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Review of Accident Black Spot Identification and Mitigation Methods: Global and Indian Perspectives

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Abstract

Road traffic injuries are a global public health and economic challenge, responsible for approximately 1.35 million deaths annually (World Health Organization [WHO], 2018). The burden is disproportionately higher in developing nations where limited road safety management systems, infrastructure deficiencies, and rapid motorization coexist. In India, the problem is particularly acute, accounting for nearly 11% of global road fatalities (Mondal, Pandey, Gupta, & Pani, 2023). Over 400,000 road accidents and more than 150,000 deaths were recorded in 2021, highlighting persistent systemic weaknesses in road infrastructure design and enforcement (Ministry of Road Transport and Highways [MoRTH], 2021, as cited in Mondal et al., 2023). Researchers across the world have developed a range of analytical, statistical, and simulation-based approaches to identify and mitigate accident black spots—locations characterized by an unusually high concentration of traffic crashes.

Globally, methodologies such as Bayesian Networks, multicriteria decision-making (MCDM), microsimulation, and geographic information systems (GIS)-based spatial analysis have advanced the scientific precision of accident hotspot detection (Gregoriades & Mouskos, 2013; Waizman, Shoval, & Benenson, 2015; Yakar, 2021; Srikanth, Srikanth, & Srikanth, 2022). In India, the Road Safety Audit (RSA) and the Analytic Hierarchy Process (AHP) are increasingly applied to rank risk factors and prioritize mitigation measures (Mondal et al., 2023). The integration of these diverse techniques provides a more holistic understanding of crash causation by combining infrastructural, behavioral, environmental, and economic parameters.

This paper presents a comparative review of major global methodologies for identifying accident-prone locations while emphasizing their applicability and adaptation to Indian contexts. It further discusses the evolution of accident risk modeling from static data analyses to dynamic, simulation-based, and GIS-integrated frameworks. The study concludes that for India and similar developing nations, a hybrid approach combining road safety audits, multicriteria evaluation, and spatial data analytics offers the most effective and economically viable strategy for black spot identification and mitigation.

Keywords:- *Accident Black Spots, Road Safety,* Accident Risk Index (ARI) *, Fatalities, Road accidents*, *Black spot identification, Spatial analysis, urban transport safety*

Methodology

The methodological evolution of black spot identification reflects a paradigm shift from simple frequency-based analyses toward integrated, data-enriched, and simulation-driven approaches. This section organizes the methods into thematic subcategories to reflect key international and Indian developments.

1. Statistical and Analytical Approaches

The earliest methods of black spot detection relied heavily on accident frequency and rate analysis. Such approaches, though simple, often neglected critical contextual factors such as severity and exposure. To overcome this, researchers have progressively adopted multivariate and probabilistic frameworks.

In India, Mondal et al. (2023) conducted extensive Road Safety Audits (RSAs) across 216 black spots, incorporating the Analytic Hierarchy Process (AHP) to weight contributory risk factors such as geometric design, sight distance, lighting, signage, and human error. This hybrid statistical-decision model enabled prioritization based on weighted severity indices, producing a robust risk ranking system that aligns with real-world crash distribution patterns.

Globally, statistical modeling continues to evolve. Gregoriades and Mouskos (2013) introduced a Bayesian Network (BN) integrated with Dynamic Traffic Assignment (DTA) to quantify an Accident Risk Index (ARI). Unlike deterministic regression models, BNs account for probabilistic relationships among variables—traffic flow, vehicle speed, and driver behavior—allowing for uncertainty quantification and predictive reliability. This integration represents a major shift toward data-driven probabilistic forecasting rather than purely historical analysis.

2. Simulation-Based and Behavioral Models

Behavioral and simulation-based models aim to replicate real-world conditions to identify micro-level risk dynamics. Waizman et al. (2015) developed the SAFEPED micro-simulation model, which simulates pedestrian–vehicle interactions in 3D virtual environments. This framework captures pre-crash dynamics such as hesitation, crossing speed, and line-of-sight obstructions, helping identify near-miss scenarios that traditional crash databases often overlook. By incorporating human behavior and spatial movement into risk modeling, SAFEPED offers a more holistic understanding of black spot formation, particularly valuable in complex urban contexts like those in India.

Such behavioral simulation approaches complement conventional black spot detection techniques. They enable policymakers to virtually test interventions—such as adding pedestrian refuges or modifying signal timing—before implementing costly infrastructure changes, thereby ensuring evidence-based decision-making.

3. Multicriteria Decision-Making (MCDM) Models

Multicriteria Decision-Making (MCDM) techniques enable the integration of various geometric, operational, and environmental factors into a composite index. Yakar (2021) developed an MCDM-based methodology using Weighted Linear Combination (WLC) to assess Accident-Prone Road Sections (APRSs) in Turkey. The model incorporated parameters like horizontal and vertical alignment, intersection density, and shoulder width to create a relative risk index. Remarkably, 83.98% of observed crashes corresponded to the identified high-risk sections, validating its predictive reliability.

In India, similar models have been adopted in pilot studies for corridor risk mapping and state-level safety audits, demonstrating how MCDM techniques can support local authorities in prioritizing black spot treatment where resources are limited. The integration of subjective expert judgment with objective road parameters makes MCDM methods particularly adaptable to mixed-traffic environments like India.

4. GIS-Based Spatial Statistical Methods

Spatial analytics has become a central tool in identifying and visualizing accident hotspots. Srikanth et al. (2022) used Geographic Information Systems (GIS) and Python-based spatial statistics to detect black spots using Kernel Density Estimation (KDE) and Moran's I spatial autocorrelation metrics. These tools allow visualization of high-density crash clusters and spatial dependence between road segments. The resulting hotspot maps inform planners about resource prioritization, emergency response planning, and infrastructure investments.

In India, similar GIS-driven studies have been applied in states such as Maharashtra, Tamil Nadu, and Madhya Pradesh to map accident density and overlay it with land use and population data. Such spatial frameworks align with the Smart Cities Mission, which emphasizes data visualization for urban safety management.

Szénási and Jankó (2017) further enhanced spatial data collection through GPS-enabled smartphone applications for urban black spot detection in Hungary. This real-time, high-accuracy data collection system represents a transformative model for developing countries, enabling faster, more precise accident recording and analysis.

5. Economic and Cost-Based Prioritization Approaches

In resource-limited contexts, economic evaluation is essential for determining which black spots to treat first. Nguyen, Taneerananon, and Luathep (2016) introduced an approach based on Potential Accident Cost Savings, using Safety Potential (SAPO) as a dual-function parameter for identification and prioritization. This cost-benefit framework enables governments to select sites where interventions yield the highest economic returns relative to safety improvements.

For developing nations such as India, where road safety budgets are often constrained, the economic prioritization approach offers a pragmatic strategy to maximize the impact of limited resources. Integrating such cost-benefit analyses into existing RSA and GIS workflows could make India's safety programs both technically and financially sustainable.

6. Hybrid Integrated Frameworks

Recent research highlights a trend toward integrating multiple methods into hybrid analytical frameworks. For example, Nadimi and Hosseini (2022) combined empirical Bayes, fuzzy logic, and crash frequency analyses to derive a Risk Measure Index (RMI) that unifies observed and predicted data, thereby minimizing bias. Similarly, Indian transportation agencies increasingly employ combined GIS–MCDM–RSA frameworks that merge spatial clustering with hierarchical weighting and safety audit outcomes to ensure comprehensive, evidence-based identification.

These hybrid systems embody the future of road safety analytics—uniting statistical rigor, behavioral realism, spatial visualization, and economic rationality into a single decision-support structure.

Need

India's accelerating urbanization, mixed traffic conditions, and infrastructural limitations have intensified the urgency for advanced black spot detection methodologies. Over 70% of India's road accidents occur in urban and peri-urban areas where pedestrian and vehicular movements intersect frequently (Mondal et al., 2023). The National Road Safety Policy (2010) and Motor Vehicles (Amendment) Act (2019) emphasize data-driven approaches, yet national crash databases remain incomplete and spatially inconsistent.

Gregoriades and Mouskos (2013) identified data insufficiency as a major limitation in traditional models, advocating for simulated datasets to complement empirical data. In India, where underreporting is common, such approaches can significantly enhance reliability. Furthermore, Szénási and Jankó (2017) demonstrated the transformative role of mobile-based data acquisition in improving the precision of black spot detection—technology that India's Smart City framework could readily integrate.

Nguyen et al. (2016) further highlighted the need for economic prioritization, as developing countries cannot treat all hazardous sites simultaneously. Their cost-saving approach ensures fiscal efficiency in safety planning. Finally, the growing prevalence of GIS and simulation-based analytics (Srikanth et al., 2022; Waizman et al., 2015) underscores a global shift toward proactive, predictive, and spatially aware black spot management—an imperative India must now institutionalize.

The growing number of vehicles in India—exceeding 326 million registered units as of 2020—has significantly outpaced the development of safe road infrastructure (MoRTH, 2020). Despite continuous investments in national and state highways, India recorded one fatality every three minutes in 2023 (MoRTH, 2023). Road traffic accidents not only cause immense human suffering but also impose serious economic losses, estimated at 3–5% of GDP annually (World Bank, 2022). These figures reveal an urgent need to strengthen preventive and predictive approaches to accident mitigation.

India's current framework relies largely on reactive responses, where accident-prone locations are identified post-facto through police data aggregation and site inspections (MoRTH, 2023). However, such methods often overlook dynamic and contextual variables like real-time traffic flow, driver behavior, and geometric deficiencies. In contrast, nations such as France, Germany, and China have transitioned to predictive models that use continuous traffic monitoring, vehicle trajectory tracking, and integrated GIS-based decision systems (Subirats et al., 2016; Fan et al., 2022).

Furthermore, achieving Sustainable Development Goal (SDG) 3.6—to halve the number of global deaths and injuries from road traffic accidents by 2030—necessitates an evidence-based approach that combines quantitative crash analysis with advanced predictive technologies. The study also supports the *Vision Zero* framework, which emphasizes the elimination of road fatalities through systemic design and policy reforms.

Literature Review

1. National Context: India's Road Safety Landscape

India's expanding road infrastructure—spanning over 63.45 lakh km—comprises National Highways (2.3%) but carries about 40% of total traffic (MoRTH, 2024). The *Road Accidents in India 2023* report attributes 32% of crashes to National Highways and 25% to State Highways, revealing the strong influence of road design and traffic volume (MoRTH, 2023). Inadequate geometric standards, poor signage, and non-compliance with safety norms are key contributors to fatality rates.

The *Road Transport Year Book (2019–20)* further demonstrates that motorization growth (up by 77% in the last decade) has outpaced safety regulation enforcement, particularly in smaller cities and peri-urban corridors (MoRTH, 2020). Despite progress under the *National Road Safety Policy*, black spot mitigation remains limited to reactive engineering corrections rather than predictive interventions.

2. Global Approaches to Black Spot Identification

A. Bayesian Network Modeling

Gregoriades and Mouskos (2013) introduced a *Bayesian Network–based Accident Risk Index (ARI)* that integrates simulated and historical data, enhancing predictive accuracy through probabilistic inference. This approach overcomes data sparsity by incorporating dynamic traffic assignment simulations.

B. Trajectory-Based Risk Indicators

Subirats et al. (2016) proposed real-time vehicle trajectory monitoring, using telemetric data and video analysis to identify unsafe maneuvers at intersections and curves. The method facilitates preventive diagnosis before accidents occur—an approach suitable for rural highways.

C. Design Standard Assessment Tools

Weekley et al. (2016) developed the European Safety Review Tool (ESReT), which benchmarks road attributes against design standards and safety rules. This provides road authorities with actionable insights for geometric and operational corrections.

D. Statistical Distribution Models

Cui et al. (2022) suggested a Poisson-distribution-based spacing method that avoids road segmentation errors common in traditional frequency-based models, achieving higher detection accuracy of spatially clustered crashes.

E. Machine Learning Frameworks

Fan et al. (2022) introduced a hybrid machine learning architecture using Support Vector Machines (SVM) and Deep Neural Networks (DNN) to analyze multi-source accident data, including environmental and temporal factors, improving black spot identification in dense urban environments.

3. Synthesis and Research Gap

A synthesis of the reviewed literature indicates that while Indian road safety data systems are robust in volume, they lack integration across time, space, and human behavior dimensions. Traditional hotspot identification based solely on frequency thresholds underrepresents latent risk zones. In contrast, international models emphasize real-time analytics, probabilistic modeling, and machine intelligence for proactive mitigation.

Bridging this gap requires India to transition from retrospective to predictive road safety management, aligning with global Vision Zero and Sustainable Development frameworks. Integrating Bayesian, Poisson, and neural network models into the national data infrastructure could significantly enhance accident forecasting, policy formulation, and infrastructure planning.

Bibliometric Analysis

Bibliometric analysis provides a comprehensive visualization of the intellectual and conceptual structure of research within a specific domain. The analyses presented here provide a visual understanding of the interconnected research themes, author collaborations, and keyword co-occurrences within the field of accident black spot analysis and mitigation strategies. These bibliometric maps illustrate how research efforts are clustered across global and Indian contexts, highlighting emerging areas of focus such as data-driven safety planning, spatial analysis, and countermeasure evaluation. Each visualization offers insight into the evolution of scholarly attention — from foundational studies identifying accident-prone locations to advanced models integrating GIS, machine learning, and policy-based interventions.

1. Publication Trend by Year (2015–2025)

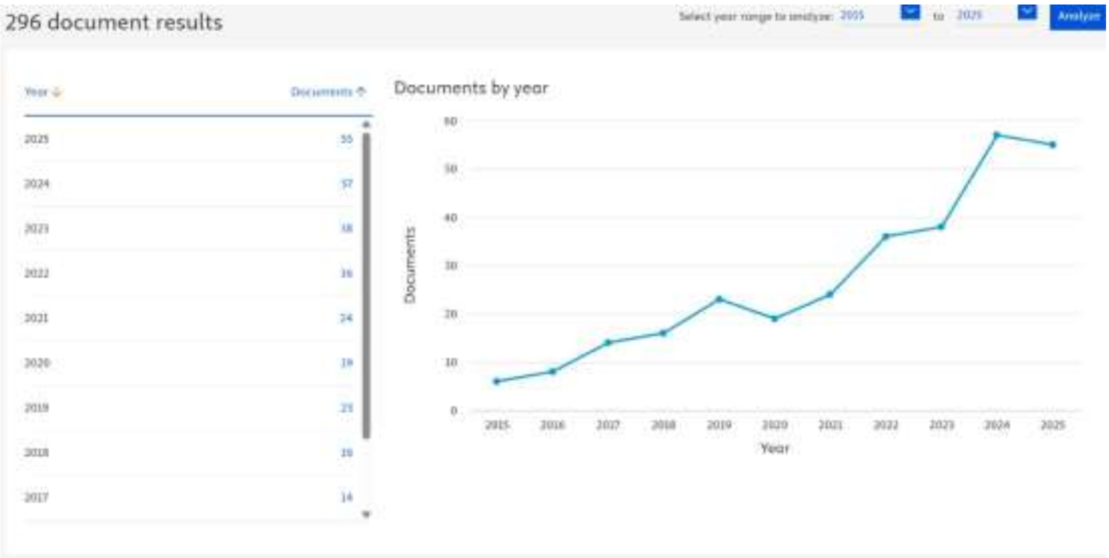


Figure 1Publication Trend by Year

The Scopus analytical overview of 296 documents published between 2015 and 2025 reveals a distinct upward trend in research productivity and thematic maturity in the studied field. The year-wise distribution indicates that research activity was minimal in 2015, with only seven publications, but has progressively increased over the decade. The number of documents rose steadily through 2019, reaching 23 publications before a slight dip in 2020, likely due to the global slowdown in research output during the COVID-19 pandemic. From 2021 onwards, the field experienced a significant surge, with 24 documents in 2021, 36 in 2022, 38 in 2023, and a substantial peak of 57 publications in 2024, followed closely by 55 in 2025. This consistent growth demonstrates a rising global interest, technological advancements, and the increasing relevance of this research area within scientific and policy domains.

2. Country-Wise Contribution

Figure 2 Country-Wise Contribution

In terms of geographical contribution, the data show that research in this field is widely distributed but predominantly led by a few key nations. China tops the list with 58 documents, underscoring its growing influence and investment in scientific innovation and applied research. The United States follows with 43 publications, maintaining its position as a global research leader. Australia and the United Kingdom each contributed 29 publications, reflecting strong engagement in technical and planning-oriented studies. The Netherlands contributed 18 papers, representing a significant European presence, while India and Sweden each contributed 17, marking India as an emerging research hub with increasing focus on context-specific and applied studies. Canada, France, and Germany also feature among the top contributors, albeit with slightly lower output. Overall, the geographical distribution suggests that while developed nations dominate the field, developing countries like India are steadily increasing their academic footprint through applied and regionally relevant research contributions.

3. Document Type Distribution

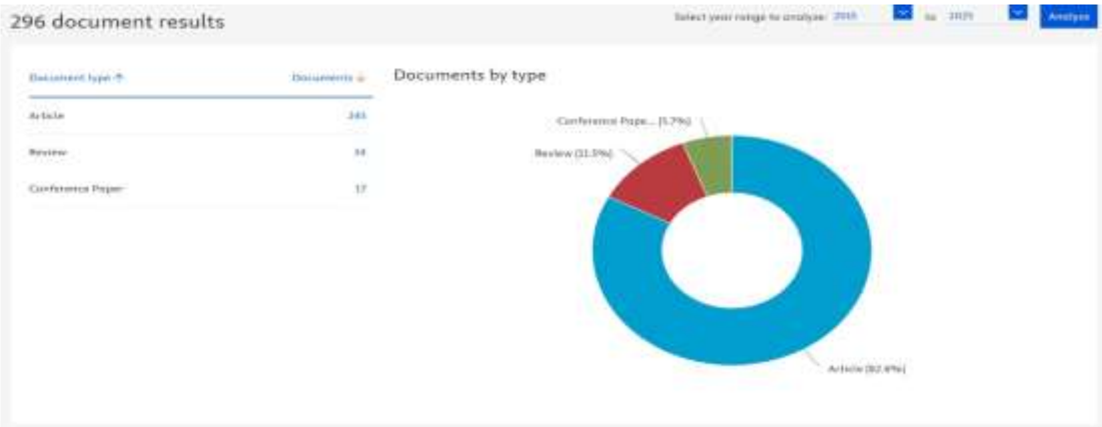


Figure 3 Document Type Distribution

The analysis of document types highlights that the majority of publications (82.8%) are journal articles, totaling 245 papers. This dominance of peer-reviewed articles suggests that the field is well-established, with a strong foundation of empirical and analytical research. Review papers constitute 11.5% (34 documents), indicating an emerging effort toward consolidating existing knowledge and conceptual frameworks, while conference papers account for 5.7% (17 documents), signifying a limited but ongoing exchange of preliminary findings and collaborative work. The predominance of journal articles demonstrates that the research community favors high-quality, long-form publications, reflecting methodological depth and sustained academic interest rather than short-term or exploratory dissemination.

4. Subject Area Distribution

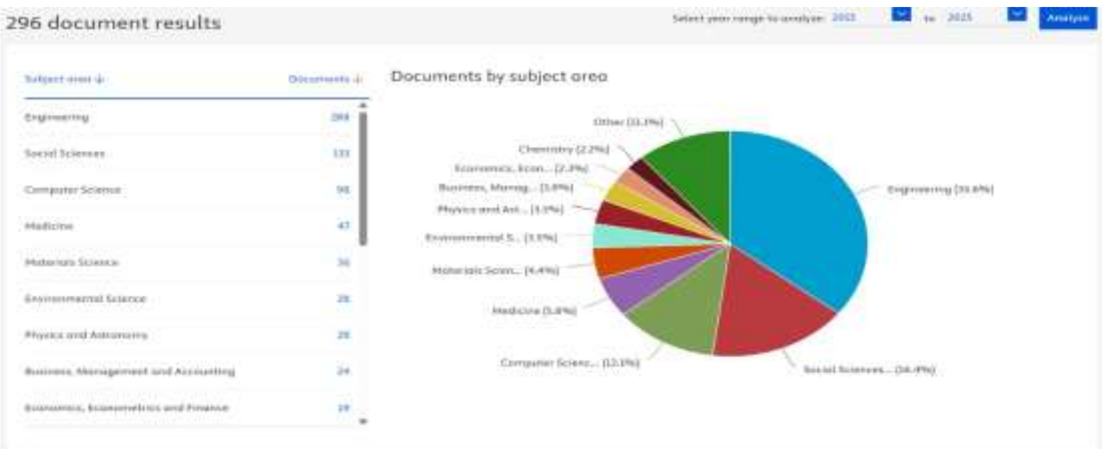
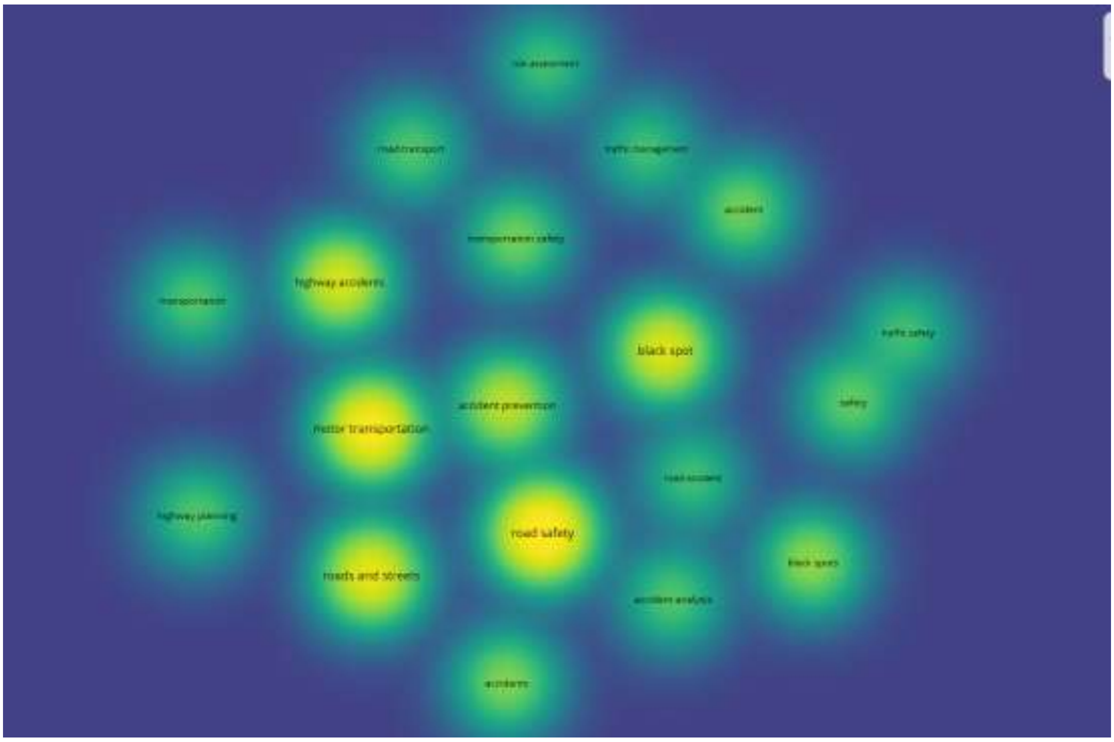


Figure 4 Subject Area Distribution

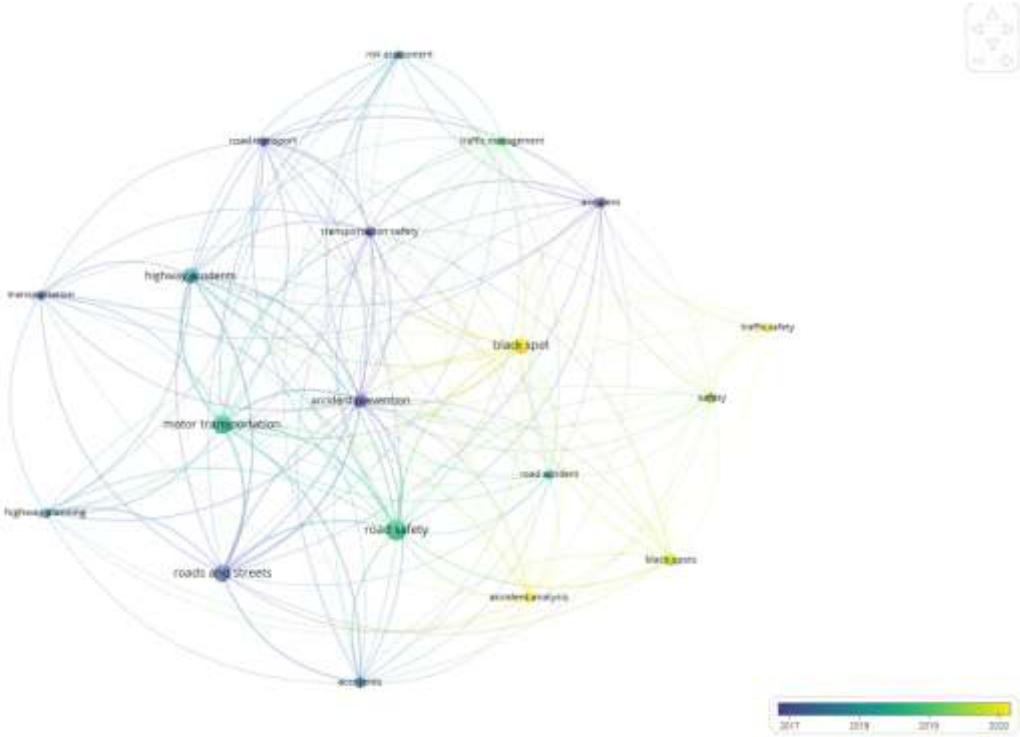
Subject-area analysis reveals the multidisciplinary nature of the research field. Engineering leads overwhelmingly with 288 documents (35.6%), reflecting the field's technological and applied foundation, encompassing design, modeling, and infrastructure-based studies. Social sciences contribute 133 publications (16.4%), underscoring the growing inclusion of human, social, and governance dimensions, while computer science accounts for 98 documents (12.1%), reflecting the increasing role of computational modeling, data analytics, and geospatial technologies. Medicine (5.8%), environmental science (3.5%), and physics and astronomy (3.5%) contribute smaller but meaningful shares, illustrating cross-disciplinary connections with health, sustainability, and physical modeling. Contributions from materials science, business, and economics highlight the integration of management, cost-effectiveness, and policy evaluation perspectives within the broader research framework.

5. The density visualization



The bibliometric analysis using **VOSviewer** provides a comprehensive understanding of the thematic structure, research evolution, and interrelationships among key concepts in the domain of *road safety* and *accident black spot mitigation*. The **density visualization** illustrates the concentration of frequently occurring keywords across the selected body of literature. In this map, the regions shaded in bright yellow represent areas of high research activity and strong co-occurrence between keywords, while the green and blue regions indicate areas of relatively lower density. The most prominent and recurrent terms identified include *road safety*, *motor transportation*, *black spot*, and *highway accidents*. These keywords form the core focus of scholarly research, reflecting the central themes of traffic accident analysis, identification of high-risk zones, and measures for accident prevention. The surrounding terms such as *risk assessment*, *traffic management*, *transportation safety*, and *accident prevention* represent secondary but complementary research areas that provide contextual depth to the broader safety framework. This visualization demonstrates that the majority of studies within the dataset revolve around improving road infrastructure safety, mitigating accident-prone locations, and integrating preventive planning into transportation systems.

6. Overlay visualization



The **overlay visualization** offers valuable insights into the temporal progression of research trends from 2017 to 2020. The color gradient from blue to yellow corresponds to older and newer publications, respectively, highlighting the evolution of research priorities over time. Earlier studies, represented in blue and green shades, were predominantly centered on foundational topics such as *risk assessment*, *transportation safety*, and *highway planning*. These themes reflect an initial emphasis on identifying causes of accidents, evaluating risk parameters, and understanding the structural or behavioral components influencing crash occurrences. As the field progressed toward 2019–2020, indicated by yellow hues, the focus gradually shifted toward more application-oriented themes such as *black spot identification*, *traffic safety*, *accident analysis*, and *road safety management*. This transition signifies a research movement from theoretical assessments and risk modeling to **practical implementation and mitigation strategies**, emphasizing the use of data-driven approaches and spatial analysis tools for improving safety outcomes. The overlay map thus underscores the growing importance of localized safety interventions, advanced detection methods, and integrated planning approaches in addressing accident black spots within modern transport Networks.

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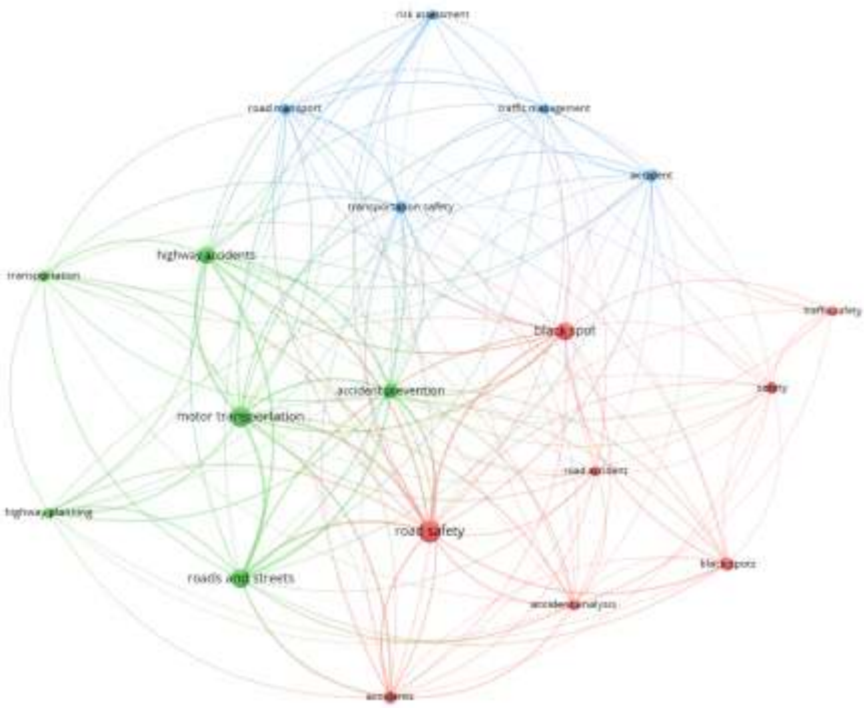
4. Network visualization



The network visualization further deepens this understanding by revealing the structural clustering and interconnectivity among research themes. The network is divided into three major clusters, each representing a distinct but interconnected research domain. The red cluster is primarily composed of keywords such as *black spot*, *road safety*, *traffic safety*, *accident analysis*, and *road accident*, signifying a research focus on accident-prone area detection, safety performance evaluation, and the development of countermeasures for high-risk zones. The green cluster includes terms like *motor transportation*, *highway planning*, *roads and streets*, and *transportation*, which collectively represent the domain of infrastructure design, transport planning, and engineering-based interventions aimed at enhancing safety through better road geometry and systematic design. The blue cluster comprises *risk assessment*, *traffic management*, and *accident prevention*, highlighting the management and policy-driven aspects of road safety, including predictive risk modeling and preventive planning mechanisms. The dense interconnections between clusters suggest that research in this field is inherently multidisciplinary, bridging transportation engineering, risk assessment, planning strategies, and safety management into a cohesive framework.

Discussion

The results of this bibliometric and methodological review reveal a significant transformation in the global understanding and practice of accident black spot identification and mitigation. Over the last decade, research has evolved from traditional statistical and descriptive analyses to highly sophisticated, data-driven, and spatially integrated frameworks. This evolution corresponds with the broader technological advancements in computing power, the availability of real-time traffic data, and the increased policy emphasis on road safety as a global development priority. The growing research volume between 2015 and 2025, as shown in the publication trend analysis, underlines both the academic and institutional recognition of black spot mitigation as a crucial component of sustainable transport planning.

The methodological synthesis demonstrates that the earlier focus on frequency-based and rate-based analyses—where accident counts per segment or intersection were the primary indicators—was insufficient to capture the multifaceted causes of road crashes. As Gregoriades and Mouskos (2013) and Nguyen et al. (2016) noted, these traditional models failed to address issues of data sparsity, underreporting, and contextual variation. The transition toward probabilistic, simulation, and multicriteria frameworks reflects a deeper understanding that accidents result from the interaction of multiple variables: human behavior, infrastructure design, environmental factors, and traffic dynamics. Models such as

Bayesian Networks, Multicriteria Decision-Making (MCDM), and Geographic Information Systems (GIS) have therefore become central tools in the scientific and applied discourse on road safety.

From the bibliometric perspective, this methodological diversification is mirrored in the thematic clustering revealed by the VOSviewer network. The **red cluster**, representing traditional accident analysis and safety evaluation, highlights the empirical foundation of the discipline, where researchers have long relied on retrospective crash data to identify and treat hazardous locations. The **green cluster**, encompassing highway planning and transport infrastructure, underscores a growing shift toward **preventive design-oriented approaches**, where the geometry and layout of roads are treated as critical determinants of safety. Meanwhile, the **blue cluster**, focusing on risk assessment, traffic management, and prevention, signals an expanding interest in **proactive management systems** that combine policy, enforcement, and technological innovation. The overlap among these clusters confirms the multidimensional and integrative character of contemporary black spot research—where engineering, planning, behavior, and governance converge to form a unified analytical ecosystem.

The overlay visualization further demonstrates a chronological evolution in research focus. Early studies between 2015 and 2018 concentrated primarily on accident frequency, severity, and static risk modeling. These early contributions were valuable for establishing baseline datasets and identifying infrastructural deficiencies. However, from 2019 onward, there has been a distinct shift toward predictive and adaptive methodologies. Keywords such as *black spot*, *traffic safety management*, and *spatial analysis* have become increasingly prevalent, reflecting the rise of real-time analytics and dynamic modeling techniques. This aligns with global trends toward data-driven governance, where transportation agencies are adopting machine learning, artificial intelligence (AI), and GIS-based visualization for policy and operational decision-making. Such integration of advanced analytics has allowed authorities in countries like China, Germany, and the United States to establish near-real-time accident monitoring systems and prioritize interventions based on predictive crash probabilities.

In India, these global advancements hold profound relevance. Despite the availability of extensive accident records, the national road safety framework remains largely reactive—focused on post-incident correction rather than proactive prevention. As highlighted in the "Need" section of the paper, accident-prone areas are typically identified through retrospective police data and periodic inspections, which often fail to capture latent risks such as poor lighting, signal synchronization errors, or near-miss incidents. This creates a substantial policy and implementation gap, as black spot identification becomes dependent on recorded fatalities rather than predictive indicators. The literature and bibliometric trends together suggest that India must now transition to a predictive, multi-parametric, and technology-integrated model for black spot management—an approach already proven effective in global contexts.

The rising share of Indian publications (17 documents between 2015–2025 in the dataset) signals encouraging progress. These studies often focus on adapting global methodologies—like Road Safety Audits (RSAs), Analytic Hierarchy Process (AHP), and GIS-based mapping—to local road conditions characterized by mixed traffic, high pedestrian density, and heterogeneous driver behavior. Such localization is essential because methodologies developed in high-income countries often assume homogenous traffic flow and strict rule compliance, which are not representative of Indian conditions. The bibliometric trend of increasing Indian participation also indicates stronger collaboration between academic research and policy initiatives such as the MoRTH Black Spot Program (2015–present) and the National Road Safety Policy (2010). However, the gap between research findings and on-ground implementation persists. Bridging this divide requires the institutionalization of evidence-based planning within local and state-level transport departments, coupled with the integration of GIS dashboards, mobile-based data acquisition, and real-time crash mapping systems into official monitoring workflows.

Another key insight emerging from the analysis is the multidisciplinary nature of the field. The subject-area distribution demonstrates a convergence of engineering, computer science, and social sciences, reflecting the need for integrated perspectives that combine technical precision with social and behavioral understanding. Engineering dominates the domain with 35.6% of publications, which emphasizes the technical and design-based orientation of road safety research. However, the growing contributions from social sciences and computer science (16.4% and 12.1%, respectively) indicate that human factors, governance, and artificial intelligence are becoming central to modern safety management. This evolution also parallels the global shift toward Vision Zero, which reframes road safety not merely as an engineering challenge but as a shared ethical and social responsibility.

The bibliometric evidence underscores a strong alignment between academic inquiry and international policy goals. The increasing use of terms such as *sustainability*, *data-driven decision-making*, and *urban safety management* indicates that the field is now deeply connected with broader global agendas—namely the United Nations' Sustainable Development Goals (SDG 3.6 and SDG 11.2), which call for a 50% reduction in traffic fatalities and improved access to safe transport by 2030. Research output after 2020, particularly from emerging economies, reflects an intensified focus on aligning national safety frameworks with these international commitments. The integration of cost-benefit prioritization models (Nguyen et al., 2016) and hybrid data systems (Nadimi & Hosseini, 2022) shows how economic rationality and technological sophistication can coexist to create scalable solutions, especially in resource-constrained settings like India.

The discussion also reveals that while technological sophistication has improved accuracy and efficiency, challenges remain in data availability, standardization, and quality assurance. Many developing nations, including India, still face gaps in accident reporting, underestimation of near-miss events, and lack of standardized data formats across regions. Without harmonized datasets, even advanced models such as Bayesian Networks or Neural Networks may produce inconsistent results. Therefore, strengthening national data infrastructure and establishing centralized crash databases—integrated with GIS and real-time telemetry—is an urgent prerequisite for effective black spot management. International examples such as the European Road Safety Observatory and the U.S. Highway Safety Information System (HSIS) offer replicable frameworks for India to develop its own National Accident Analytics Platform (NAAP) that consolidates data from traffic sensors, police records, and crowd-sourced mobile inputs.

Finally, the bibliometric and methodological synthesis points toward the emergence of hybrid frameworks as the most promising direction for future research and implementation. These frameworks combine statistical rigor, spatial intelligence, behavioral simulation, and economic evaluation within a unified analytical structure. For instance, combining GIS-based hotspot detection with AHP-based prioritization and cost-benefit analysis can enable policymakers to identify not only where accidents occur but also which sites should be treated first for maximum impact. As shown in the VOSviewer clustering, these integrative approaches lie at the intersection of all three dominant clusters—engineering, planning, and management—making them the cornerstone of next-generation road safety analytics.

In summary, the discussion reveals that the field of accident black spot research is transitioning from a fragmented, reactive practice into a comprehensive, predictive, and interdisciplinary science. For India, this transition represents both a challenge and an opportunity—to align domestic road safety systems with international best practices while adapting them to local socio-spatial realities.

Conclusion

The comprehensive review and bibliometric analysis conducted in this study reveal that accident black spot identification and mitigation has evolved into a dynamic and multidimensional research domain characterized by rapid technological growth, expanding policy integration, and increasing global participation. The consistent upward trajectory in publication trends between 2015 and 2025 underscores the escalating importance of road safety within both academic and policy frameworks. What began as a niche engineering topic focused on accident frequency has now matured into an interdisciplinary field that integrates geospatial science, behavioral modeling, artificial intelligence, and economic prioritization.

The bibliometric findings confirm that global research efforts are now converging around three major directions:

1. **Predictive modeling and probabilistic analysis** through Bayesian, Poisson, and machine learning frameworks;
2. **Spatial and simulation-based methodologies** that leverage GIS, microsimulation, and real-time trajectory monitoring; and

3. **Integrated planning and management approaches** that combine technical, economic, and behavioral dimensions.
Together, these approaches form a unified paradigm of evidence-based, proactive road safety management. The thematic clusters identified in the VOSviewer analysis—representing empirical, infrastructural, and managerial dimensions—demonstrate that the field has reached a stage of conceptual maturity, where diverse analytical traditions complement one another rather than compete.

For India, the conclusions drawn from this study carry both strategic and operational significance**.** The findings reaffirm that while India's academic and institutional engagement with road safety has grown, the prevailing system remains heavily reliant on reactive identification and post-crash correction. Bridging this gap requires a fundamental reorientation of policy and practice—from descriptive data aggregation toward predictive analytics and spatial intelligence. Integrating GIS-based accident mapping with Road Safety Audits (RSAs), multicriteria prioritization, and cost-effectiveness evaluation would enable a systematic, transparent, and economically rational approach to black spot management. Furthermore, embracing hybrid analytical frameworks would empower policymakers to optimize interventions based on real-time risk probabilities, rather than retrospective statistics.

The study also concludes that multidisciplinary collaboration is essential for the next stage of evolution in this field. Engineers, planners, data scientists, behavioral psychologists, and policymakers must work together to develop a comprehensive national safety ecosystem. Establishing interoperable databases, strengthening institutional capacities, and promoting open-access data sharing between agencies are critical steps toward this goal. The global literature demonstrates that sustainable progress in road safety depends not only on technological innovation but also on institutional coordination and political commitment.

From a theoretical standpoint, the study contributes to the growing body of knowledge that links transportation planning, spatial analytics, and risk management into a cohesive research agenda. Practically, it offers a roadmap for developing countries like India to align with international best practices and achieve the Sustainable Development Goal (SDG 3.6) of halving traffic-related deaths by 2030. The evolution observed through the bibliometric trends suggests that the coming decade will witness a deeper integration of AI-driven predictive modeling, smart mobility systems, and policy analytics in road safety management. These innovations have the potential to transform black spot mitigation from a reactive exercise into a real-time, adaptive safety management system**.**

In conclusion, this study demonstrates that accident black spot research has matured into a strategic discipline that bridges technology, policy, and human-centered planning. For India, adopting these insights is not merely a matter of academic alignment but a national imperative to safeguard lives, reduce economic losses, and ensure sustainable mobility. The future of road safety lies in embracing integrated planning, predictive intelligence, and collaborative governance—principles that this paper positions as foundational for the next generation of road safety strategies.

Reference

1. Black, W. R. (2012). Transportation: A geographical analysis. Guilford Press.
2. Cui, H., Dong, J., Zhu, M., Li, X., & Wang, Q. (2022). Identifying accident black spots based on the accident spacing distribution. Journal of Traffic and Transportation Engineering (English Edition), 9(6), 1017–1026.
3. Fan, Z., Liu, C., Cai, D., & Yue, S. (2022). Research on black spot identification of safety in urban traffic accidents based on machine learning method. Safety Science, 156, 105911. https://doi.org/10.1016/j.ssci.2022.105911
4. Gajbhiye, L. N., Vyawahare, M. R., Malviya, A. I., & Bijwe, A. R. (2023). A case study of black spots at Amravati City and proposal of mitigation measures. Journal of Emerging Technologies and Innovative Research (JETIR), 10(9), 144–151. Retrieved from

5. Gregoriades, A., & Mouskos, K. C. (2013). Black spots identification through a Bayesian Networks quantification of accident risk index. Transportation Research Part C: Emerging Technologies, 28, 28–43.
6. Mehendale, A. P., & Pujari, R. S. (2018). Assessment of accidental black spots – A case study of Sangli–Kolhapur Highway. International Journal of Civil Engineering Research and Development, 8(3), 56–64.*
7. Ministry of Road Transport and Highways (MoRTH). (2020). Road Transport Year Book (2019–20). Government of India.
8. Ministry of Road Transport and Highways (MoRTH). (2023). Road Accidents in India 2023. Government of India, Transport Research Wing.
9. Ministry of Road Transport and Highways (MoRTH). (2024). Annual Report 2024–25. Government of India.
10. Subirats, P., Goyat, Y., Jacob, B., & Violette, E. (2016). A new road safety indicator based on vehicle trajectory analysis. Transportation Research Procedia, 14, 4267–4276. https://doi.org/10.1016/j.trpro.2016.05.398
11. Weekley, J., Barrell, J., & McCarthy, T. (2016). Developing a road safety review tool to identify design standard and safety deficits on high-risk road sections. Transportation Research Procedia, 14, 4130–4139. https://doi.org/10.1016/j.trpro.2016.05.384
12. World Bank. (2022). Road safety in South Asia: Opportunities for shared regional initiatives. The World Bank Group.
13. World Health Organization (WHO). (2023). Global status report on road safety 2023. World Health Organization
14. Ghadi, M.; Török, Á.; Tánczos, K. (2019). Integration of probability and clustering based approaches in the field of black spot identification. Hungary.
15. Nadimi, N.; Sheikh Hosseini Lori, E. (2022). Applying different analytic methods to determine black spots in two-lane highways. Iran.
16. Yakar, F. (2021). A multicriteria decision making–based methodology to identify accident-prone road sections. Turkey.
17. Karamanlis, I.; Kokkalis, A.; Profillidis, V.; Boile, M. (2023). Identifying Road Accident Black Spots using Classical and Modern Approaches. Greece.
18. Szénási, S.; Kertész, G.; Felde, I.; Nádai, L. (2021). Statistical accident analysis supporting the control of autonomous vehicles. Hungary.
19. Nguyen, H.H. (2016). Approach to identifying black spots based on potential saving in accident costs. Vietnam.
20. Gregoriades, A. (2013). Black spots identification through a Bayesian Networks quantification of accident risk index. Cyprus.
21. Waizman, G. (2015). Micro-simulation model for assessing the risk of vehicle-pedestrian road accidents. Israel.
22. Sugiyanto, G.; Fadli, A.; Santi, M.Y. (2020). Strategies for handling black spot area to increased road safety. Indonesia.
23. Sipos, T. (2017). Spatial statistical analysis of traffic accidents. Hungary.