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Original Article

Drivers' safety from the perspective of integrated triangular assessment of human, environmental, and vehicle factors on Nepal's major highways

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ABSTRACT

Introduction: Drivers' safety remains a critical concern within the context of Nepal's major highway network, threatened by a triangular interaction of human, environmental, and vehicle-related factors. Despite alignment with global safety initiatives, Nepal records a disproportionately high fatality rate of 15.9 per 100,000 population, significantly exceeding the South Asian regional average. This crisis impacts young, economically active drivers, while risks are further intensified by rapid motorization, poor infrastructure, and weak vehicle inspection systems. This study aimed to assess the multidimensional determinants affecting driver safety across Nepal's highways.

Methods: Mixed-methods approach evaluated these determinants by integrating secondary crash data (2016–2025) from Nepal Police with road infrastructure audits. Field assessments examined geometry, pavement conditions, and signage, while 155 structured surveys and stakeholder interviews (including police and residents) provided qualitative insights into behavioral challenges. Spatial analysis using Kernel Density Estimation and Moran's I was utilized to scientifically identify high-risk crash hotspots.

Results: Results indicate driver risk is amplified by human factors (over-speeding, fatigue, alcohol use, inexperience), environmental hazards (inadequate lighting, poor geometry, monsoon-induced landslides), and vehicle defects (overloading, brake failures). Corridor-level analysis highlights Banepa and Chisapani as critical risk zones, while the Prithvi Highway exhibits dispersed crash patterns linked to fatigue and weak barriers.

Conclusion: Driver safety in Nepal is defined by the interplay between human behavior, infrastructure flaws, and vehicle condition. Key measures must include strengthening governance, upgrading road and vehicle standards, and tackling fatigue through a comprehensive, well-enforced strategy.

Keywords: Driver safety, Human factors, Environmental risks, Vehicle inspection, Nepalese highways

Introduction

Road safety (RS) is a growing global public health and development challenge, with over 1.3 million annual deaths and 20–50 million injuries, many resulting in long-term disabilities that undermine quality of life.[1] Low and middle-income countries (LMICs) account for about 90% of road traffic deaths despite owning only half of the world's vehicles.[2] Road traffic injuries (RTIs)

also impose substantial economic costs, estimated at 2-5% of GDP in many LMICs, primarily due to productivity losses, medical expenditures, and disability care. Drivers play a pivotal role in both risk creation and control, with human errors contributing to over 90% of crashes globally.[3] It is also associated with multiple causal factors related to the environment and the vehicle.[4,5]

In Nepal, RTIs represent a pressing concern with national fatality rates reported between 7.7 and 9.9 per 100,000 (2019-2022), though WHO estimates suggest closer to 15.9, reflecting significant underreporting.[6] Highways are particularly vulnerable due to dangerous alignments, poor geometry, and frequent mass-casualty crashes, disproportionately affecting young and economically active populations.[7] Vulnerable Road users, including pedestrians, cyclists, and motorcyclists, comprise over 70% of deaths.[8] Human, road, vehicle, and environment are the critical factors leading to RTIs where driver's health status such as behavior, lifestyle, hearing problems, high speed, fatigue and drowsiness, respiratory problems, alcohol drinking, adventure, drug abuse, using a cell phone, stress, aggressive behavior, anxiety, distraction, fatigue, and limited driving experience, often compounded by poor ergonomics have significant role.[9] Likewise, vehicle overloading, weak enforcement, mountainous terrain, poor road geometry, inadequate lighting, fog, rainfall, landslides, and mechanical failures are additional environmental and vehicle-related determinants that elevate risks.[10-13]

Despite these challenges, most studies in Nepal have examined human, environmental, and vehicle dimensions in isolation, limiting a systemic understanding of drivers' safety. Addressing this gap requires an integrated triangular assessment framework that captures the interactions among these determinants and identifies leverage points for policy and practice. Thus, the study advances a comprehensive triangular assessment of human, environmental, and vehicle factors to generate actionable insights to improve driver safety and guide institutional responses across Nepal's highway system.

Methods

This study adopted a mixed-methods approach to assess driver safety along the Araniko, Prithvi, and East–West (Kohalpur–Gaddachauki) highways across four provinces and twelve districts of Nepal, as displayed in Figure 1. The selection of these specific highway corridors was influenced by key factors such as high traffic density, a history of crashes or fatalities, distinct geographic or maintenance challenges, critical risk exposure, along with infrastructure deficiencies, including design flaws or poor geometry. These highways also hold strategic policy importance due to their economic significance and frequent inclusion in national road-safety programs. Quantitative data included nine years of crash records (July 2016–June 2025) obtained from Nepal Police. Since these records were district-based, AI–ML techniques were used to extract and reorganize them at the highway level, enabling the identification of high-risk segments. Field surveys further captured driver-related factors, environmental conditions, and road infrastructure characteristics. Geo-spatial analysis was conducted using crash locations, road data, and land use information, with Moran's I applied to detect clustering and black spots. Qualitative data were collected through a structured questionnaire survey using the Kobo Tool, yielding 155 valid responses: 100 drivers, 20 Nepal Police (Traffic) personnel, 10 engineers, five academic experts, and 20 law and policy makers. These participants provided diverse perspectives on driver behavior, crash risks, and potential road safety interventions. Additionally, semi-structured interviews were conducted with traffic police, transport operators, and local stakeholders to enrich the findings further. These provided insights into behavioral patterns, enforcement challenges, and infrastructure gaps, complementing the quantitative findings.

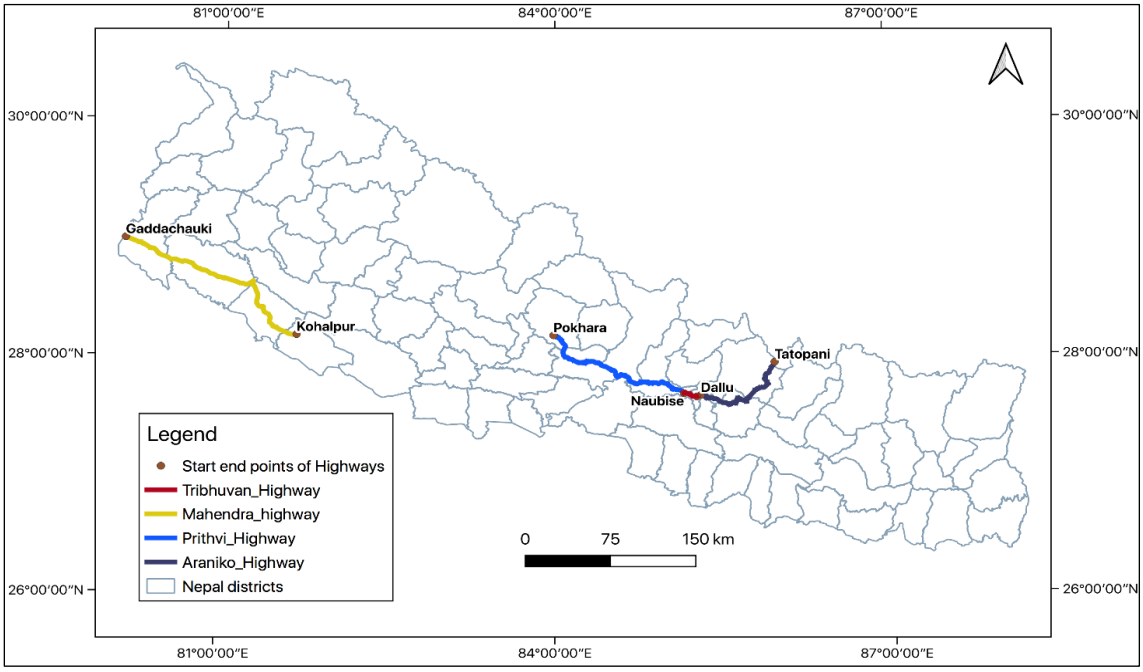

Figure 1: Study area of three strategic highways.

Figure 2 illustrates the flow of the methodological framework adopted in this study, outlining the sequential integration of human, environment, and vehicular factors within the triangular assessment approaches. This structured flow ensures that each component is evaluated systematically, leading to a comprehensive and reliable overall assessment.

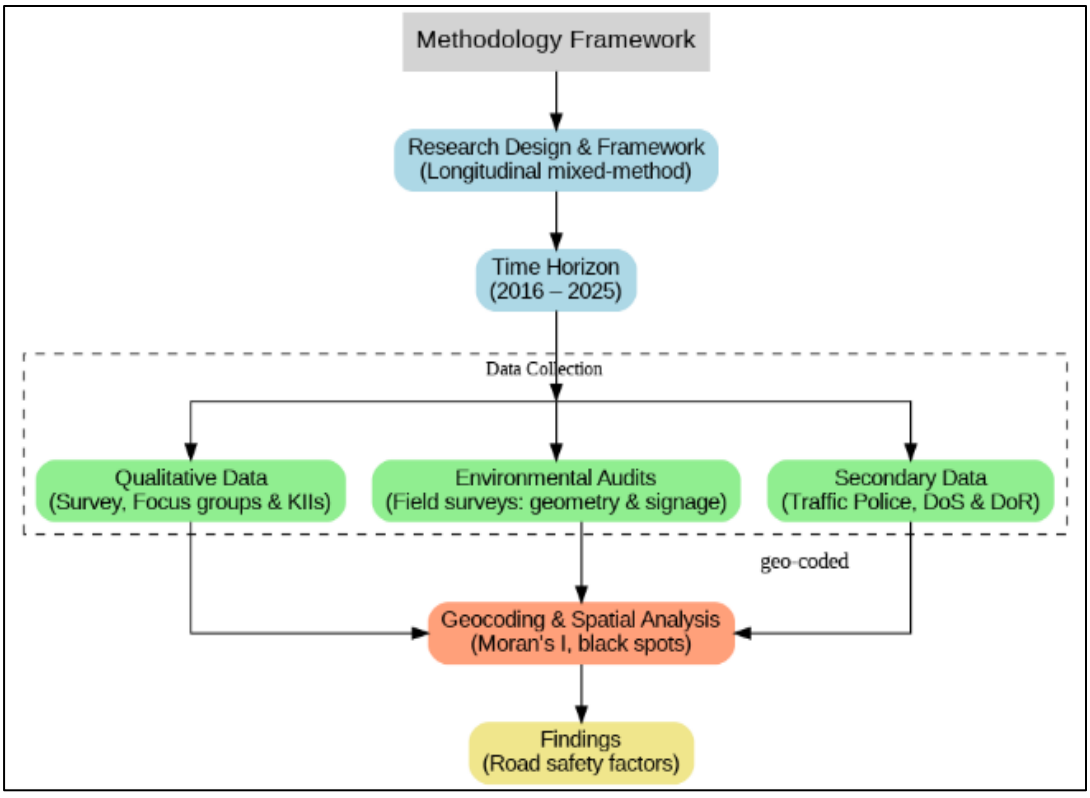

Figure 2: Methodology framework

Results

Human factors in highway crashes

The analysis (Table 1) revealed that driver-related crash risks were primarily associated with over-speeding (27.4%) and risky or aggressive behaviors, including distraction, reckless maneuvers, and cell phone use (22.1%) while driving. Fatigue was another major factor,

with 15.2% of crashes linked to continuous long-hour driving without rest and 9.6% to extended trips undertaken without breaks, particularly among freight drivers. Additional contributors included health impairments such as illness and eyesight problems (8.2%), limited driving experience or inadequate training (7.9%), unfamiliarity with local road conditions (4.5%), and socioeconomic constraints related to insufficient training and substandard vehicles (3.4%). Collectively, these results highlight the multifaceted impact of behavioral, physiological, and contextual factors on highway crash risk.

Table 1: Distribution of human factors (Drivers) in highway crashes from 2016 to 2025.

Human Factor	Frequency (n)	Percentage (%)	Issues
Over-speeding	3,410	27.4 %	Speeds >60 km/h; linked to fatal outcomes.
Risky/aggressive behaviors	2,750	22.1 %	Distraction, reckless maneuvers, and mobile phone use
Long-distance driving (no break)	1,200	9.6 %	Commercial/freight drivers under time pressure
Driver health issues	1,020	8.2 %	Illness, eyesight, fatigue-related health problems
Low experience / poor training	980	7.9 %	<3 years licensed, poor hazard perception
Lack of familiarity with the road	560	4.5 %	Unfamiliar with terrain, curves, and local hazards

The survey results in Figure 3 indicate that several driver-related factors have a notable influence on highway crashes. Among them, driver behavior and over-speeding appear as the most significant contributors, reflecting how unsafe driving practices and excessive speed frequently lead to hazardous situations. Driver fatigue and long-distance driving without breaks also show high significance, suggesting that prolonged driving hours and insufficient rest considerably increase the likelihood of accidents. Driver's health and experience, skill, and education are recognized as moderately influential factors, implying that health conditions and inadequate training can compromise driving performance and decision-making on highways. The socio-economic profile of drivers shows a moderate level of influence, hinting that those external burdens, such as income or work-related stress, may indirectly affect safe driving habits. The familiarity with road and journey risks is identified as relatively less influential compared to other factors, although it still plays a role in cases where drivers operate in unfamiliar environments or challenging terrain.

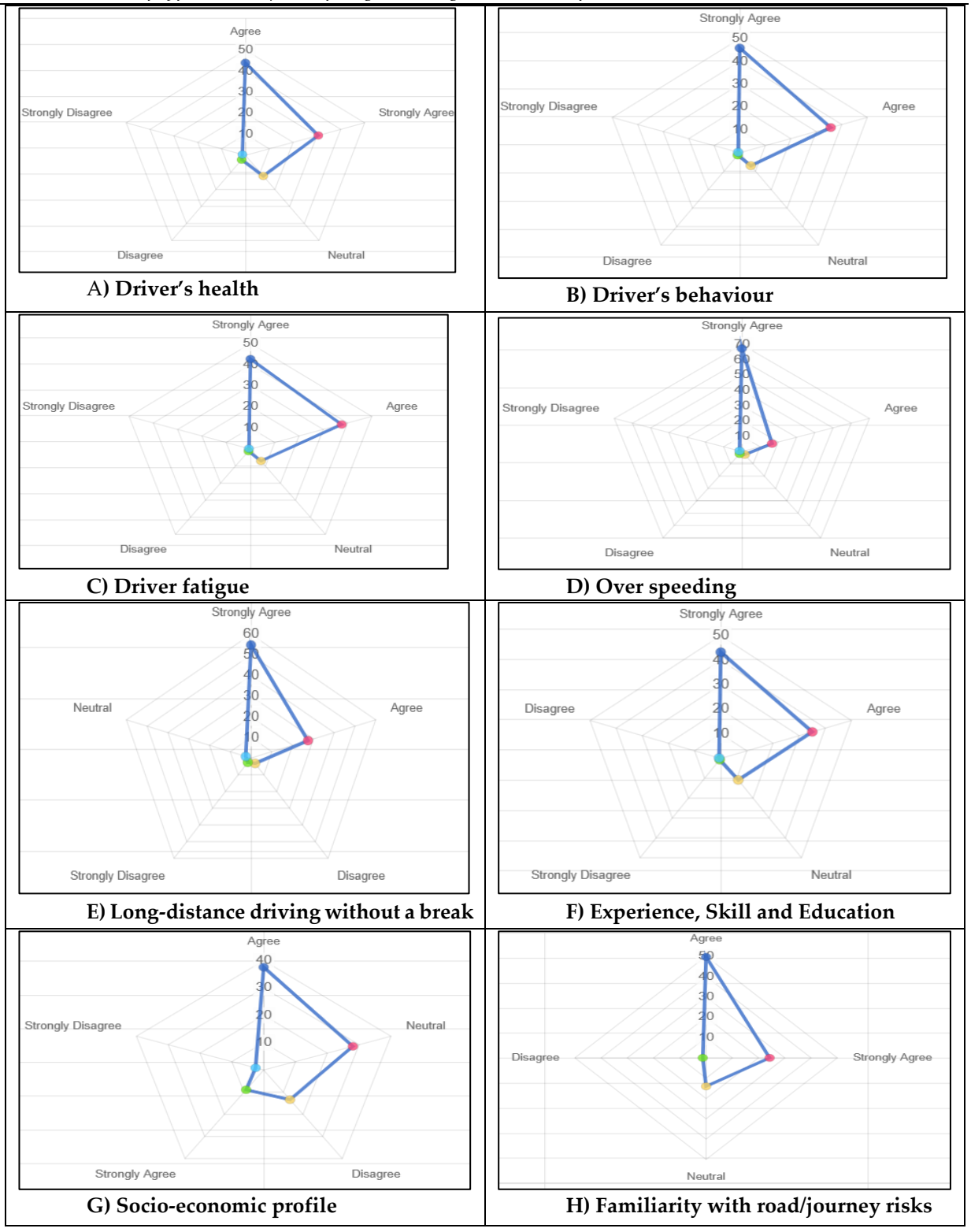

Figure 1: Drivers' factors contributing to highway crashes.

Environmental and Road Infrastructure factors

Environmental and road-related conditions were identified as significant determinants of highway crash risk and severity, directly affecting drivers' safety (Table 2). Road safety audits and survey responses revealed that deteriorated pavement quality, poor geometric design, and inadequate safety infrastructure increased the risk to drivers associated with misjudgment, over-speeding, and delayed reactions. Vulnerable road users (Figure 4) showed that motorcyclists were the most frequently affected group (42%), followed by pedestrians (18%), light vehicle drivers (15%), passengers (13%), and heavy vehicle drivers (12%). These findings highlight the elevated risks for drivers in mixed-traffic environments across highways.

Table 2: Environmental and road infrastructure factors contributing to highway crashes.

Factor	Risk Level	Risk Road Section	Issues
Poor road design/ geometry	High	Prithvi, Araniko	Sharp curves, steep gradients, and weak junctions are linked to run-off-road crashes
Inadequate signage/ lighting/ pedestrian infrastructure	Moderate	Araniko, East-West	Missing/faded signs, lack of pedestrian crossings, poorly lit stretches
Poor surface quality	High	All corridors	Potholes, erosion, and hydroplaning risks; major contributors to severity
Poor drainage systems	Moderate	Prithvi, East-West	Waterlogging during monsoon, hydroplaning
Roadside encroachment/ lack of setback	Moderate	Araniko, East-West	Market areas, narrowing carriageway, vehicle–pedestrian conflicts
Natural calamities (landslides, fog, floods)	High	Prithvi, Araniko, East-West	Landslides in hilly terrain; fog/flooding in Terai increasing collision risk
Lack of lane separation/markings	Moderate	East-West, Araniko	Faded or absent markings are causing head-on collisions
Bridge and approach road safety	High	Prithvi	Weak barriers, poor approach transitions, and frequent severe accidents

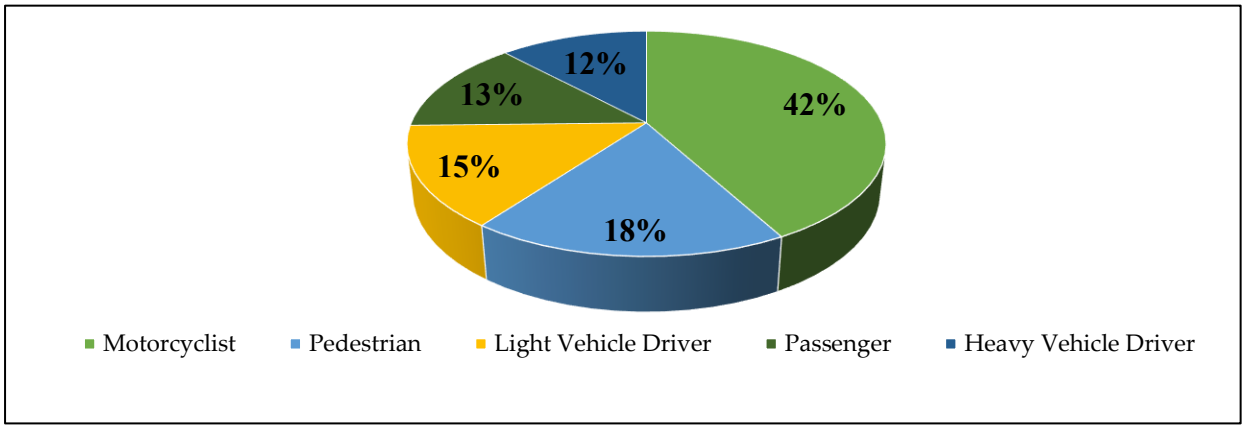

Figure 2: Vulnerable Road user groups involved in highway crashes in Nepal.

Vehicle Related Factors

Vehicle-related factors strongly influence drivers' safety on highways. Overloading (35%), brake failure (20%), poor maintenance (18%), tire bursts (15%), and other defects (12%) (Figure 5) compromise stability, braking, and control. Additionally, most of the responses rated on structural (manufacturing) features such as seat design, seating arrangement, headrests, steering, ergonomics, and mirror placement affecting comfort, visibility, and reaction time. Combined

with speeding and poor road conditions, these mechanical and structural vulnerabilities significantly increase the risk and severity of crashes and harm to drivers, highlighting the essence of strict enforcement of vehicle fitness, proper vehicle design, safety regulations, and operational practices.

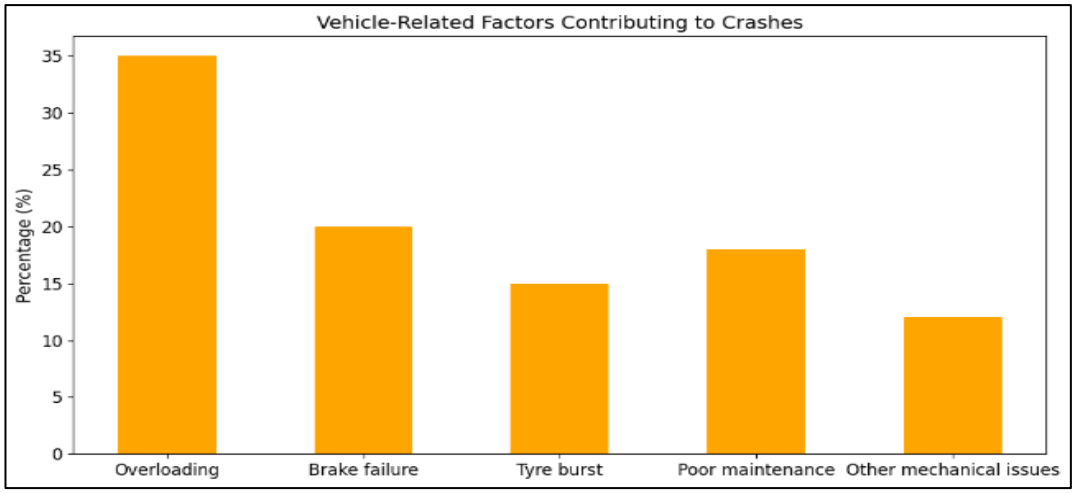

Figure 3: Vehicle-related factor contributing to crashes.

Crash Severity Indices (WSI & PI)

The Weighted Severity Index (WSI) and Perception Index (PI) comparison of the highway corridor is shown in Figure 6. With WSI = 78 and PI = 82, Banepa (Araniko Highway) had the greatest results, while Yampa (Prithvi Highway) had the lowest (WSI = 59 and PI = 63). At Kohalpur (WSI = 68, PI = 71), Chisapani (WSI = 72, PI = 74), and Malekhu (WSI = 65, PI = 70), intermediate values were noted. The combined effects of human, environmental, and vehicle-related factors resulted in a higher perceived risk than measured severity across all segments, where PI surpassed WSI.

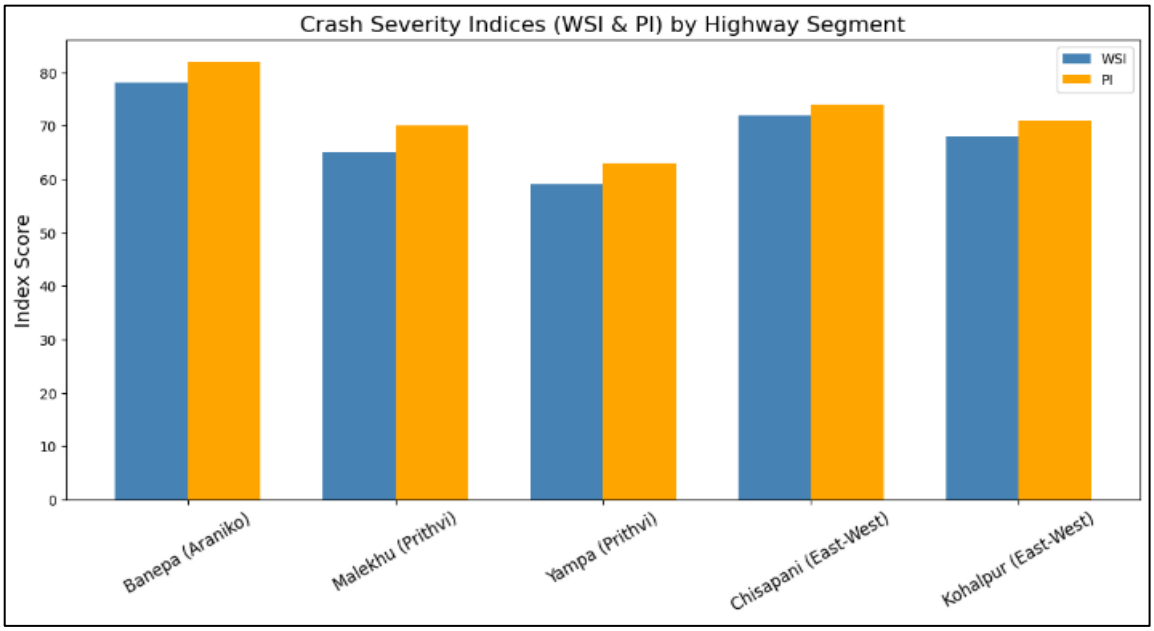

Figure 4: Crash severity indices.

Integrated Crash Cause Patterns Across Highways

The heatmap analysis indicates varying crash causes on the highways: Prithvi Highway is associated with driver distraction and fatigue due to long-distance travel and passenger vehicles; Araniko Highway has more overtaking and overloading issues due to steep gradients and mixed traffic; Mahendra Highway sees high rates of overloading, speeding, and fatigue as a key freight corridor. Alcohol and brake-related crashes appear across all highways.

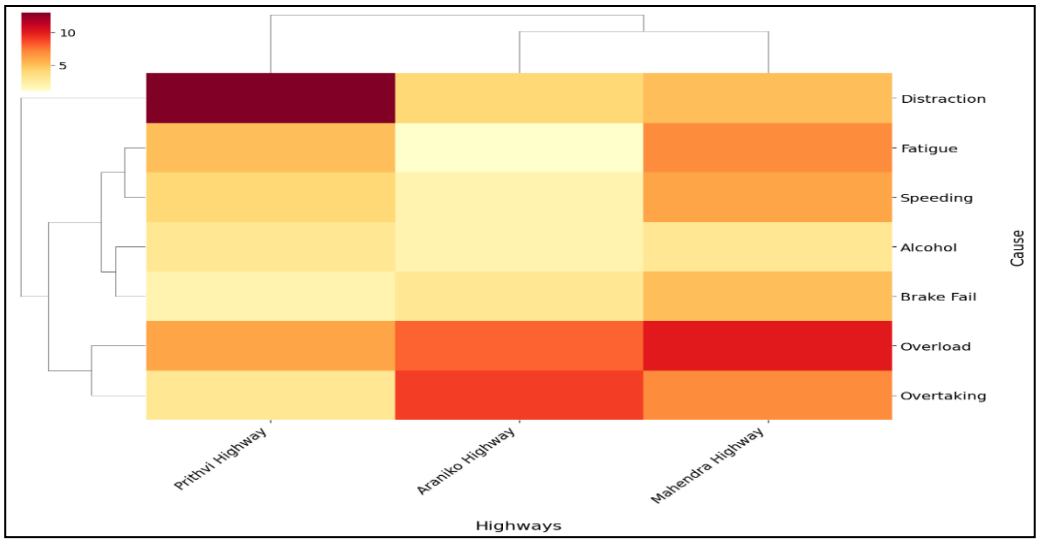

Figure 5: Integrated crash cause pattern across the highway.

Driver & Road Crash Hotspot Analysis

The combined heatmap and spatial analysis reveals clear spatial-causal patterns of crash risks across Nepal's roadways. Driver weariness and distraction are the primary causes of crashes on Prithvi Highway (Cluster 0; 84°–85° E), but overtaking and overloading are more common on Araniko Highway (Cluster 4; 85.5°–86° E). Consistent with its freight dominance, the East-West Highway (Clusters 1–3; 81°–88° E) exhibits the highest concentration of crashes attributable to overloading, speeding, and weariness. All things considered, the central and mid-eastern corridors are identified as high-risk areas that need specific safety measures.

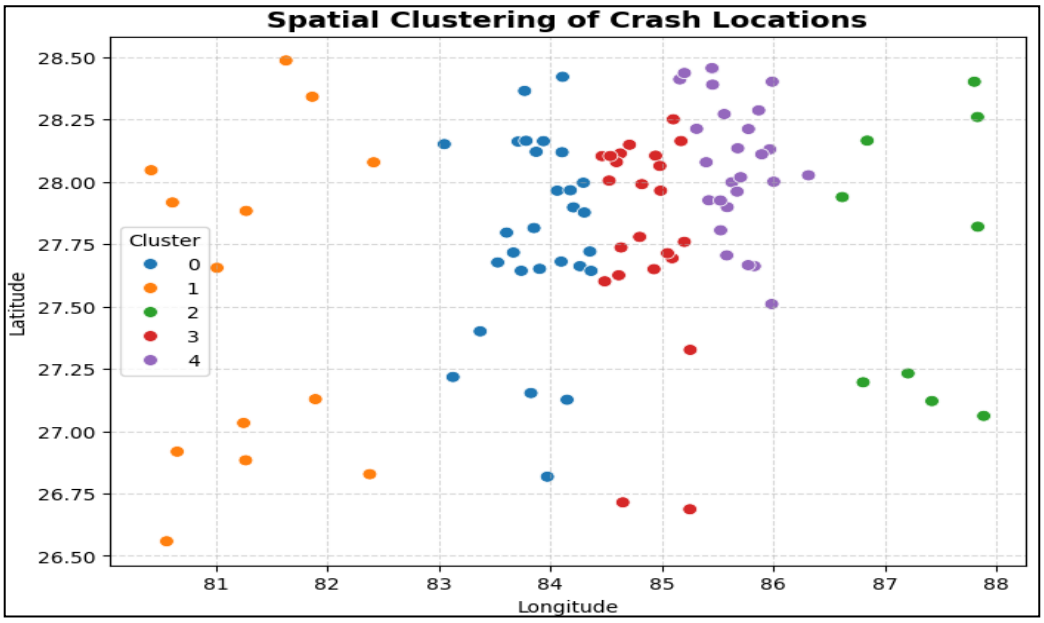

Figure 6: Spatial cluster of crash locations on the highways.

Driver Safety Cluster Analysis

The box plot (Figure 9) illustrates the distribution of stakeholder Likert scores (1–3) across six crash-risk clusters associated with driver's safety. The assessment reveals that vulnerable road users and governance issues are the most critical crash-risk factors, followed by road user behavior and infrastructure conditions. Safety features and environmental factors scored lower but showed wider variability in perceptions.

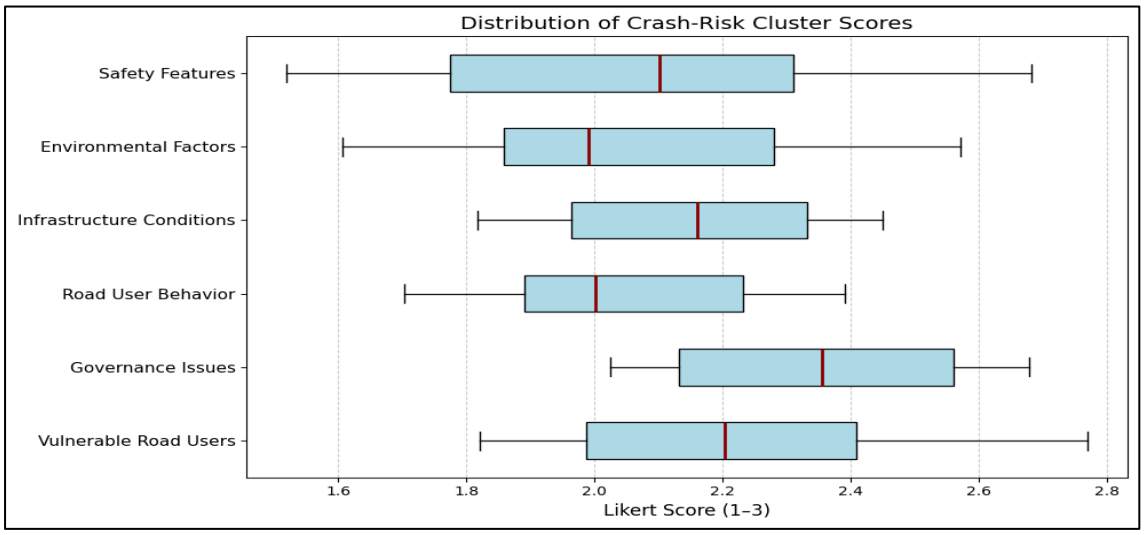

Figure 7: Distribution of score by cluster.

Discussion

The analysis of crash records, survey data, and road audits confirms that drivers' safety on Nepal's major highways is the outcome of a complex interaction of human, environmental, and vehicle-related factors rather than isolated risks. Human elements such as over speeding, fatigue from long-haul journeys, risky maneuvers, and distractions, including cell phone use, consistently emerged as dominant contributors to crashes, influencing drivers' safety.[14,15] Long distance driving without rest further compounds fatigue risks, particularly for freight drivers under time pressure.[16,17] Younger and less experienced drivers were disproportionately represented, echoing findings that highlight the heightened vulnerability of novice drivers in high-speed and complex traffic conditions.[7,13] Socioeconomic disparities further shaped safety outcomes,18as drivers with limited access to training.[19] On substandard vehicles, drivers had reduced competence and resilience on the road.[20] These results underscore the importance of targeted education, licensing reform, and fatigue management programs as central strategies for reducing human error and mitigating crash risks.[21,22,23]

Environmental and infrastructural conditions were equally decisive in shaping crash severity and frequency. Poor pavement quality, degraded road geometry, inadequate signage, and the absence of protective barriers forced drivers into risky maneuvers and amplified the consequences of mistakes.[24,25] Survey responses and field audits indicated that fatigued or inexperienced drivers were particularly vulnerable in poorly lit stretches, waterlogged sections, or areas encroached by roadside activities. Natural hazards such as landslides, fog, and monsoon flooding further compromised drivers' ability to navigate safely, amplifying risks associated with fatigue or risky maneuvers. These findings suggest that infrastructural shortcomings not only worsen outcomes but also actively influence driver behavior by increasing misjudgment and loss of control. Similar to previous assessments in Nepal, the results highlight how systemic infrastructure deficiencies interact with human

and vehicle-related weaknesses to create persistent high-risk environments.[11,26]

Vehicle related factors also played a critical role. Overloading, brake failures, tire bursts, and poor maintenance of vehicles were frequently cited as underlying causes of severe crashes.[27] Despite existing legal frameworks, overloading persists due to weak enforcement and economic dependence on freight transport. The persistence of such risks is consistent with some studies, which emphasize that inadequate vehicle inspection systems remain a defining challenge across many low- and middle-income countries.[12] Beyond mechanical issues, this study also identified ergonomic shortcomings such as poorly designed seating, inadequate mirrors, and steering difficulties that reduced driver comfort and visibility, further increasing the likelihood of errors during long hour journeys.[28,29]

The integrated triangular assessment revealed that each highway corridor carries a distinct crash risk profile shaped by its terrain, traffic composition, and functional role. On the Prithvi Highway, dispersed crashes were closely associated with fatigue and distraction during long-distance passenger travel, often compounded by weak barriers and infrastructure gaps. The Araniko Highway, by contrast, exhibited clustered high severity crashes linked to overloading, overtaking, and steep gradients in combination with geometric constraints. The East–West Highway demonstrated pronounced risks from freight-related overloading, speeding, and fatigue, reflecting its function as the country's key freight corridor. Table 3 summarizes these variations, showing how corridor-specific risks require tailored strategies rather than uniform solutions. Fatigue management programs are particularly relevant for the Prithvi, while strict enforcement of anti-overloading laws is critical along the Araniko, and freight regulation and inspection reforms are urgently needed on the East-West.

Overall, the results confirm that highway crashes in Nepal arise from systemic interactions among human, environmental, and vehicle related determinants. Unsafe driving behaviors remain central, but they are reinforced by poor infrastructure, weak enforcement, and inadequate vehicle standards. This conclusion is consistent with the studies carried out by the World Health Organization, which states that the high burden of crashes in low and middle income countries stems less from policy absence than from institutional weaknesses in implementation, monitoring, and governance.[3] The integrated triangular framework used here highlights the importance of addressing these factors simultaneously rather than in isolation. Effective improvement of driver safety in Nepal will therefore depend on comprehensive strategies that combine behavior change and training, infrastructural upgrades resilient to environmental hazards, rigorous vehicle inspection and enforcement, and stronger institutional accountability. Only through such coordinated, corridor specific measures can Nepal make sustained progress in reducing fatalities and protecting drivers on its major highways.

Conclusion

This study demonstrates that driver safety on Nepal's major highways is shaped by the dynamic interplay of human, environmental, and vehicle-related factors, rather than isolated risks. Human behaviors such as over speeding, fatigue, distraction, and risky maneuvers dominate crash causes, but weak infrastructure, poor road geometry, natural hazards, and vehicle defects, including overloading and poor maintenance, reinforce these. The triangular assessment further revealed corridor-specific risk patterns: fatigue on the Prithvi, overloading on the Araniko, and freight-related speeding and fatigue on the East–West highway, emphasizing the need for tailored interventions. Strengthening institutional accountability, improving road and vehicle safety standards,

and investing in driver training and fatigue management are essential for reducing risks. Integrated strategies that simultaneously address human, environmental, and vehicle dimensions, backed by stronger governance, sustained financing, and effective enforcement, offer the most viable pathway for safeguarding drivers and reducing highway fatalities in Nepal.

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