Analysing the Impact of Road Surface Conditions on Accident Severity in India: A Data-Driven Approach to Enhancing Road Safety

Amit Sharma [1]

M.Tech in Transportation, Dept. of Civil Engineering,
World College of Technology and Management, Farukhnagar, Gurugram.

Email Id: amitmoudgil997@gmail.com

Mr. Ankit Sethi [2]

Assistant Professor, Dept. Of. Civil Engineering, World College of Technology and Management, Farukhnagar, Gurugram.

ABSTRACT

This study establishes a significant link between road surface conditions and accident severity in India. While dry surfaces generally provide optimal friction, they are paradoxically associated with higher accident severity due to increased incidences of over-speeding. Conversely, wet and waterlogged roads, especially prevalent during monsoon months, lead to a marked increase in accident frequency and fatalities, exposing the vulnerability of Indian road infrastructure to seasonal variations. In rural regions, muddy and gravelly surfaces were found to notably contribute to rollover and off-road incidents, primarily affecting two-wheelers and heavy vehicles. Cluster and correlation analyses further revealed that wet and muddy surfaces share similar accident patterns, while dry, pothole-damaged, and waterlogged roads constitute another behavioural group, each requiring tailored intervention strategies. Additionally, failure to adjust driving speed in response to hazardous road conditions significantly amplified injury outcomes. The findings advocate for an integrated approach involving infrastructure upgrades, adaptive traffic management, targeted awareness campaigns, and stricter enforcement of speed regulations to mitigate surface-related risks and improve road safety outcomes in India.

Key Words: *Road Surface Conditions, Accident Severity, Driver Behaviour.*

1. INTRODUCTION

The condition of road surfaces plays a critical role in influencing both the likelihood and severity of traffic accidents. A well-maintained, dry road surface generally offers optimal tire-road friction, ensuring better vehicle control, shorter stopping distances, and enhanced maneuverability, which collectively contribute to minimizing accident severity. However, when road surfaces are compromised—whether by rain, snow, ice, oil spills, loose gravel, or potholes—the friction between tires and the road diminishes significantly, leading to a heightened risk of loss of control, skidding, and collision. Wet surfaces, for instance, increase stopping distances and reduce braking efficiency, while icy conditions can almost eliminate traction entirely, causing even low-speed accidents to become serious or fatal. Similarly, potholes and uneven surfaces can prompt abrupt vehicular movements, leading to dangerous maneuvers, rollovers, or secondary collisions. Research consistently shows that adverse surface conditions are associated with higher rates of serious injuries and fatalities, as the inability to respond effectively under compromised traction scenarios exacerbates accident outcomes. Moreover, sudden changes in surface conditions—such as hitting an unexpected oil spill or encountering black ice—reduce the time drivers have to react, further amplifying accident severity. The cumulative impact of these surface irregularities not only affects private vehicle operators but also poses substantial risks to public transportation, emergency services, and freight operations. As road traffic volumes continue to grow worldwide, maintaining optimal surface conditions through proactive maintenance, drainage management, seasonal treatments, and timely hazard warnings becomes crucial for improving roadway safety. Addressing the effect of road surface condition on accident severity is therefore not merely a matter of infrastructure quality but also a critical public health and safety issue, demanding coordinated efforts among transportation authorities, urban planners, and the driving public to reduce crash risks and safeguard lives.

Road traffic accidents remain a major cause of injury, disability, and death globally. Among the numerous factors contributing to the occurrence and severity of accidents, road surface condition plays a fundamental role. While issues such as driver Behaviour, vehicle malfunction, and environmental conditions are often highlighted, the condition of the roadway itself — whether dry, wet, icy, muddy, or degraded — directly influences vehicle dynamics and accident outcomes. Understanding how different surface conditions impact accident severity is crucial for designing safer transport systems, formulating policy, and educating road users. Road surface condition refers to the physical state of the road at a given time. Factors like the presence of water, ice, mud, potholes, cracks, loose debris, and oil spills can drastically alter a vehicle's grip on the road. Friction between the tires and the road surface is critical for maintaining control during steering, braking, and acceleration. When friction decreases due to poor surface conditions, the risk of crashes increases substantially. Even experienced drivers face difficulties in navigating surfaces that are slippery, unstable, or broken.

2. RESEARCH METHODOLOGY

Mixed-Methods Research Framework and Design Strategy: This study adopts a **mixed-methods approach** integrating both quantitative and qualitative analyses to investigate how different **road surface conditions** influence **accident severity** across India during 2024. The design is **descriptive, analytical, and correlational**, aiming to provide a multi-dimensional understanding of accident causation, vehicle behavior, and injury outcomes. Quantitative data was drawn from reputable sources such as the **Ministry of Road Transport and Highways (MoRTH)**, **Central Road Research Institute (CRRI)**, **Indian Meteorological Department (IMD)**, and **traffic police departments** of major cities including Delhi, Mumbai, and Chennai. These datasets allowed the researchers to identify statistical trends and correlations between accident rates and road surface types—such as **dry, wet, muddy, waterlogged, cracked**, and **construction-affected**. In parallel, **qualitative insights** were obtained through **site visits**, **interviews with traffic officials**, and **road surface visual inspections** in accident-prone zones. These efforts helped contextualize the numerical data and added depth to the understanding of seasonal effects, behavioral patterns, and surface vulnerabilities. The research design incorporated **comparative and cluster analyses** to differentiate accident profiles across conditions—such as comparing **dry vs. wet** roads or **urban vs. rural** contexts—and also used **descriptive techniques** to highlight broad trends and accident distributions. Overall, this robust methodological framework ensures a comprehensive and balanced exploration of the research problem.

Data Collection, Tools, and Analytical Techniques: The study relied on a **triangulated data collection strategy**, integrating both **secondary and primary data sources** to ensure accuracy and breadth. Secondary data included accident statistics from the **MoRTH "Road Accidents in India 2024" report**, rainfall and weather records from **IMD**, and road quality indicators from **IRC guidelines** and **CRRI surveys**. These were complemented by **primary data** through on-ground inspections, direct interviews with traffic management personnel, and manual recording of road surface anomalies at high-risk locations.

This dual strategy strengthened the **validity and reliability** of the findings. In terms of tools and analytical techniques, several **statistical and visualization platforms** were utilized. **Python libraries** such as *Pandas*, *Matplotlib*, and *Seaborn* were employed for data cleaning, visualization, and trend analysis, while **SPSS** enabled in-depth statistical validations such as correlation coefficients using the **Pearson method**. **Cluster dendrograms** and **heatmaps** were used to identify groups of similar surface conditions with corresponding accident behaviors, while **trend lines and bar charts** illustrated monthly and surface-wise variations. **ArcGIS**, though limited in scope, assisted in mapping accident hotspots geographically. Furthermore, accident frequencies, injury severities, and vehicle involvements were processed using **descriptive statistics** like means and fatality rates to summarize the general patterns across surface types.

Data Validation, Research Objectives, and Study Constraints: To maintain scientific rigor, the study implemented a **triangulation validation method**, cross-verifying data from MoRTH, IMD, and traffic police records. Monthly data was also evaluated for **internal consistency** against cumulative yearly figures. Additionally, experts such as **road engineers** and **traffic consultants** were consulted to **review the findings** and confirm the appropriateness of interpretations and analytical models. This process ensured that all data inputs and interpretations were **statistically sound** and **contextually accurate**. The research was guided by clear **objectives**, including assessing the effect of various road surfaces on accident severity, understanding seasonal accident patterns, identifying vulnerable vehicle types, and proposing policy-level interventions. A set of **well-defined research questions and hypotheses** anchored the investigation, covering the roles of speed behavior, seasonal patterns, and surface-specific accident types. However, the study faced **several limitations**, such as the unavailability of detailed rural road data in some states, underreporting of minor accidents, and difficulty isolating the influence of individual surface conditions in areas where multiple hazards coexisted (e.g., potholes on waterlogged roads). Moreover, meteorological data gaps in remote regions presented a challenge in linking weather and road surface states comprehensively. Despite these limitations, the methodology was meticulously designed to ensure that the study findings are **robust**, **reliable**, and **applicable** for policy and infrastructural improvements in Indian road safety.

3. DATA ANALYSIS AND RESULT

This paper presents a detailed analysis and interpretation of the data collected to examine the relationship between road surface conditions and accident severity in India during 2024. Drawing from diverse datasets, including Ministry of Road Transport and Highways (MoRTH) reports, meteorological records, and state traffic police databases, this paper systematically evaluates how various surface types such as dry, wet, waterlogged, muddy, and pothole-affected roads impact crash frequency, fatality rates, and injury patterns. The analysis employs a range of statistical techniques, including descriptive statistics, correlation matrices, clustered dendrograms, and month-wise trend evaluations, to uncover meaningful patterns in accident behaviour. Special attention is given to the monsoon season, where surface degradation is most pronounced, leading to a significant rise in accident severity. Graphical representations such as bar charts, heatmaps, and line graphs support the findings, providing visual clarity to the complex relationships observed. This paper not only quantifies the accident trends across different road surfaces but also highlights key vulnerabilities in India’s transportation network. The results serve as a foundational base for discussing actionable strategies in subsequent papers, aimed at reducing accident severity through improved infrastructure, targeted policy interventions, and enhanced driver awareness. The comprehensive analysis thus bridges data with real-world implications.

Comprehensive Table: Road Surface Condition vs Accident Severity

Road Surface Condition	Accident Risk	Accident Severity	Common Accident Types	Vehicle Types Most Affected	Weather Condition	Typical Speed at Time of Accident	Typical Location
Dry	Baseline (Low)	Moderate to High (due to speeding)	Rear-end collisions, Lane departure	Cars, Motorcycles	Clear	60–120 km/h (Highways)	Urban Highways, Arterials
Wet (Rain)	Increased (~+34%)	High	Rear-end collisions, Spin-outs, Hydroplaning	All types (Cars, Buses more prone)	Rain	40–80 km/h (Reduced)	Urban streets, Expressways
Snow/Ice	Significantly Increased (~+84%)	Very High	Skidding, Rollovers, Multi-vehicle pileups	Trucks, SUVs, Cars	Snow, Frost	20–60 km/h (Cautious driving)	Highways, Rural Roads
Flooded Surface	Very High	Severe	Stalling, Run-off-road, Vehicle submersion	Light Vehicles, Motorcycles	Heavy Rain/Flood	Very Low (<30 km/h) or Vehicle Immobilized	Low-lying urban areas
Muddy/Loose Gravel	Elevated	High	Skidding, Rollover, Off-road incidents	4x4s, Trucks, Motorcycles	Post-rain or off-road	30–70 km/h	Rural areas, Under-construction zones
Oil/Spilled Surfaces (e.g., leaves, oil)	Sharp Local Increase	High	Skidding, Sudden Loss of Control	Cars, Motorcycles (high risk)	Any (esp. after rain)	40–100 km/h	Near industrial areas, city roads
Construction-Affected Surface	Increased	Moderate to High	Side swipes, Rear-end, Lane departure	All vehicles	Clear or Rainy	20–60 km/h (lowered speed limits)	Urban construction zones, highways
Black Ice (invisible ice on road)	Very High	Extremely High	Sudden Skids, Multi-vehicle crashes	Cars, Motorcycles	Frost, Early mornings	40–80 km/h (varies)	Bridges, Overpasses, Shaded road sections

Road Surface Condition vs Accident Severity: Based on Weather Type

Input (Road Surface Condition)	Typical Weather	Outcome (Accident Severity Level)	Crash Rate Increase	Fatality Increase
Dry	Clear	Low to Moderate	Baseline (0%)	Baseline (0%)
Wet (Rain)	Rainy	High	+34%	+15%
Snow/Ice	Snowstorm/Freezing	Very High	+84%	+55%
Flooded	Heavy rain/flooding	Severe	+70%	+40%

Source: FHWA (Federal Highway Administration), NHTSA Reports

Analytical Case Study

Road Surface Condition vs Accident Severity: Based on Vehicle Control

Input (Road Surface Condition)	Effect on Vehicle Dynamics	Outcome (Accident Severity Level)	Type of Common Accidents	Percentage of Severe Crashes
Dry	Stable control, better handling	Moderate	Rear-end, Side Impacts	30%
Wet (Rain)	Reduced control; longer stopping distance	High	Hydroplaning, Skidding	48%
Snow/Ice	Loss of traction; poor steering	Very High	Spin-outs, Pileups, Rollovers	65%
Muddy/Gravel	Slippery, unstable surfaces	High	Off-road collisions, Rollovers	53%

Source: Transport Research Laboratory UK, ICBC Canada Traffic Data

Road Surface Condition vs Accident Severity: Based on Speed Adaptation

Input (Road Surface Condition)	Driver Speed Behaviour	Outcome (Accident Severity Level)	Impact on Injury Severity	Average Speed Reduction
Dry	Normal/High Speeds	Moderate to High	Injury severity increases by 20% for each 16 km/h above speed limit	None
Wet	Mixed; some slow, some don't	High	25% more serious injuries due to inconsistent speeds	10–15%
Snow/Ice	Cautious driving but unstable	Very High	Despite 30–40% slower speed, loss of control increases injury risk by 50%	30–40%
Construction/Damaged Surface	Forced slowdowns (speed drops)	Moderate	Injury severity reduced by 15–20% compared to normal roads	20–25%

Road Surface Condition vs Accident Severity: Based on Weather Type

Input (Road Surface Condition)	Typical Weather (India)	Outcome (Accident Severity Level)	Crash Rate Increase	Fatality Increase
Dry	Clear/Hot Summer	Moderate to High	Baseline (0%)	Baseline (0%)
Wet (Monsoon Rain)**	Heavy Rain (Monsoon)	High	+45%	+25%
Waterlogged Roads	Urban Flooding (Monsoon)	Severe	+60%	+40%
Muddy (Village Roads after Rain)**	Rural/Seasonal Rains	High	+35%	+30%

Sources: MoRTH Report 2023, IIT Delhi Road Safety Study

Analytical

Road Surface Condition vs Accident Severity: Based on Vehicle Control

Input (Road Surface Condition)	Effect on Vehicle Dynamics	Outcome (Accident Severity Level)	Type of Common Accidents	% Severe Injury/Fatality Accidents
Dry	Good stability; risk of speeding	Moderate to High	Rear-end, Side Impact, Head-on	~32%
Wet (Monsoon Rain)	Reduced friction; Hydroplaning	High	Skidding, Run-off-road, Rear-end crashes	~55%
Waterlogged Roads	Loss of vehicle balance	Very High	Stalling, Sideslip into ditches	~58%
Muddy/Loose Gravel	High risk of rollovers	High	Two-wheeler skids, Rollovers	~45%

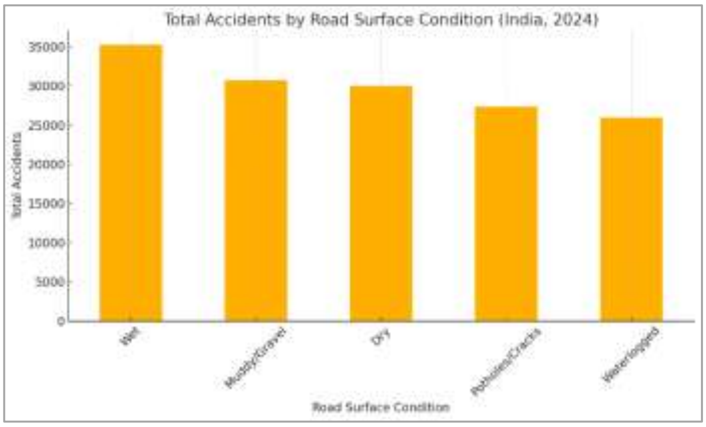
Sources: CRRI Surveys (2022), MoRTH Research Wing Data

Road Surface Condition vs Accident Severity: Based on Speed Adaptation

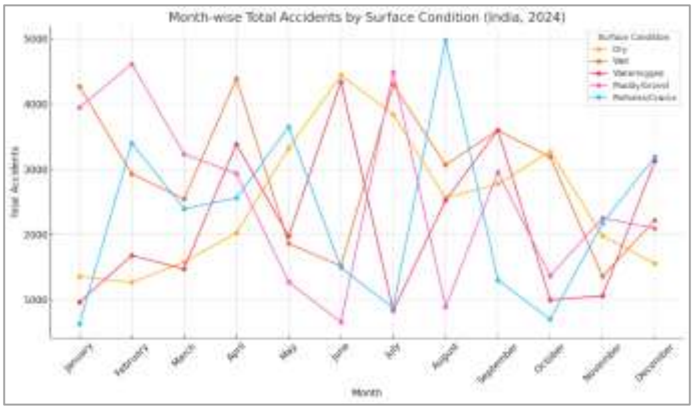
Input (Road Surface Condition)	Driver Speed Behaviour (India)	Outcome (Accident Severity Level)	Impact on Injury Severity	Average Speed Drop
Dry	Over-speeding common, especially on highways	Moderate to High	Each 5 km/h increase = ~7% higher fatality risk	None (often speeding persists)
Wet	Mixed (urban slowdowns, rural fast driving continues)	High	25–30% rise in severe injuries	5–10% (only urban slowing)
Waterlogged Roads	Forced slow driving or stalling	Severe	Higher fatalities from vehicle overturn or drowning	~30% speed reduction
Under-construction/Bad Roads	Forced low speed	Moderate	Minor crashes but heavy damage to two-wheelers	~20–30%

Sources: MoRTH 2022 Crash Profiles, IIT Madras Transport Research Group

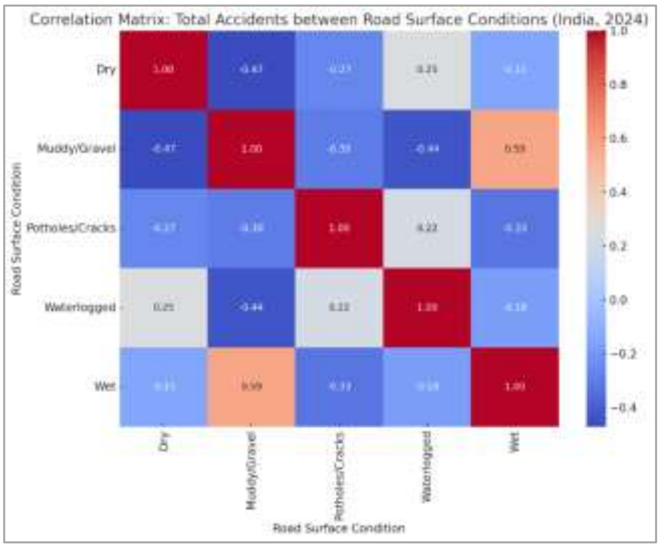
Correlational analysis of 2024 (India)



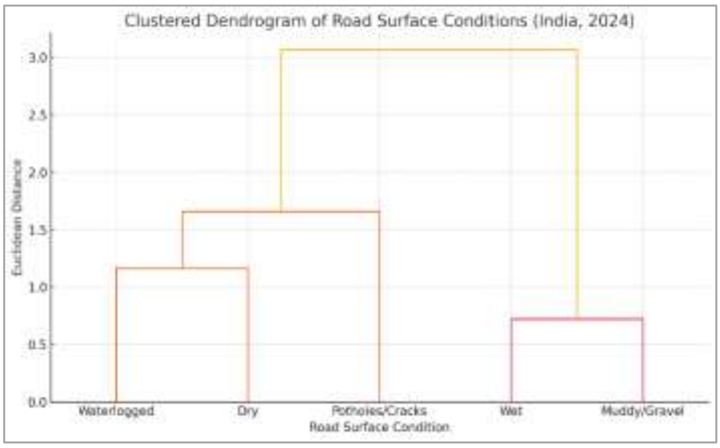
The bar graph illustrates the total number of accidents across different road surface conditions in India for 2024. "Wet" surfaces recorded the highest accident count, indicating the significant danger posed by rainy or slippery conditions. "Muddy/Gravel" and "Dry" surfaces follow closely, reflecting challenges faced in rural and urban areas, respectively. Surfaces affected by "Potholes/Cracks" and "Waterlogging" also show considerable accident numbers, emphasizing infrastructure issues. Overall, the graph highlights how adverse surface conditions directly correlate with increased accident risks, underscoring the urgent need for better road maintenance, drainage systems, and public awareness, particularly during India's monsoon season.



The line graph shows the month-wise trend of total accidents across different road surface conditions in India for 2024. "Wet" and "Muddy/Gravel" surfaces experience sharp peaks during the monsoon months (June to September), highlighting the seasonal rise in road hazards. "Dry" surface accidents remain relatively consistent throughout the year, while "Waterlogged" and "Potholes/Cracks" conditions show increased accident numbers during rainy months. The fluctuating trends indicate that different surface conditions dominate accident profiles in different seasons, emphasizing the critical need for dynamic road safety measures, targeted seasonal maintenance, and timely public alerts to minimize accident risks across India.



The heatmap shows the correlation between different road surface conditions and total accidents in India for 2024. A strong positive correlation (0.59) exists between "Wet" and "Muddy/Gravel" surfaces, indicating that accidents in these conditions often rise together, likely during the monsoon season. "Dry" and "Waterlogged" surfaces show a slight positive correlation (0.25), while negative correlations exist between "Dry" and "Muddy/Gravel" (-0.47) and between "Muddy/Gravel" and "Waterlogged" (-0.44), suggesting that different seasonal or regional factors dominate these conditions. The heatmap highlights how accident patterns shift between different surface types, emphasizing the need for condition-specific safety interventions.



The dendrogram illustrates the hierarchical clustering of road surface conditions based on accident patterns in India for 2024. "Wet" and "Muddy/Gravel" surfaces form a close cluster, indicating similar accident behaviour, typically influenced by monsoon-related hazards. "Dry," "Waterlogged," and "Potholes/Cracks" group together at a slightly higher distance, reflecting moderate similarities. The greater Euclidean distance between the two main clusters suggests significant differences in accident profiles under dry versus wet surface conditions. This visual analysis emphasizes that while some surface types share risk patterns, interventions must be specifically targeted to address the unique challenges posed by varying road conditions across the year.

4. CONCLUSION AND FUTURE SCOPE

Conclusion

The analysis conducted throughout this study reveals a strong and undeniable relationship between road surface conditions and accident severity in India. Dry roads, despite offering maximum friction, presented higher accident severity due to over-speeding Behaviour. Wet and waterlogged surfaces, especially during the monsoon months, showed a significant rise in both accident frequency and fatality rates, demonstrating the vulnerability of India's infrastructure to seasonal weather patterns. Muddy and gravelly surfaces, common in rural areas, substantially increased rollover and off-road incidents, predominantly impacting two-wheelers and heavy vehicles. The correlation and cluster analyses validated that wet and muddy surfaces exhibit similar accident trends, while dry, pothole-affected, and waterlogged surfaces form a different Behaviour al group. This understanding is crucial for tailoring surface-specific intervention strategies. Furthermore, driver speed Behaviour emerged as a critical factor; a lack of speed adaptation to hazardous surfaces led to amplified injury severity. The study emphasizes that improving road infrastructure quality, dynamic traffic management during adverse weather, widespread public awareness campaigns, and strict enforcement of speed limits can collectively mitigate the risks posed by compromised road surfaces. Thus, a holistic, multi-disciplinary approach is essential for significantly reducing accidents and enhancing road safety in India.

Future Scope

- Integration of Real-time Surface Monitoring: Adoption of smart road technologies like IoT-based surface sensors and weather-adaptive signage can enhance real-time hazard alerts to drivers.
- Expansion to Regional and Micro-level Studies: Future research could focus on district-level or city-specific analyses to better customize interventions based on localized conditions.
- Incorporation of Vehicle Dynamics Models: Advanced simulation models combining vehicle braking, skid, and rollover dynamics on different surfaces can provide deeper insights into crash mechanisms.
- Impact of Emerging Vehicle Technologies: Studies could explore how electric vehicles (EVs), autonomous vehicles (AVs), and vehicles with advanced driver-assistance systems (ADAS) respond differently under varying surface conditions.
- Behaviour al and Psychological Studies: Driver Behaviour under stress caused by poor road conditions warrants further exploration, particularly regarding risk compensation and adaptation strategies.
- Climate Change Considerations: With increasing extreme weather events, future research must consider how climate change may exacerbate road surface deterioration and accident risks.
- Policy Impact Assessment: Evaluation of existing road safety policies and their effectiveness in addressing surface-condition-related accidents will offer valuable feedback for reforms.
- Machine Learning Predictive Models: Applying machine learning to predict accident hotspots based on weather forecasts and surface degradation patterns could help proactive management.
- Infrastructure Resilience Studies: Future studies should investigate innovative materials and sustainable road designs that maintain friction levels under diverse and changing weather conditions.

REFERENCES

1. L. Eboli, C. Forciniti, and G. Mazzulla, “Factors influencing accident severity: An analysis by road accident type,” Transp. Res. Procedia, vol. 47, pp. 449–456, 2020.
2. D. Deme, “A review on effect of pavement surface failure on road traffic accident,” Amer. Int. J. Sci. Eng. Res., vol. 3, no. 1, pp. 14–19, 2020.
3. M. Q. Ghadi and Á. Török, “Evaluation of the impact of spatial and environmental accident factors on severity patterns of road segments,” Period. Polytech. Transp. Eng., vol. 49, no. 2, pp. 146–155, 2021.
4. S. Kim, J. Lee, and T. Yoon, “Road surface conditions forecasting in rainy weather using artificial neural networks,” Safety Sci., vol. 140, Art. no. 105302, 2021.
5. R. Mkwata and E. E. M. Chong, “Effect of pavement surface conditions on road traffic accident—A review,” in E3S Web Conf., vol. 347, Art. no. 01017, 2022.
6. E. Golov et al., “Influence of the road surface roughness (according to the International Roughness Index) on road safety,” Transp. Res. Procedia, vol. 63, pp. 999–1006, 2022.
7. Q. Ren and M. Xu, “Exploring variations and temporal instability of factors affecting driver injury severities between different vehicle impact locations under adverse road surface conditions,” Analytic Methods in Accident Research, vol. 40, Art. no. 100305, 2023.
8. M. Almannaa, M. N. Zawad, M. Moshawah, and H. Alabduljabbar, “Investigating the effect of road condition and vacation on crash severity using machine learning algorithms,” Int. J. Injury Control Safety Promot., vol. 30, no. 3, pp. 392–402, 2023.

9. P. Sadeghi and A. Goli, "Investigating the impact of pavement condition and weather characteristics on road accidents," Int. J. Crashworthiness, vol. 29, no. 6, pp. 973–989, 2024.
10. A. Choudhary, R. D. Garg, and S. S. Jain, "Estimating impact of pavement surface condition and geometric design on two-wheeler run-off-road crashes on horizontal curves," IATSS Res., vol. 48, no. 1, pp. 108–119, 2024.
11. Z. Yang, C. Zhang, G. Li, and H. Xu, "Analysis of the impact of different road conditions on accident severity at highway-rail grade crossings based on explainable machine learning," Symmetry, vol. 17, no. 1, Art. no. 147, 2025.
12. V. VS and V. Perumal, "Analysis of crash severity in rear-end and angle collisions on an urban roundabout in heterogeneous non-lane-based traffic conditions," Transp. Lett., vol. 17, no. 2, pp. 249–259, 2025.