, vol. 32, pp. 172–176, 2022, doi: 10.16265/j.cnki.issn1003-3033.2022.S2.0195.

[64] A. Consilvio, M. Iorani, V. Iovane, M. Sciutto, and G. Sciutto, "Real-time monitoring of the longitudinal strain of Continuous Welded Rail for safety improvement," *Proc Inst Mech Eng F J Rail Rapid Transit*, vol. 234, no. 10, pp. 1238–1252, 2020, doi: 10.1177/0954409719890166.

[65] P. G. Martínez-Llop, J. D. S. Bobi, Á. S. Jiménez, and J. G. Sánchez, "Condition-based maintenance for normal behaviour characterisation of railway car-body acceleration applying neural networks," *Sustainability (Switzerland)*, vol. 13, no. 21, 2021, doi: 10.3390/su132112265.

[66] H. Lin, N. Hu, Q. He, Z. Zhao, and W. Bai, "Construction of a Multi-Modal Knowledge Graph for Railway Equipment Operation and Maintenance Based on Building Information Model Data-Driven Approach," *Tongji Daxue Xuebao/Journal of Tongji University*, vol. 52, no. 2, 2024, doi: 10.11908/j.issn.0253-374x.23362.

[67] E. Thron, S. Faily, H. Dogan, and M. Freer, "Human factors and cyber-security risks on the railway – the critical role played by signalling operations," *Information and Computer Security*, vol. 32, no. 2, 2024, doi: 10.1108/ICS-05-2023-0078.

[68] S. Soderi, D. Masti, and Y. Z. Lun, "Railway Cyber-Security in the Era of Interconnected Systems: A Survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 7, 2023, doi: 10.1109/TITS.2023.3254442.

[69] Y. Jiao *et al.*, "Data-Driven Detection and Assessment for Urban Railway Transit Driver Fatigue in Real Work Conditions," in *Transportation Research Record*, vol. 2677, no. 1, School of Transportation & Logistics, Southwest Jiaotong University, Sichuan, Chengdu, China: SAGE Publications Ltd, 2023, pp. 1367–1375. doi: 10.1177/03611981221104689.

[70] A. H. S. Garmabaki *et al.*, "Risk Assessment of Climate Change Impacts on Railway Infrastructure Asset," in *Lecture Notes in Mechanical Engineering*, 2024. doi: 10.1007/978-3-031-39619-9_57.

[71] C. Szymula and N. Bešinović, "Passenger-centered vulnerability assessment of railway networks," *Transportation Research Part B: Methodological*, vol. 136, 2020, doi: 10.1016/j.trb.2020.03.008.

[72] C. Xu, H. Hu, and H. Wang, "A Theoretical Study on the Resilience Evaluation Method of Operational Road Tunnel Systems," *Applied Sciences (Switzerland)*, vol. 13, no. 24, 2023, doi: 10.3390/app132413279.

[73] D. Švorc, T. Tichý, M. Růžička, and P. Ivasienko, "Use of One-Stage Detector and Feature Detector in Infrared Video on Transport Infrastructure and Tunnels," *Sustainability (Switzerland)*, vol. 15, no. 3, 2023, doi: 10.3390/su15032122.

[74] I. Tušer and Š. Hošková-Mayerová, "Traffic safety sustainability and population protection in road tunnels," *Qual Quant*, vol. 57, 2023, doi: 10.1007/s11135-020-01003-8.

[75] P. Singh, M. A. Dulebenets, J. Pasha, E. D. R. S. Gonzalez, Y. Y. Lau, and R. Kampmann, "Deployment of Autonomous Trains in Rail Transportation: Current Trends and Existing Challenges," 2021. doi: 10.1109/ACCESS.2021.3091550.

[76] M. Ishige, "Recent activities in vehicle technology research and development," *Quarterly Report of RTRI (Railway Technical Research Institute)*, vol. 62, no. 1, pp. 1–5, 2021, doi: 10.2219/RTRIQR.62.1_1.

[77] J. Wang, H. Zhai, Y. Yang, N. Xu, H. Li, and D. Fu, "A Review of Intrusion Detection for Railway Perimeter Using Deep Learning-Based Methods," *IEEE Access*, vol. 12, pp. 184142–184157, 2024, doi: 10.1109/ACCESS.2024.3510746.

[78] Y. Cao, Y. An, S. Su, G. Xie, and Y. Sun, "A statistical study of railway safety in China and Japan 1990–2020," *Accid Anal Prev*, vol. 175, 2022, doi: 10.1016/j.aap.2022.106764.

[79] J. Li *et al.*, "Pattern Recognition for Distributed Optical Fiber Vibration Sensing: A Review," *IEEE Sens J*, vol. 21, no. 10, pp. 11983–11998, 2021, doi: 10.1109/JSEN.2021.3066037.

[80] C. Liu and S. Yang, "Using text mining to establish knowledge graph from accident/incident reports in risk assessment," *Expert Syst Appl*, vol. 207, 2022, doi: 10.1016/j.eswa.2022.117991.

[81] L. Guan, L. Jia, Z. Xie, and C. Yin, "A Lightweight Framework for Obstacle Detection in the Railway Image Based on Fast Region Proposal and Improved YOLO-Tiny Network," *IEEE Trans Instrum Meas*, vol. 71, 2022, doi: 10.1109/TIM.2022.3150584.

[82] A. Kampczyk and K. Dybeł, "The fundamental approach of the digital twin application in railway turnouts with innovative monitoring of weather conditions," *Sensors*, vol. 21, no. 17, 2021, doi: 10.3390/s21175757.

[83] Z. Wang *et al.*, "Practical multi-class event classification approach for distributed vibration sensing using deep dual path network," *Opt Express*, vol. 27, no. 17, pp. 23682–23892, 2019, doi: 10.1364/OE.27.023682.