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Research Article

Multivariate geospatial analysis of road accidents in Bangladesh: A case study on the Khulna-Rajshahi corridor

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A R T I C L E I N F O

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A B S T R A C T

Bangladesh and other developing nations face road traffic accidents (RTAs) as a major public safety issue. Accidents have grown due to growing motor vehicle use, obsolete infrastructure, and lax traffic law enforcement. The Khulna–Rajshahi Highway experiences frequent and severe road crashes, resulting in high fatalities, injuries, and economic losses. The study aims to identify crash hotspots, assess land-use influences on road safety across varying road environments, and propose infrastructure and policy measures to enhance safety along the Khulna–Rajshahi corridor, with particular emphasis on VRU risks due to their disproportionate burden in Bangladesh's mixed-traffic environment. The research relied on a combination of Geographic Information System (GIS) tools, police-reported accident data from 2023 to 2024 integrated with VRU survey data (n = 208), and high-resolution satellite imagery. Advanced spatial techniques such as Kernel Density Estimation (KDE), Getis-Ord Gi* hotspot analysis, and Geographically Weighted Regression (GWR) were used to uncover meaningful patterns, yielding a model fit of $R^2 = 0.27$. The results indicate a notable clustering of accidents (Moran's I = 0.065, $p < 0.05$), with urban stretches along the corridor reporting the highest concentrations, reaching up to 30–35 accidents per square kilometer. Severity mapping revealed critical danger zones in places like Puthia (Rajshahi), Boraigram Upazila (Natore), among others. Due to poor infrastructure and traffic management, motorcyclists (77% of VRUs) and pedestrians were especially susceptible in mixed-use zones near lively markets and junctions, where approximately 45% of vulnerable road user (VRU) incidents occurred. This study suggests immediate, focused safety measures to decrease accidents. Building pedestrian overpasses and placing traffic lights in high-risk areas are key. A replicable GIS-based, corridor-level evidence framework that uniquely integrates VRU behavioral data with spatial statistics allows planners and transport authorities to prioritize location-specific interventions to reduce road traffic accidents in developing-country highway contexts.

1. Introduction

Road traffic accidents (RTAs) pose a significant threat to worldwide public health and injury prevention, particularly in developing countries (Hossain & Faruque, 2019). Additionally, they are one of the main causes of death for young people aged 15-29 worldwide and one of the common causes of death overall (WHO, 2013). Furthermore, by the end of the decade, automobile accidents killed more

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people than malaria, and projections indicate that automobile accidents will surpass HIV/AIDS as a leading cause of death (IRTAD, 2013). In recent years, road accidents have been ranked as the eighth leading cause of death or disability globally, with approximately 1.35 million fatalities and up to 50 million injuries annually, and this number continues to rise (WHO, 2023). Young people, particularly those aged 5–29, are among the most affected by road traffic accidents (WHO, 2022). By 2030, traffic accidents are expected to rank as the fifth leading cause of mortality worldwide (WHO, 2015).

Road traffic crashes are a major risk to public safety in Bangladesh. According to a 2020 World Bank report, annual road crash deaths are estimated to be between 20,736 and 21,316, with a mortality rate of approximately 13.6 per 100,000 population. Furthermore, the increase in the per capita fatality rate in Bangladesh has been three times higher than the South Asian regional average over the past three decades (World Bank, 2020). The rising trend of road traffic injuries in Bangladesh underlines an imperative for interventions of a targeted and evidence-based nature, specifically in areas of high traffic volume and exposure along major transport routes.

The Khulna-Rajshahi Highway is a crucial route in Bangladesh. It connects big metropolitan areas and is involved in crucial economic and social tasks. Nonetheless, a series of serious road accidents has been recorded on the Khulna-Rajshahi Highway. There are a variety of reasons that qualify the frequent occurrence of road accidents on Khulna-Rajshahi Highway, and these include the combination of traffic flows, varied land use characteristics, and the lack of appropriate highway infrastructures, including the absence of a median on poorly constructed roads, parking along the roads, and speeding while passing on two-lane roads (Islam et al., 2018). Recent anecdotal reports from local media highlight the severity of road safety challenges along the corridor. For instance, a collision in Khulna occurred when a truck struck a motorbike, while three people were killed in another collision involving a pickup van and an e-bike. In Rajshahi, three people were killed, and around fifty were injured when a bus collided with a stranded truck (BSS, 2025b). These incidents are cited solely to illustrate the recurring severity of road traffic accidents in the study area and are not part of the empirical dataset used in the spatial analysis. On the basis of data from both 2024 and 2025, the death rates in the Khulna and the Rajshahi divisions stood out as alarmingly high, at around 92 and 99 fatalities for every 100 accidents, respectively (Saha et al., 2025). Although a great many research pieces have been dedicated to trying to locate accident hotspots and analyze accident data, very few studies focus on the particular corridor in the country of Bangladesh. Most studies that already exist tend to be conducted in urban or regional settings in Bangladesh. Very few studies exist that identify the effect of mixed land use on the safety of vulnerable road users (VRUs) in rural and urban settings. Even fewer studies have investigated corridor-specific VRU behavior. Conditions of low visibility, lack of pedestrian infrastructure, and dangerous crossing conditions still prevail against VRUs like pedestrians, bicyclists, and two-wheeler riders. However, corridor-specific studies tend to generate very few disaggregated results on VRU behavior.

With this background, the aim of the proposed study is to provide policy insights that could help mitigate traffic accidents, ensure public safety, and enable sustainable development on the Khulna-Rajshahi route with explicit emphasis on Vulnerable Road Users. To fulfill the aim, the proposed work intends to address the following three objectives: (1) identification of traffic accident spots on the Khulna-Rajshahi route, (2) investigation into the effects of land use on the safety and occurrence of traffic accidents on various categories of roads and environments, and (3) assessment of VRU safety risks and formulation of strategies based on the improvements needed for achieving higher safety on the selected route.

2. Literature review

2.1. Road traffic accidents: causes and risk factors

The black spot of road accidents is also known as high-risk locations, where accidents are more likely to occur because of a combination of factors such as traffic volume, condition of the road, weather conditions, and environmental factors. According to broad groups, the literature categorizes the causes of road crashes into three: human factors, vehicle-related factors, and environmental/road condition-related factors.

Human factors loom largest, entailing unsafe driving behaviors such as speeding, distraction, and all forms of traffic rule violations (Rolison et al., 2018). Vehicle-related factors include mechanical failures, the absence of safety features, and generally poor states of vehicles, which add significantly to both high frequency and severity, especially in developing nations (Endalew et al., 2024). Besides these, road and environmental conditions comprise improper road geometric configuration, poor signage, reduced visibility, and hazardous intersection design, which were proven to increase crash vulnerability (Ahmed et al., 2023).

2.2. Spatial patterns and hotspot studies

Across the world, a growing body of literature is now identifying common locations for road traffic crashes. In Japan, Nakao et al. (2024) show that more than half of all traffic accidents happen at or near junctions, with the surprising number of fatalities at small crossings where only minor roads meet. In Iran, Saheli and Effati (2019) found rural roads responsible for over 70% of fatal collisions, many of which happen on routes lacking access control and permitting direct connections from adjacent land uses. Within Turkey, a similar trend can also be observed. Gungor et al. (2021) have shown how a spatial and temporal pattern exists for crashes, meaning certain locations and time periods in which the crash rate is significantly higher. In Istanbul, Srikanth et al. (2019) have shown how crash hotspots are mainly concentrated on busy roads and road intersections in general.

2.3. Road safety interventions and best practices

A number of studies and real-world examples show how targeted road-safety measures work. For example, IndiaRAP (2021) found that upgrading the Belgaum–Yaragatti State Highway through smarter road design and better protection for vulnerable users, increased road-safety star ratings and resulted in a significant reduction of collisions. In Vietnam, pilot efforts to enhance pedestrian safety, such as school area slow zones, infrastructure enhancements, and public awareness campaigns underscore how these localized actions, coupled with supportive policy, can reduce crash risks (Case Studies – Road Safety Toolkit, n.d.). Taken altogether, these findings emphasize the fact that well-thought-out infrastructure design, stringent enforcement of policies, and awareness at the community level form the core of any viable road-safety plan.

2.4. Road safety research in Bangladesh

In Bangladesh, scientists have been employing various statistical techniques and Geographic Information System techniques to identify high-risk locations and build accident hotspots. According to a study by Rahman and Newaz in 2013, a GIS case study of accident data along the Dhaka-Aricha-Banglabandha corridor identified HRLs by marking accident-prone areas where three or more people had been fatally injured in an accident. Some studies tend to focus on prominent routes in Bangladesh—Dhaka to Mawa to Barisal to Patuakhali; Dhaka to Sylhet to Tamabil; and Dhaka to Chittagong to identify accident hotspots and their contributing factors (Alam & Ahsan, 2014; Rahman et al., 2015; Sarkar et al., 2016). In their recent literature piece, scientists Khatun et al., 2024 made a clear emphasis on the application of GIS and statistics to identify high accident-prone areas in Bangladesh.

However, despite all the progress that has been made, the vast majority of studies relate to urban areas/rural areas in general or focus on transport corridors in very superficial ways. The effect that mixed land use has on the incidence and severity of accidents, particularly on the most vulnerable road users and on different road infrastructure types, is considered untested. Furthermore, corridor-specific VRU behavior has not typically been differentiated in existing studies.

2.5. Urban transportation planning

Urban transport planning is at the very core of sustainable urban development in its endeavors to offer safe, efficient, and equitable transport to all citizens while addressing problems of traffic congestion, pollution, and safety on roads. Transport planning not only reduces traffic congestion and accidents, but it also plays a vital role in regional development. For example, Kayes et al. (2025c) and Pramanik et al. (2025) select transportation network as a crucial component of regional development. Recent research in the field of urban transportation planning is calling for a shift away from car-centric systems to integrated, sustainable, policy-driven mobility (Almatar, 2024). The available evidence points to rapid urban growth and poorly planned land use having stacked inefficiencies over traffic jams and pollution in trying to get around, with a pressing need for strategic planning that will place transportation infrastructure in line with sustainability goals. Indeed, many studies have emphasized the importance of green mobility or low-carbon options, meaning that the acceptance of electric vehicles, along with the integration of renewable energy and supportive infrastructure, will lead to reduced emissions with increased urban environmental quality and efficiency in travel.

Meanwhile, it is in this condition that the most important planning approach, transit-oriented development, meets the goals of combining investment in land use and public transportation to generate compact, walkable neighborhoods, reducing dependence on private cars while increasing the ability to travel longer distances. In turn, improving access to employment, education, health, goods, and services (Almatar, 2022; Rahman et al., 2021). Poorly designed road networks and coordination across institutions, data also show, further increase congestion and reduce system performance, requiring comprehensive planning frameworks supported by capable governance and data-driven decision-making mechanisms.

Having considered the factors mentioned above, it is evident that literature suggests that there is one fundamental principle of urban transport planning: integration. With this principle in mind, it is essential to note that it is important to choose environmentally sound modes of transport and to develop land use and transport solutions that support this principle. As suggested, Almatar, (2023) and Hasan, (2022) have presented the ways through which integration can be achieved.

2.6. Review of spatial and geospatial analyses of road traffic accidents in Bangladesh

Recent studies applying geospatial models to road traffic accident locations in Bangladesh are just beginning to leverage possibilities in GIS and spatial statistical models to analyze spatial distribution and hotspots of accident occurrences. In urban settings, GIS models also help in identifying accident hotspots in an urban setting in the Dhaka Metropolis using Local Moran's I, Getis-Ord Gi, and Kernel Density Estimation methods, identifying 22 accident hotspots from 2010 to 2012, highlighting the application of spatial statistical models in accident mapping in urban areas (Ahmad et al., 2020). In contrast, even national highway settings are also in focus; for example, recent studies are applying GIS models such as accident severity rate and Kernel Density Estimation methods to identify black spots in the Kushtia-Jhanaidah Highway (N704) and propose corresponding interventions based on accident spatial pattern and factor analysis, marking identification of 35 black spots (Khatun et al., 2024b). Even smaller administrative zones, such as districts, like Bogura, also contemplate and apply GIS models in identifying accident hotspots outside urban areas and propose safety actions in semi-urban and rural settings, mixing spatial models with behavior and statistics (Ashraf & Khan, 2025).

2.7. Research gap

Though international and domestic studies in the region have explained the factors of road crashes, locations of these events, as well as how hotspots emerge, no study has examined the Khulna-Rajshahi region as a distinct entity. This particular region combines all possible factors of traffic, mixed traffic conditions, land use patterns, and the absence of roads to demand attention in its own right. An investigation into such details will help expand our understanding of safety dynamics as a corridor-level concern and inform evidence-based policy actions in the region of Bangladesh.

2.8. Conceptual framework

The conceptual framework of this research, Fig. 1, establishes a seven-layer systematic pipeline for corridor-level accident analysis. This integrates foundational data inputs with advanced geospatial statistics. The framework begins with Layer 1: The collection of multi-source data, including police records, Sentinel -2 satellite imagery & survey data of 208 vulnerable road users. In layer 2, it undergoes geocoding and cleaning to create a standardized spatial dataset. Layer 3, comprises multiple analyses which are Kernel Density Estimation (KDE), Getis-Ord Gi* hotspot identification, and Geographically Weighted Regression (GWR). These methods allow for the contextualization of thematic risks in Layer 4. Which specifically focusing on land-use-accident interactions and VRU exposure. The final stages (Layers 5, 6 and 7) translate these spatial metrics into tier-based risk maps and policy implications. That ensures the framework remains replicable and transferable to other mixed-traffic corridors in developing regions.

2.9. Contribution of the research

This research offers a substantial practical contribution by establishing a replicable GIS-based, corridor-level analytical framework that amalgamates vulnerable road user (VRU) behavioral characteristics with sophisticated spatial statistical methodologies to systematically analyze road traffic accident trends. This framework integrates micro-level behavioral data with spatial hotspot detection and regression outputs, offering a more nuanced comprehension of risk formation along highway corridors in developing-country contexts, in contrast to traditional crash studies that primarily depend on aggregate accident records.

3. Study area profile

Khulna-Rajshahi National Highway consists of contiguous parts of the N6, N704, and N7 national highways forming a significant corridor through seven districts of the Khulna and Rajshahi divisions. The highway connects the southwestern and northwestern parts of Bangladesh, facilitating huge trade, transport, and regional connectivity. The national highway geographically spans a belt from approximately 23° 24′ to 24° 21′ north latitudes and from 88° 18′ to 89° 33′ east longitudes and passes through the Upazilas of the Khulna, Jashore, Jhenaidah, Kushtia, Pabna, Natore, and Rajshahi districts. The total length of this two-lane bituminous highway system is around 265 km (Fig. 2), covering the N6, N704, and N7 sections from Khulna to Rajshahi. The Khulna and Rajshahi areas are classified as high economic areas since they contribute significantly to the agricultural production of Bangladesh, industrialization, and trading activities. The Khulna Division serves as the key center for industry, comprising the production of jutes, fisheries, as well as shipbuilding, whereas Rajshahi is famous for generating the country's maximum agricultural output, especially in terms of mangoes, silk production, and textile production. The two areas jointly accommodate a significant part of the nation's economy, significantly impacting regional and national trading streams (Rahman et al., 2021). In addition, these divisions provide significant trade links with other places in Bangladesh, whereby the Khulna-Rajshahi highway acts as a principal corridor enhancing economic connectivity nationwide in the country's southwest and northwest corners (Hossain & Islam, 2022).

4. Methodology

4.1. Data collection and processing

To ensure a comprehensive analysis of the 269 km Khulna-Rajshahi National Highway, accident records (2023–2024) were aggregated from multiple authoritative sources. Primary data was obtained from the Bogura and Khulna Highway Police Headquarters. However, centralized HQ records often lacked precise district-level granularity. To address this, additional data was directly collected from respective district police stations and cross-referenced with reports from the Bangladesh Road Transport Authority (BRTA**)** and local newspapers. The records collected contain the following notable information:

- When and where the accidents happened.
- Accidents' latitude and longitude.
- How bad the accident was (fatal, injury, or property damage).
- Types of accidents, like rear-end crashes and side-impact crashes.
- Cars that got into accidents (sedans, SUVs, buses, trucks, etc.).
- Details on the demographics of vulnerable road users, such as cyclists, motorcyclists, and pedestrians.
- Information about the amount of traffic (if it's available).

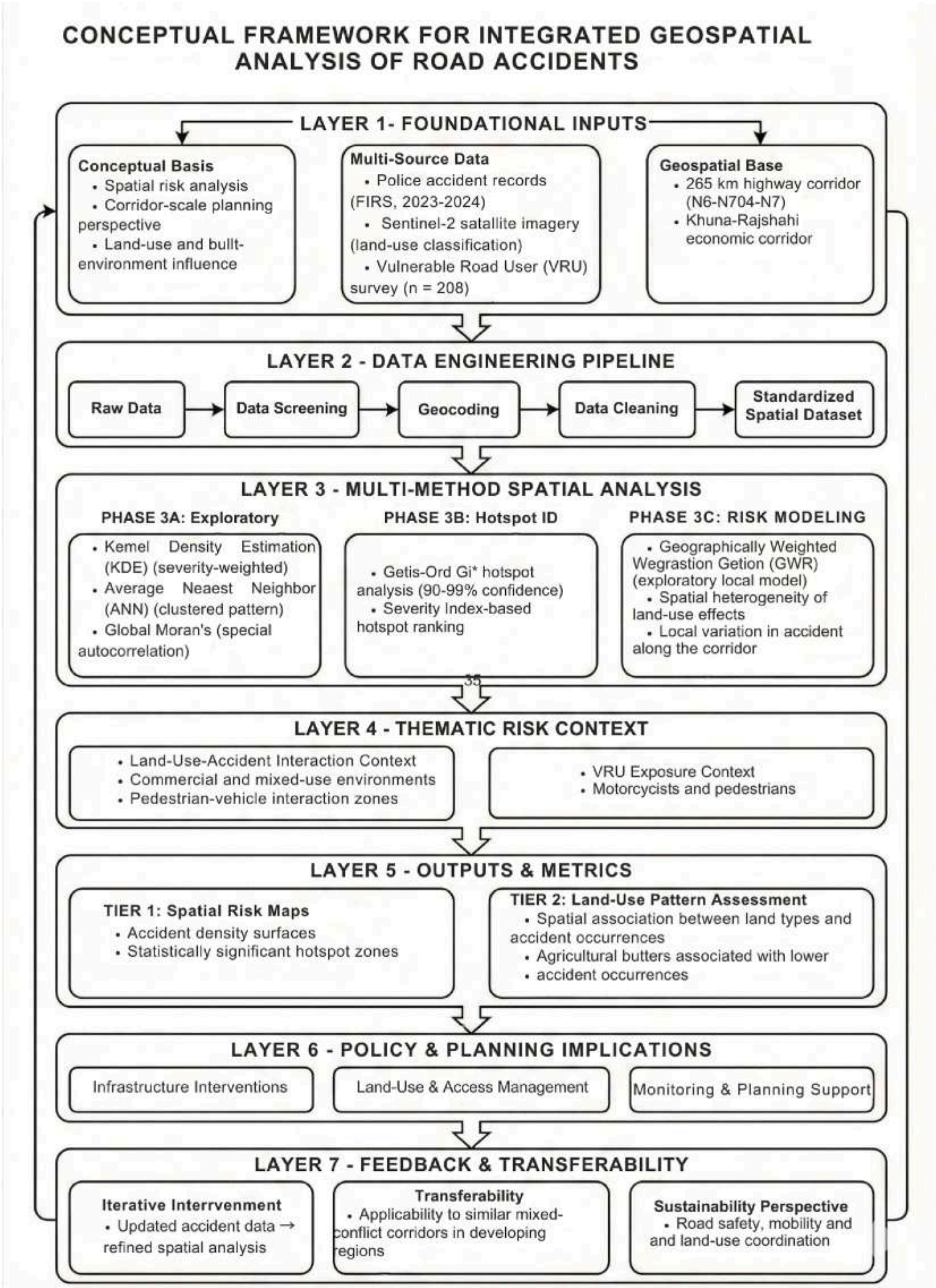

Fig. 1. Conceptual Framework of the research.

The data is from 2023 to 2024 and tells us how many accidents happened on this important transportation route, how bad they were, and where they happened.

4.1.1. Data processing and cleaning

To ensure spatial and statistical accuracy, the raw dataset underwent a rigorous three-stage processing workflow:

Geocoding Verification: Raw police records often provided descriptive locations (e.g., “Near Puthia Bazar” or “beside Km post 15"). We utilized **Google Earth Pro** to manually verify these landmarks and convert them into precise Latitude and Longitude coordinates.

Redundancy Removal: Since data was aggregated from multiple sources (Police and Media), duplicate entries were identified by matching date, time, and vehicle details and removed to prevent double-counting.

Attribute Standardization & Filtration: Inconsistent terminologies (e.g., “Heavy Truck” vs. "Lorry”) were standardized into uniform categories. Furthermore, incomplete records that lacked critical spatial information or injury severity details were excluded from the final analysis to maintain model integrity.

4.2. *Spatial analysis for hotspot identification*

4.2.1. *Severity index/crash hazard level*

The accident severity index (SI) was created to figure out how bad an accident was using data from the last five years. It is very hard

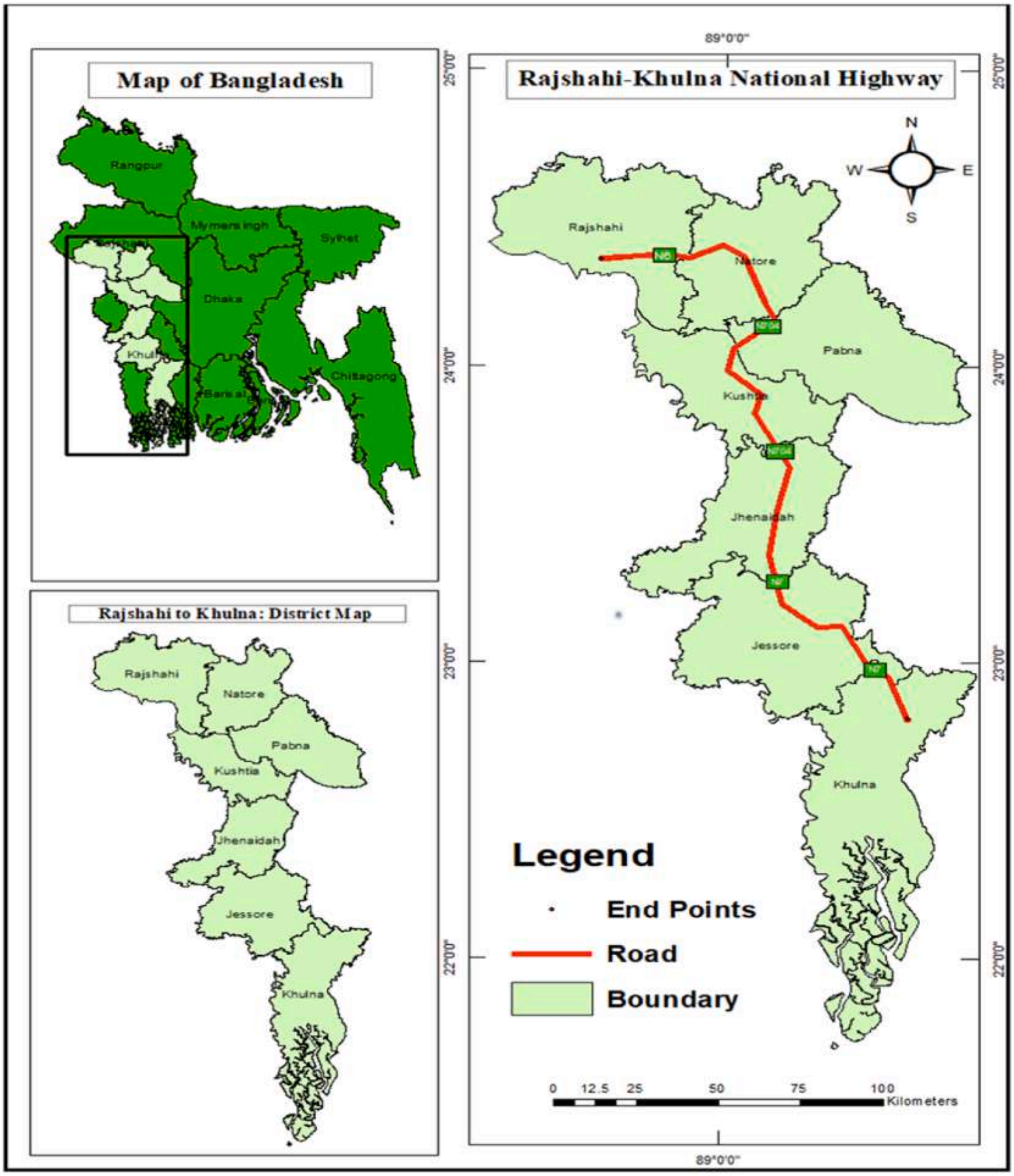

Fig. 2. Study area of the Rajshahi-Khulna highway.
Source: Authors' drawing, 2025

to tell if the clustering we see is correct without weighted data. The Belgian severity weighting method assigns individual weights of 5, 3, and 1 to fatal, severe, and minor accidents, respectively, in order to analyze high and low clustering of accident data (Geurts et al., 2004). This threshold was used in this study to find accident dark patches. The severity index (SI) can be calculated for each location using the following equation (1) (Zheng et al., 2024):

$$\frac{SI}{CHL} = 5 \times De + 3 \times Se + Le \tag{1}$$

where De is the total number of fatalities, Se is the total number of severe injuries, and Le is the total number of minor injuries, and SI/CHL is the severity index for each site.

4.2.2. Identification of the spatial pattern of accidents

We performed an “Average Nearest Neighbor” (ANN) analysis to analyze the spatial pattern of the accidents. ANN shows if accidents occur randomly, in clusters, or scattered over the studied region. This research determined which locations had a greater prevalence of accidents by using the Nearest Neighbor Index (NNI). Potential hotspots are suggested by clustering, which is indicated by a NNI value smaller than 1. Conversely, a NNI number around 1 indicates a random distribution, but a value over 1 indicates a dispersed distribution. Hotspot analysis was used to identify high-risk areas, which are defined as crash spots with NNI values less than 0.6 for this investigation. ArcGIS software was used to perform the ANN analysis. equations (2) and (3), and 4weres used to do so:

$$NNI = \frac{D_o}{D_e} \tag{2}$$

$$D_o = \sum_{i=1}^{n} \frac{D_i}{n} \tag{3}$$

$$D_e = 0.5 \times \sqrt{\frac{A}{n}} \tag{4}$$

where A is the area of the minimal enclosing rectangle containing all features, Do is the average observed distance, De is the average predicted distance, and n is the total number of features.

4.2.3. Cluster analysis

This study employed cluster analysis, a conventional technique for examining spatial autocorrelation, to analyze the distribution of accidents. At the same time, the method looks at where features were placed and what their values were. It looks at the dataset to see if accidents are spread out, grouped, or randomly, and it gives one output for general spatial pattern analysis (Afolayan et al., 2022). Cluster Analysis provides an enhanced understanding of spatial relationships. The main measure is Moran's I statistic, which goes from −1 to 1. If the number is close to 1, it means that there is a cluster pattern with spatial autocorrelation. If the number is close to −1, it means that there is a dispersed pattern with no spatial autocorrelation (Liu & Lin, 2019). We used a weight matrix to get Moran's statistic, which is shown in Equation (5):

$$I = \frac{n \sum \sum w_{ij}(x_i - \bar{x})}{w \sum (x_i - \bar{x})^2} \tag{5}$$

The spatial weight between units I and J is represented by wij, the number of spatial units is represented by n, the attribute value for unit I is represented by xi, and the mean attribute value is denoted by x.

4.2.4. Methods of heat map preparation

KDE was selected for this study because it transforms discrete accident points into a continuous density surface, allowing for the visualization of risk intensity without being constrained by administrative boundaries. This research created a heat map of the area's most likely to have traffic accidents using the Kernel Density Estimation (KDE) approach. KDE estimates the density of accidents in the study area and produces a smoothed surface of where the accidents are most likely to happen, ranging from high to low, at every point (Afolayan et al., 2022). KDE estimates the density of accidents in the study area and produces a smoothed surface of where the accidents are most likely to happen, ranging from high to low, at every point (Afolayan et al., 2022). The performance of KDE is primarily influenced by cell size and bandwidth, which are the most significant parameters in this context.

$$f(x, y) = \frac{1}{nh^2} \sum_{i=1}^{n} k\left(\frac{d_i}{h}\right) \tag{6}$$

In equation 6, f(x,y) represents the density estimate at the location (x,y), n denotes the total number of observations, and h indicates the bandwidth, which affects the smoothness of the estimate. K represents the Kernel function, which defines the form of the smoothing curve, while di denotes the Distance from each observation point to the location (x,y)(x, y)(x,y).

4.2.5. Hotspot identification and spatial clustering analysis

While KDE visualizes density, the Getis-Ord Gi statistic was utilized to identify statistically significant spatial clusters ($p < 0.05$).

This method distinguishes actual hotspots from random spatial noise by comparing local averages to the global average. A hotspot analysis was performed to pinpoint clusters of accident occurrences along the study route by analyzing accident records. This analysis employed spatial analysis and mapping techniques, specifically using the "Getis-Ord Gi* statistic", to identify clusters within the spatial data according to ESRI (2023). "Getis-Ord Gi* statistic" examines the degree of concentration of weighted points so that statistically significant hot spots (high-density clusters) and cold spots (low-density clusters) may be determined (Getis & Ord, 2010). "Getis-Ord Gi* statistic" is calculated as (Getis et al., 2004):

$$G_i^* = \frac{\sum_{i=1}^{n} w_{i,j} x_j - \overline{x} \sum_{j=1}^{n} w_{i,j}}{s\sqrt{\frac{n\sum_{j=1}^{n} w_{j,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2}{n-1}}} \tag{7}$$

Where,

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{8}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\overline{x})^2} \tag{9}$$

In this context, Gi* represents the Getis-Ord statistic corresponding to each point, while xj denotes the attribute value associated with each feature. j, wi,j represents the spatial weight between features i and j, n denotes the total number of features, $\overline{x}$ indicates the mean attribute value, and S signifies the standard deviation of the attribute values.

4.2.6. Vulnerable road user (VRU) assessment

4.2.6.1. Survey design and sampling. To corroborate the statistical findings derived from the spatial analysis (KDE and Getis-Ord Gi) and to contextualize the high-risk zones identified, a primary survey of Vulnerable Road Users (VRUs) was conducted. While spatial tools identify where clusters occur, this qualitative assessment aims to understand why these locations are hazardous from the user's perspective, providing behavioral ground-truthing to the geospatial data. Selection of the participants for Vulnerable Road User (VRU) analysis was done through systematic sampling of those who frequently use the Khulna-Rajshahi corridor. With the nearly unlimited size of the population, a target sample size of 208 participants was planned to achieve 85% confidence and ±5% margin of error. The sample was representative of all the types of VRUs, i.e., pedestrians, cyclists, and motorcyclists. Recruitment was focused at various locations along the corridor, such as major junctions, market areas, and schools, where traffic composed of VRU is exceptionally high. Participants were approached randomly and asked to complete a structured survey assessing their experiences and perceptions of road safety. The structured survey assessed five variable categories: (1) demographics (age, gender, occupation), (2) travel behavior (frequency of travel and modes used), (3) safety perceptions (feelings of safety, hazard awareness), (4) infrastructure quality (pedestrian paths, bike lanes), and (5) accident history (past involvement in road accidents or injuries).

4.3. Assessing land use impact on road safety and accidents

4.3.1. Land use data

Acquired high-resolution satellite imagery and used remote sensing techniques to classify land use such as residential, commercial, industrial, farmland, and green space within a 500-m radius around the highway. To analyze land cover changes and surface temperature, Sentinel-2 Level-2A surface reflectance imagery obtained from the Copernicus Open Access Hub for 2023 was utilized (Table 1). To minimize the seasonality effect, we employed three multispectral scenes that were acquired in March of the year, a period with low rainfall and clear weather. The best time for land surface temperature calculations is March, which has low rainfall and good weather. This imagery with a resolution of 10 m enables intensive examination of land cover variations. This study accounted for Bands 3, 2, and 4 (Green, Blue, Red) due to low cloud cover (<10%) and favorable temporal distribution in order to provide seasonal land use and vegetation patterns.

Table 1
Land use data.

Satellite	Sensing date	Tile ID	Spectral Bands	Resolution	Instrument	Cloud Coverage (%)
SENTINEL-2A	2017-03-23	45QZF	Band 2 Band 3 Band 4	10m	MSI	2.68%

4.3.2. Spatial regression ("Geographically Weighted Regression" – GWR)

Standard global regression models (like OLS) assume relationships are constant across space. GWR was chosen for this corridor analysis specifically to capture spatial heterogeneity, allowing us to observe how the influence of land use on accident severity varies across different rural and urban segments of the highway. To capture the spatially varying land use to accident risk relationship, "Geographically Weighted Regression" (GWR) was utilized (Xu et al., 2020). GWR was applied using Severity Index (SI) as the dependent variable and proportions of urban area and crop land (within 500m buffer) as explanatory variables. Equation (10) represents the GWR specification. The GWR model enables the estimation of local regression coefficients, which will aid in identifying the spatial variations in the influence of land use on accident frequency. To capture spatially varying relationships between land use and accident risk

$$Y_i = \beta_o(u_{i,}v_i) + \sum_{k=1}^{k} \beta_k(u_{i,}v_i)X_{ik} + \epsilon_i \tag{10}$$

In this context, Y_i represents the accident frequency at location i, while β_o $(u_{i,}v_i)$ serves as the intercept tailored to the coordinates

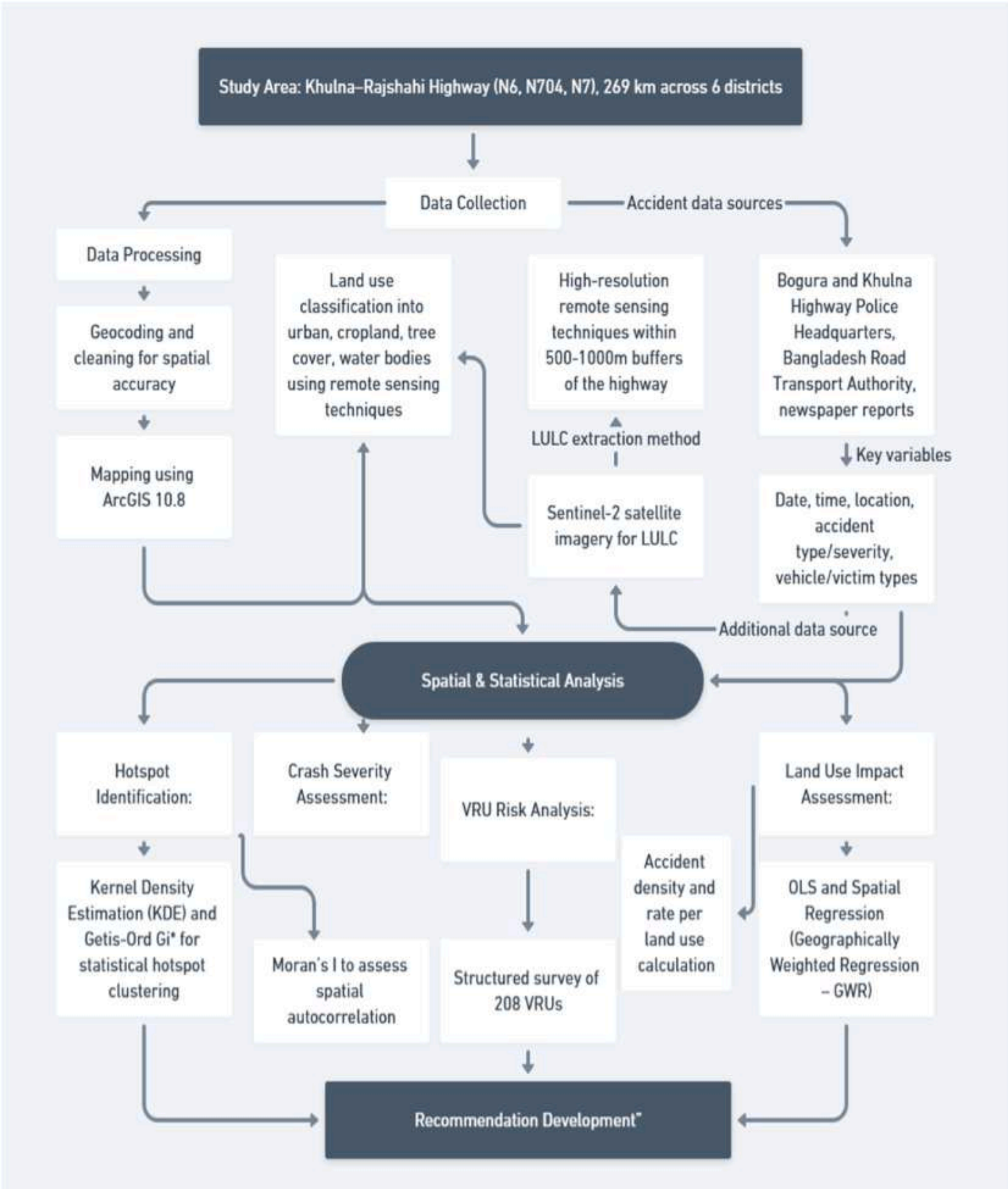

Fig. 3. Methodological steps.

Table 2
Examination of physical characteristics at 100 high-incident locations.

Serial No.	Name of the place	Road Markings	Speed Breaker	Street Light	Traffic Sign	Traffic Signal	SI Value	Ranking
1	Boraigram Upazilla	✓	✗	✗	✓	✗	82	1st
2	Kaliganj	✓	✗	✗	✓	✗	78	2nd
3	Muradnagar	✓	✗	✗	✓	✗	70	3rd
4	Barobazar	✓	✓	✓	✓	✗	70	4th
5	Churamankathi	✓	✗	✗	✓	✗	67	5th
6	Dasuria Bus Stand	✓	✓	✓	✓	✗	65	6th
7	Fultola Bus Stand Mosjid	✓	✓	✓	✓	✗	64	7th
8	Abhaynagar Upazila Parishad	✓	✓	✓	✓	✗	64	8th
9	Modondanga Bazar	✓	✓	✓	✓	✗	63	9th
10	Fhulbari More	✓	✓	✓	✓	✗	61	10th
11	Puthia	✓	✗	✗	✓	✗	58	11th
12	Laudia Bazar	✓	✓	✓	✓	✗	57	12th
13	Shantidanga	✓	✗	✗	✓	✗	56	13th
14	Battali	✓	✗	✗	✓	✗	56	14th
15	Islamic University area	✓	✓	✓	✓	✗	54	15th
16	Satmile Bazar	✓	✓	✓	✓	✗	53	16th
17	Laxmipur Bazar	✓	✓	✓	✓	✗	52	17th
18	Afilgate Bypass Bus Stand	✓	✓	✓	✓	✗	46	18th
19	BMDB Puthia	✓	✗	✗	✗	✗	46	19th
20	Mojompur Bus Terminal	✓	✓	✓	✓	✗	40	20th
21	Kapashia High School	✓	✗	✗	✓	✗	38	21st
22	Rajghat LPG Filling Station	✓	✓	✓	✓	✗	37	22nd
23	Bosundia Mor	✓	✗	✗	✓	✗	37	23rd
24	Katakhai Bazar	✓	✓	✓	✓	✗	36	24th
25	Bonpara Bypass	✓	✗	✗	✓	✗	35	25th
26	Battail Notun Para	✓	✗	✗	✓	✗	34	26th
27	Binodia Park	✓	✗	✗	✓	✗	34	27th
28	Katakhali Bazar	✓	✓	✓	✓	✗	34	28th
29	Bonpara Fire Service	✓	✗	✗	✓	✗	33	29th
30	Baspara	✓	✗	✗	✓	✗	31	30th
31	Nogor Hat	✓	✗	✗	✗	✗	31	31st
32	Bondhu Kollyan Area	✓	✓	✓	✓	✗	29	32nd
33	Akij City Public Park	✓	✗	✗	✓	✗	29	33rd
34	Hatkhola Durga Temple	✓	✗	✗	✓	✗	29	34th
35	Behramara CGS	✓	✗	✗	✓	✗	28	35th
36	Gopalpur	✓	✗	✗	✓	✗	27	36th
37	Besic Office Natore	✓	✗	✗	✓	✗	26	37th
38	Bittipara Bazar	✓	✓	✓	✓	✗	24	38th
39	Vatoy Bazar	✓	✓	✓	✓	✗	23	39th
40	Dasuria Rail Gate	✓	✓	✓	✓	✗	23	40th
41	Gabla	✓	✗	✗	✓	✗	22	41st
42	Woodland Mills	✓	✗	✗	✓	✗	22	42nd
43	Gunaihati Bazar	✓	✓	✓	✗	✗	22	43rd
44	Bonpara Catholic Church	✓	✗	✗	✓	✗	22	44th
45	Baitus Salam Mosque	✓	✗	✗	✓	✗	22	45th
46	Makka Traders	✓	✗	✗	✓	✗	21	46th
47	Bihas	✓	✗	✗	✓	✗	21	47th
48	Jhalmolia Primary School	✓	✗	✗	✓	✗	21	48th
49	Jhamolia Bazar	✓	✓	✓	✓	✗	21	49th
50	Lalon Mor	✓	✗	✗	✓	✗	21	50th
51	Noapara Ferry Ghat	✓	✗	✗	✓	✗	21	51st
52	Global Tobacco Company	✓	✗	✗	✓	✗	21	52nd
53	Akij Ideal School Area	✓	✓	✓	✓	✗	19	53rd
54	Bardah	✓	✗	✗	“✗	✗	19	54th
55	IT Park Abasik Alaka	✓	✗	✗	✓	✗	19	55th
56	Rajshahi Cancer Hospital	✓	✗	✗	✓	✗	19	56th
57	Godhora Bazar	✓	✓	✓	✓	✗	19	57th
58	Sristy Center School	✓	✗	✗	✓	✗	19	58th
59	Senbegh Bazar	✓	✓	✓	✓	✗	19	59th
60	Mirkamari	✓	✗	✗	✓	✗	18	60th
61	Puthia Central Mosque	✓	✗	✗	✓	✗	18	61st
62	Kachutia Central Mosque	✓	✗	✗	✗	✗	18	62nd
63	Sorai Kandi Dumurtola	✓	✗	✗	✓	✗	18	63rd
64	Jaforpur Matri Temple	✓	✗	✗	✓	✗	18	64th
65	Customs Jinaidha	✓	✗	✗	✓	✗	18	65th
66	Bishal Khali	✓	✗	✗	✗	✗	18	66th
67	Phultola Plastic Depo	✓	✗	✗	✓	✗	18	67th
68	Hemel Poultry Farm	✓	✗	✗	✓	✗	17	68th

(*continued on next page*)

Table 2 (*continued*)

Serial No.	Name of the place	Road Markings	Speed Breaker	Street Light	Traffic Sign	Traffic Signal	SI Value	Ranking
69	Tauhid Place	✓	✗	✗	✓	✗	16	69th
70	Takia	✓	✗	✗	✓	✗	16	70th
71	Bonpara Pouro Market	✓	✗	✗	✓	✗	16	71st
72	Akdala Natore	✓	✗	✗	✓	✗	16	72nd
73	BGPS Park	✓	✗	✗	✗	✗	16	73rd
74	Chutlia	✓	✗	✗	✓	✗	16	74th
75	JHM Filling Station	✓	✓	✓	✓	✗	16	75th
76	Mizan Filling Station	✓	✓	✓	✓	✗	16	76th
77	BRAC Avayanagor Area	✓	✓	✓	✓	✗	14	77th
78	Rogunarthpur	✓	✗	✗	✓	✗	14	78th
79	Shibpur Bazar	✓	✓	✓	✗	✗	13	79th
80	Hindu Mandir	✓	✗	✗	✓	✗	13	80th
81	Puthia Fire Service	✓	✗	✗	✓	✗	13	81st
82	Daru Ulumshapamr	✓	✗	✗	✓	✗	13	82nd
83	Shekpara	✓	✗	✗	✓	✗	13	83rd
84	Dhokkhin Bonpara	✓	✗	✗	✓	✗	13	84th
85	Paksey Rail Station Area	✓	✓	✓	✓	✗	13	85th
86	Nowda Gobindapur	✓	✗	✗	✓	✗	13	86th
87	Rajarhat Chamrar Bazar	✓	✓	✓	✓	✗	13	87th
88	Rajghat Bazar	✓	✓	✓	✓	✗	13	88th
89	Akij Foundation Center	✓	✗	✗	✓	✗	13	89th
90	Health Complex Fulala	✓	✓	✓	✓	✗	13	90th
91	Nowapara Pirsaheb Mazar	✓	✗	✗	✓	✗	11	91st
92	Battail Natun Para	✓	✗	✗	✓	✗	11	92nd
93	Tetultala	✓	✗	✗	✓	✗	11	93rd
94	Betel Leaf Market	✓	✗	✗	✗	✗	11	94th
95	Children Care Center	✓	✗	✗	✓	✗	11	95th
96	Chadpur Madrasa	✓	✗	✗	✓	✗	11	96th
97	Mim Filling Station	✓	✓	✓	✗	✗	10	97th
98	Palbari Mor	✓	✗	✗	✓	✗	10	98th
99	Shiromoni Bazar	✓	✓	✓	✓	✗	8	99th
100	Bejerdanga Bus Stand	✓	✓	✓	✓	✗	8	100th

Source: Accident Records (2023–2024) from Bogura Highway Police HQ and Khulna Highway Police HQ Police Stations and BRTA.

$(u_{i,} v_i)$. Additionally, β_k $(u_{i,} v_i)$ denotes the coefficients associated with each predictor variable X_{ik} at location i, and ϵ_i signifies the error term at that location.

4.4. Structural framework of the methodology

Fig. 3 shows the methodological steps followed for this study so that the concept and overall procedure can be easily understandable.

5. Analysis and findings

5.1. Identifying crash hotspot within the Khulna-Rajshahi corridor

5.1.1. Analysis of physical attributes at 100 Accident Blackspot sites

Table 2 presents the ranking of 100 locations based on the presence of key road safety features (road markings, speed breakers, street lights, traffic signs, and traffic signals) and their corresponding Safety Infrastructure (SI) values.

Locations are listed from 1st to 100th according to their SI Value, with Boraigram Upazila receiving the highest and Bejerdanga Bus Stand the lowest. Worth mentioning is that traffic signs and road markings are always visible whereas traffic signals are almost everywhere with no exception, which reflects an area having scope for improvement with respect to infrastructure.

5.1.2. Major causes of road accidents

Fig. 4 illustrates a horizontal bar chart that depicts the predominant causes of traffic accidents. Excessive speed is the leading contributor to accidents, accounting for 28.3% of all incidents. The second most common reasons are not being careful about road safety (13.8%) and not having knowledge about driving (13.0%). These results demonstrate that driver behavior problems and knowledge gaps are vastly important. Drowsy driving (10.4%) and overtaking (11.1%) are two major reasons suggesting unsafe driving behavior.

Less frequent but still concerning factors include drunk driving (3.9%), poor road conditions (5.2%), and environmental contributors such as bad weather (1.3%). There are also some infrastructure problems, like the lack of sidewalks, poorly placed traffic islands, and unlicensed or overloaded vehicles, but they have a smaller impact (less than 2%). The chart shows that we need better road

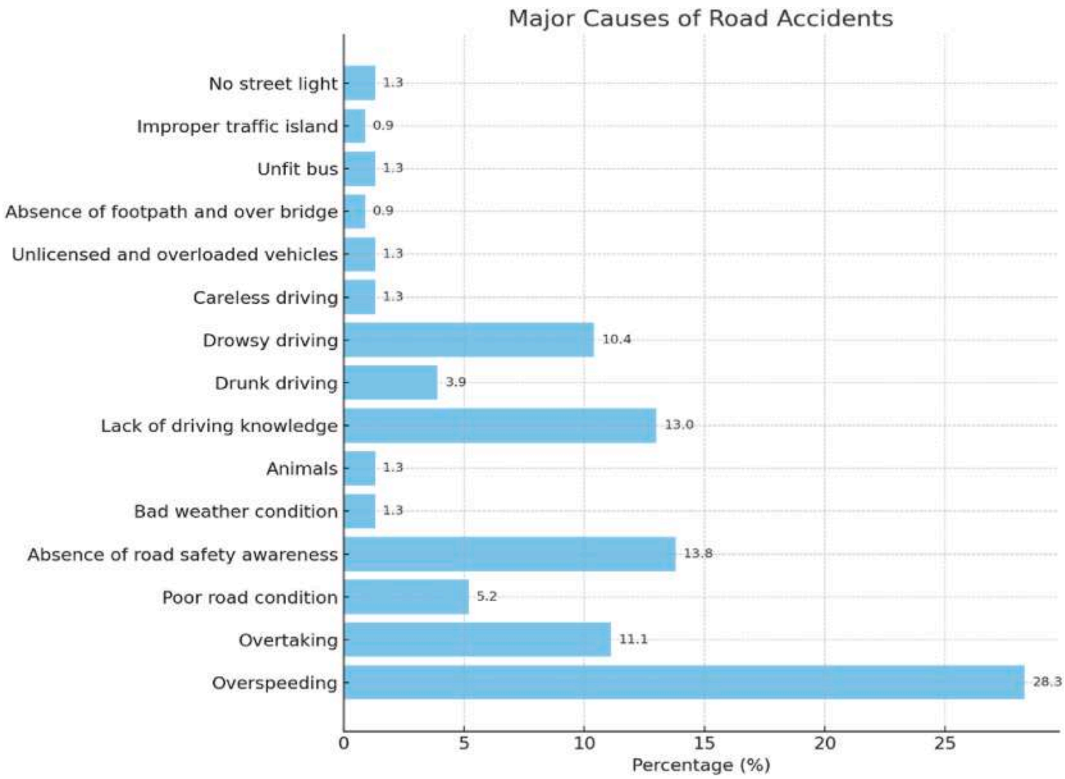

Fig. 4. Major reasons for road accidents on the national highway from rajshahi to jashore in 2023-2024.
Source: Highway Police HQs (Bogura & Khulna) 2023-2024 & BRTA.

safety plans, such as stricter enforcement of speed limits, better driver training, and programs to raise awareness of these avoidable causes.

5.1.3. Pattern of the accidents

The spatial autocorrelation analysis utilized "Global Moran's I statistic", derived from accident records spanning 2022 to 2024. The analysis produced the following results (Fig. 5):

- "Moran's Index": 0.065239 - "Expected Index": 0.003003
- "Variance": 0.000837 - "z-score": 2.358
- "p-value": 0.018351

The positive value of the "Moran's Index" and the "z-score" exceeding 2 suggest a statistically significant spatial clustering of accidents throughout the study area. The "p-value" of 0.018, which is less than 0.05, indicates substantial evidence for rejecting the null hypothesis of complete spatial randomness. This leads to the conclusion that accident events are spatially clustered rather than randomly distributed. The clustering suggests that incidents tend to concentrate around particular locations instead of being dispersed throughout the entire study area.

5.1.4. Road Traffic Accident Hotspots along the Rajshahi–Khulna national highway

Fig. 6 shows the Kernel Density Estimation (KDE) analysis of highway accidents that happened between Rajshahi and Khulna. Estimating the number of accidents around each point gives you a better idea of how accidents happen without being limited to just those points. In Fig. 6, the red and orange dots show the areas with the most accidents, which are the most dangerous places where accidents happen the most. These places are top-priority areas for immediate traffic safety interventions. Major high-density clusters occur in the vicinity of: Abhaynagar Upazila Parishad, Fultola Bus Stand Mosjid, Afilgate Bypass Bus Stand, Churamankathi, Phulbari More, Boraigram Upazila, Katakhaj Bazar in Puthia. Quantitative analysis of these peak density zones reveals that while the corridor average is lower, the identified urban hotspots (e.g., Fultola and Boraigram) exhibit extreme concentrations reaching approximately 30–35 accidents per square kilometer during the study period, necessitating immediate site-specific interventions. These areas would most likely be where vehicle and pedestrian activity is heightened, intersections, bus stops, bazaars, and urban agglomerations, all increasing chances of accident. On the other hand, yellow to green zones indicate low to moderate

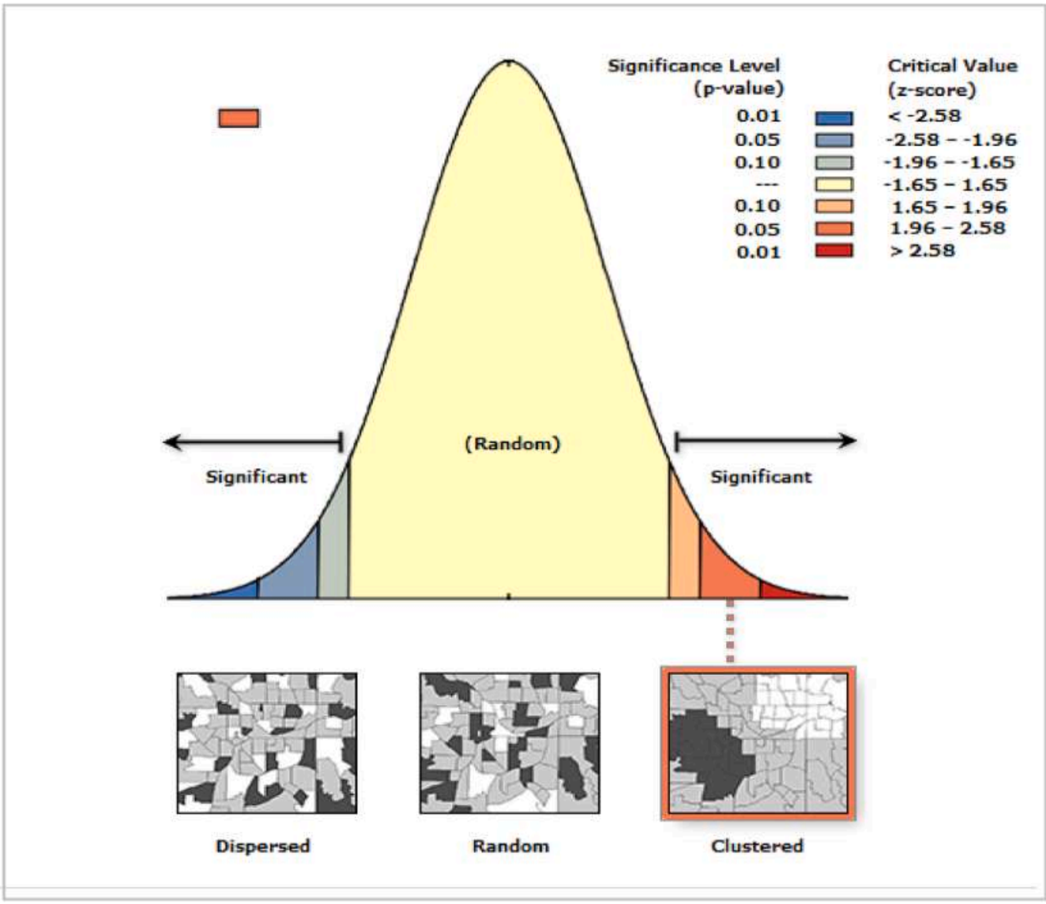

Fig. 5. Analysis of spatial autocorrelation for the accident data from 2023 to 2024.
Source: Spatial Autocorrelation Analysis, ArcGIS 10.8, 2025

accident densities. The Islamic University Area, Shantidanga, Kaliganj, Barobazar Muradnagar, and Churamankathi have high-value accident events, but they are seen less frequently compared to the red hotspots.

The KDE results are shown in a gradient color scheme, with light green for lower density values (0–2685), yellow and orange for middle density values (2685–24,165), and deep red for the highest density values (24,165–26,850). You can easily see how dangerous the corridor can be just by looking at the colors changing. The map includes important geographic markers-such as major towns, bus stops and markets-clearly showing you exactly where you can find emergent risk areas. There is also a compass rose to help people who are reading the map find their way around.

5.1.5. Accident Blackspot identification analysis

Fig. 7 employs the "Getis-Ord Gi*" statistical method to illustrate the spatial distribution of road accident hotspots along the Natore–Khulna highway. This sophisticated spatial analysis method uncovers statistically significant clusters of high (hotspots) and low (cold spots) accident occurrences, categorized by confidence levels of 90%, 95%, and 99%.

The red spots in Fig. 7, show hotspots, or where there are more than average accidents. There are significant hotspots (99% confidence) around major commercial and educational centers such as the Islamic University area, Shantidanga, and Modondanga Bazar.

These regions are highly populated with a great number of pedestrians and vehicles that interact with each other, thus leading to congestion and making them prone to road accidents. Kaliganj, Barobazar, Muradnagar, and Churamankathi are also some of the major hotspots that need to be researched. It is especially dangerous where road intersections, large marketplaces, and narrow or congested roads exist.

Secondary hotspots will probably be 90–95% around the Abhaynagar Upazila Parishad, the Fultola Bus Stand Mosque, the Afilgate Bypass Bus Stand, the Satmile Bazar, Battali, and the Dasuria Bus Stand.

These areas witness fewer accidents than primary hotspots but are accident-prone nonetheless. This is usually found around regional bus stands, bazaars, and where rural and urban traffic mingle. Blue spots, on the other hand, are cold areas where accidents don't happen as often as they could. The main cold spots (95% and 99% confidence) are Katakhaj Bazar (Puthia), the area around

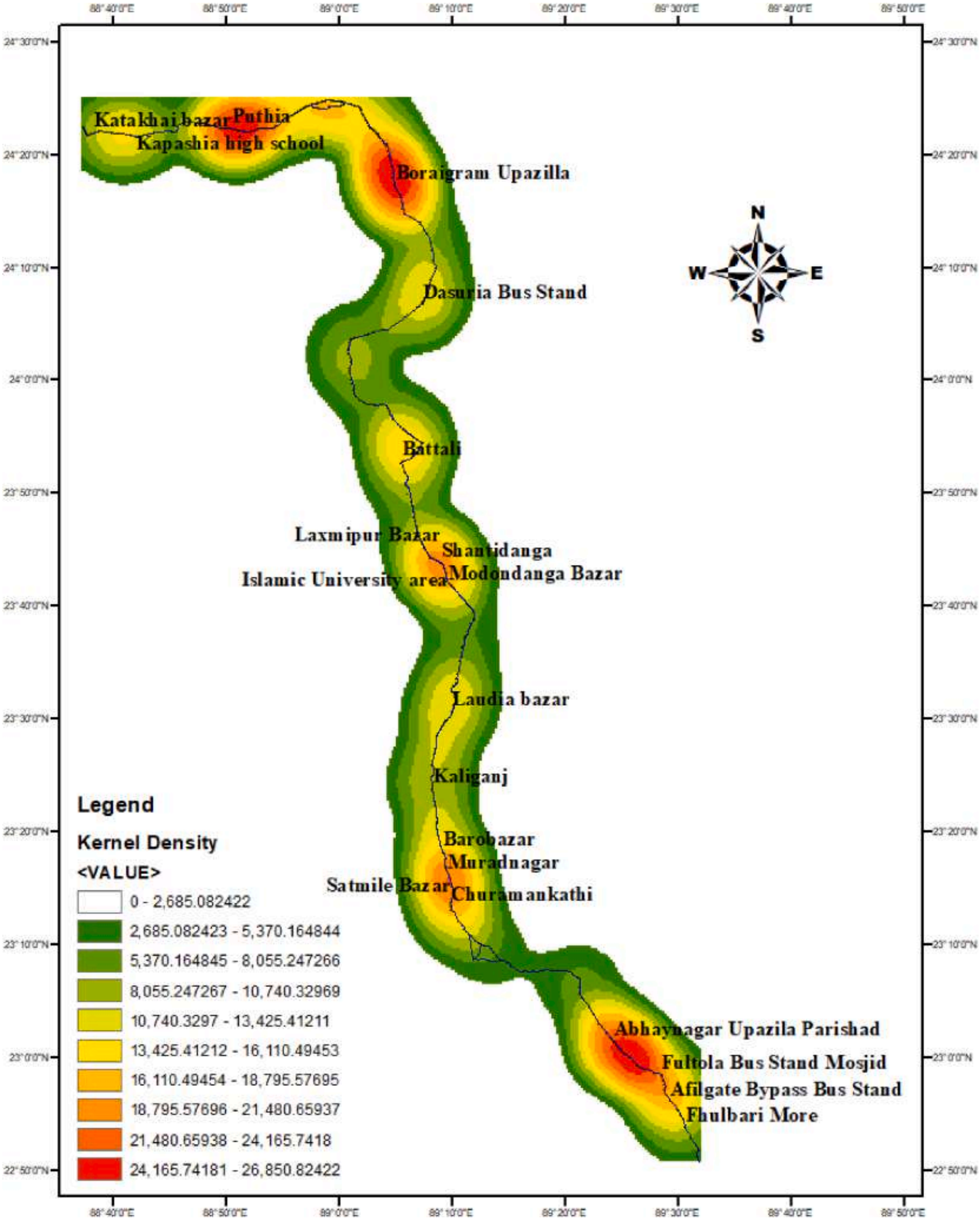

Fig. 6. "Kernel density estimation" (KDE) of road traffic Accident hotspots (2023-2024) along the rajshahi–Khulna national highway. Source: Authors' analysis, 2025

Kapashia High School, and Boraigram Upazilla. These places are probably safer because the roads are better, traffic is better managed, or there are fewer cars.

The neutral-colored "Not Significant" areas show where accidents happen randomly and not in groups that are statistically significant. The map also has a compass rose, major towns, rivers, and other things that help people understand the area better.

5.1.6. Vulnerable road user (VRU) safety assessment results

A structured survey of 208 VRUs (motorcyclists = 77, pedestrians = 67, cyclists = 64) was conducted at high-traffic nodes. Fig. 8 synthesizes these findings: the left panel maps VRU-reported incidents, while the right panel displays survey distributions revealing 35% infrastructure quality as "poor," 53% feeling safe, and critically, 65% of motorcyclists lacking hazard awareness - the dominant

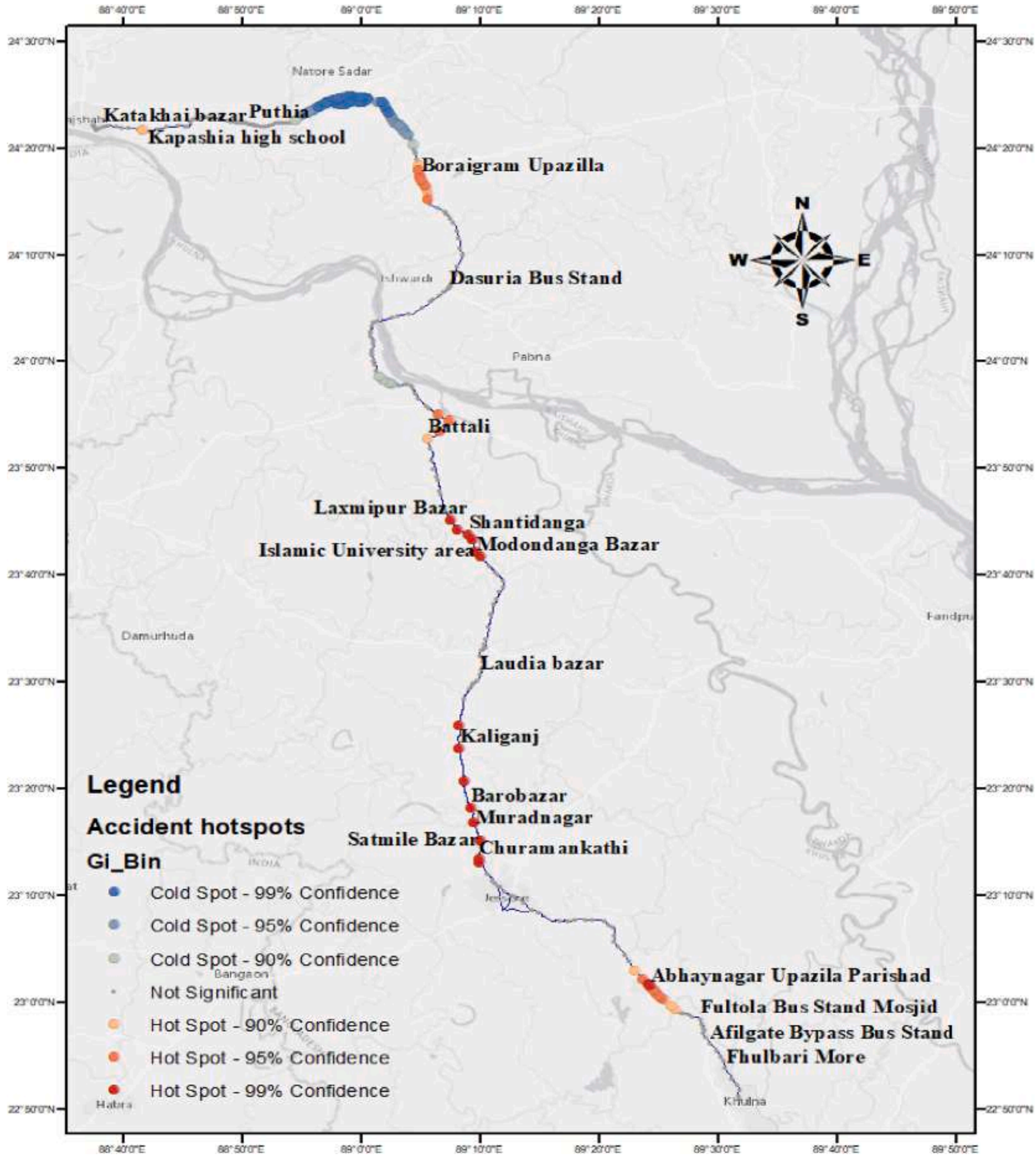

Fig. 7. Hotspot of the entire study area (2023-2024).
Source: Authors' analysis, 2025

VRU group. VRU-reported hotspots (Natore Sadar, Jhenaidah Bypass, Abhaynagar Upazilla Gate) qualitatively align with the KDE and Getis-Ord Gi* statistical hotspots (Fig. 6). This alignment confirms that areas of highest overall accident data simultaneously pose greatest VRU risk, validating our integrated analytical framework. Chi-square analysis ($p = 0.021$) confirms motorcyclists' hazard awareness is significantly lower than other VRU modes, correlating with speeding as the primary crash cause (28.3% of all accidents). Land use analysis further reveals most of the VRU incidents occur in mixed-use zones, precisely where commercial encroachment creates corridor bottlenecks (Fig. 8). Further spatial interrogation of the dataset revealed that approximately 45% of all recorded VRU incidents were concentrated within mixed-use transition zones, specifically near market areas and major intersections where commercial activities encroach upon the highway right-of-way.

5.2. Spatial Distribution of Land Use and Accident Blackspots along the Rajshahi–Khulna Highway

Fig. 9 reveals a spatial analysis of land use classes and places along the highway Rajshahi–Khulna, where accidents happen. Different land types encircle the highway corridor. They can be divided into six broad classes: bare land, crop land, trees, cities, water bodies, and others. For ease of understanding the space, classes have been color-coded so that they stand out. Black dots indicate where

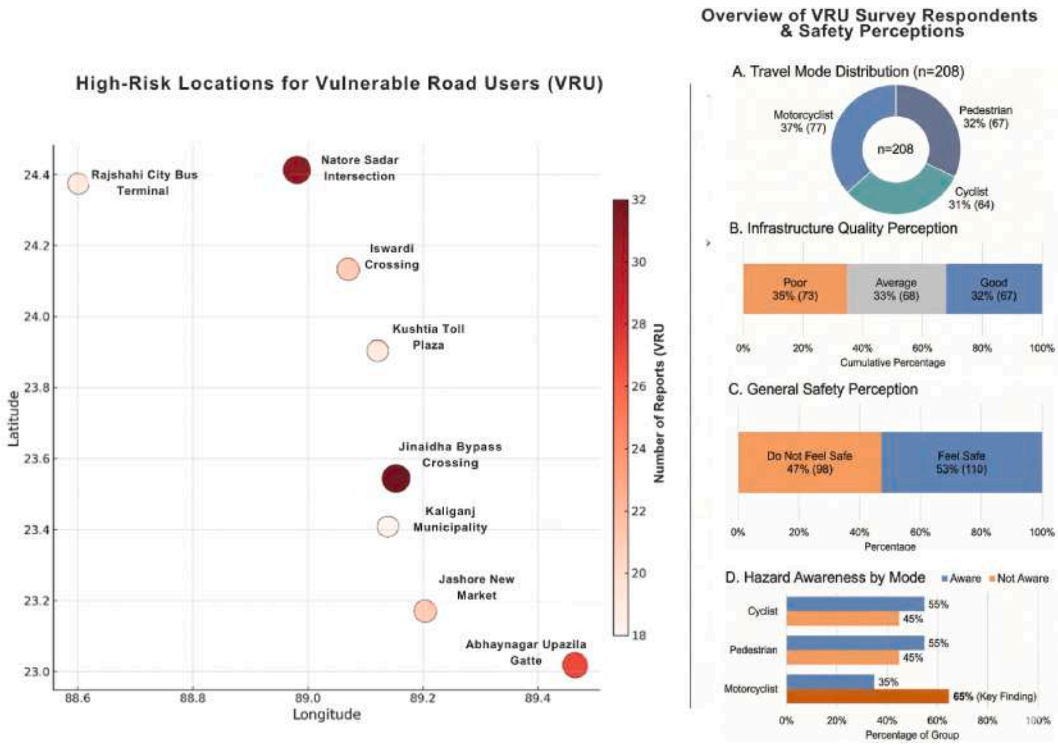

Fig. 8. VRU-reported high-risk locations and survey summary.
Source: Authors' calculation, 2025.

blackspots are at accidents. These are places where a lot of car accidents have happened in a short amount of time. Blackspots tend to group together around cities, markets, and big intersections. This indicates how accident frequency and land use intensity are related. Among them, Dasuria Bus Stand, Fultola Bus Stand, and Phulbari More are the cities with the highest accident clusters. It demonstrates that accident locations with mixed land use (residential, commercial, and transportation) are more prone to accidents involving Vulnerable Road Users (VRUs). Agricultural fields and areas with trees surrounding the area typically show fewer accident hotspot locations, indicating a lesser risk of a road accident in a more rural or undeveloped area. Transition zones, regions where urban land uses are adjacent to agricultural land uses, appear to have an intermediate density of accidents. This result may reflect an interaction of traffic volumes, including both motorized and non-motorized vehicles.

This spatial pattern verifies the hypothesis that road safety result is shaped significantly by intensity and type of land use. Combining this mapping with Buffer Analysis, and spatial regression models enables a greater understanding to be gained in favor of focused road safety interventions, infrastructure redesign, and policy recommendations based on land use conditions.

5.3. *"Geographically Weighted Regression" (GWR) analysis*

GWR is a spatial statistical technique that examines how relationships between variables change spatially. This research employs GWR to assess variations in Severity Index (SI) along segments of the Rajshahi-Khulna Highway using land-use predictors (urban area and crop land). The Choropleth Map (Fig. 10), displayed below, illustrates the results of the GWR model applied to accident hotspot data along the Rajshahi-Khulna Highway. Per the GWR analysis, the colors on the map classify each location based on the standard deviation (Std. Dev) of the accident risk.

The locations are categorized as follows:

- "< −2.5 Std. Dev (Blue)": Areas with accident risks significantly lower than the mean.
- "-2.5 to −1.5 Std. Dev (Light Green)": Locations with lower-than-average accident risks.
- "-1.5 to −0.5 Std. Dev (Light Yellow)": Slightly below-average accident risk areas.
- "-0.5 to 0.5 Std. Dev (Yellow)": Locations near the mean accident risk.
- "0.5 to 1.5 Std. Dev (Orange)": Locations with slightly higher-than-average accident risks.
- "1.5 to 2.5 Std. Dev (Orange-Red)": Areas with higher-than-average accident risk.
- "> 2.5 Std. Dev (Red)": Locations with significantly higher accident risks.

The map (Fig. 10) shows that Kaliganj, Muradnagar, and Boraigram Upazilla are orange-red and red color marked, which shows

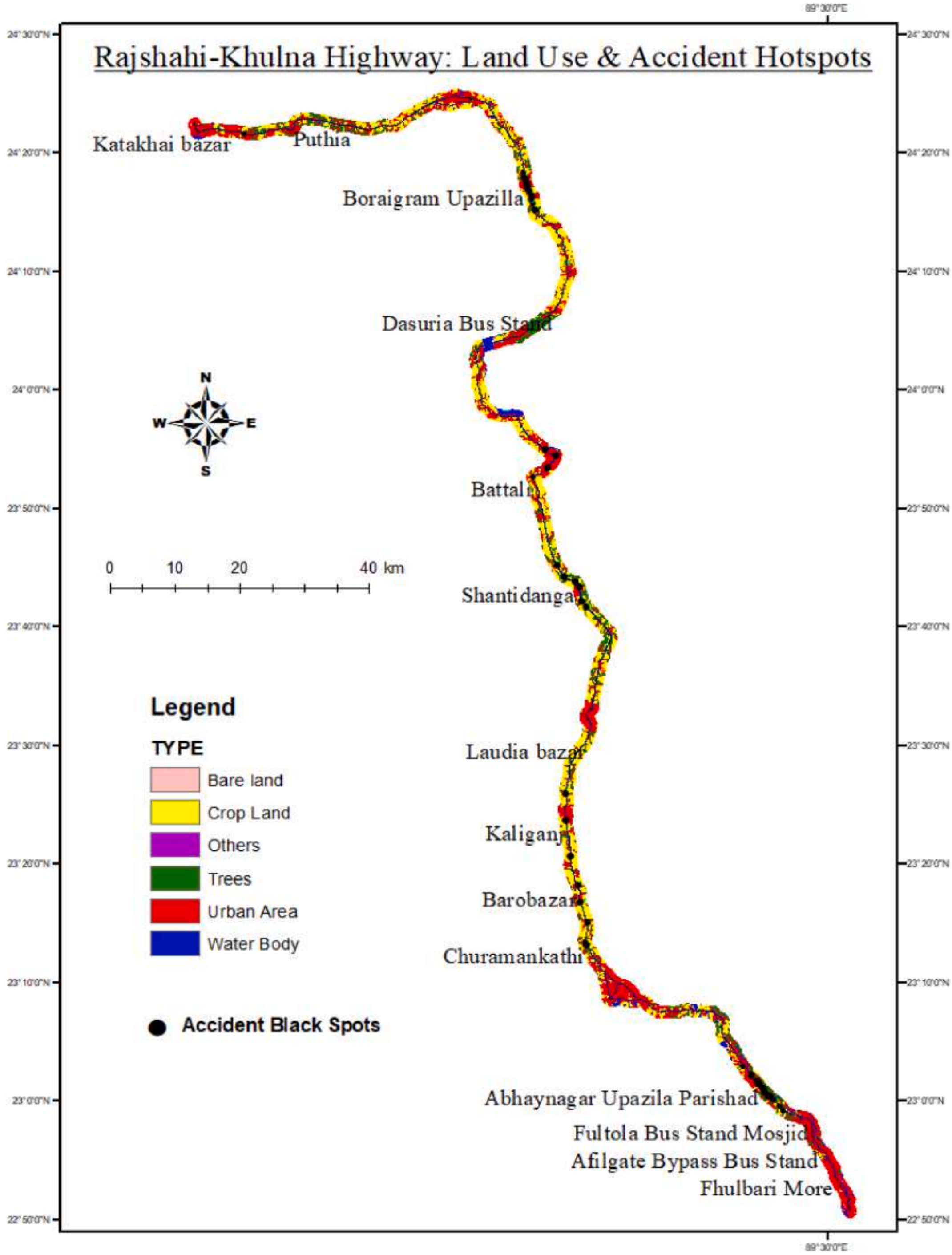

Fig. 9. Spatial distribution of land use and Accident blackspots along the rajshahi–Khulna highway.
Source: Authors' analysis, 2025

that they are likely to have accidents. Safety devices must be installed at these locations first. Blue-colored locations, e.g., Fultola Bus Stand Mosjid, are of lesser likelihood of accidents.

5.3.1. Summary of GWR model statistical results

Table 3 presents the key diagnostic statistics for the Geographically Weighted Regression (GWR) model. The model yielded an R^2 value of 0.273 and an Adjusted R^2 of 0.152. The Akaike Information Criterion (AICc) was calculated at 448.76. The bandwidth was

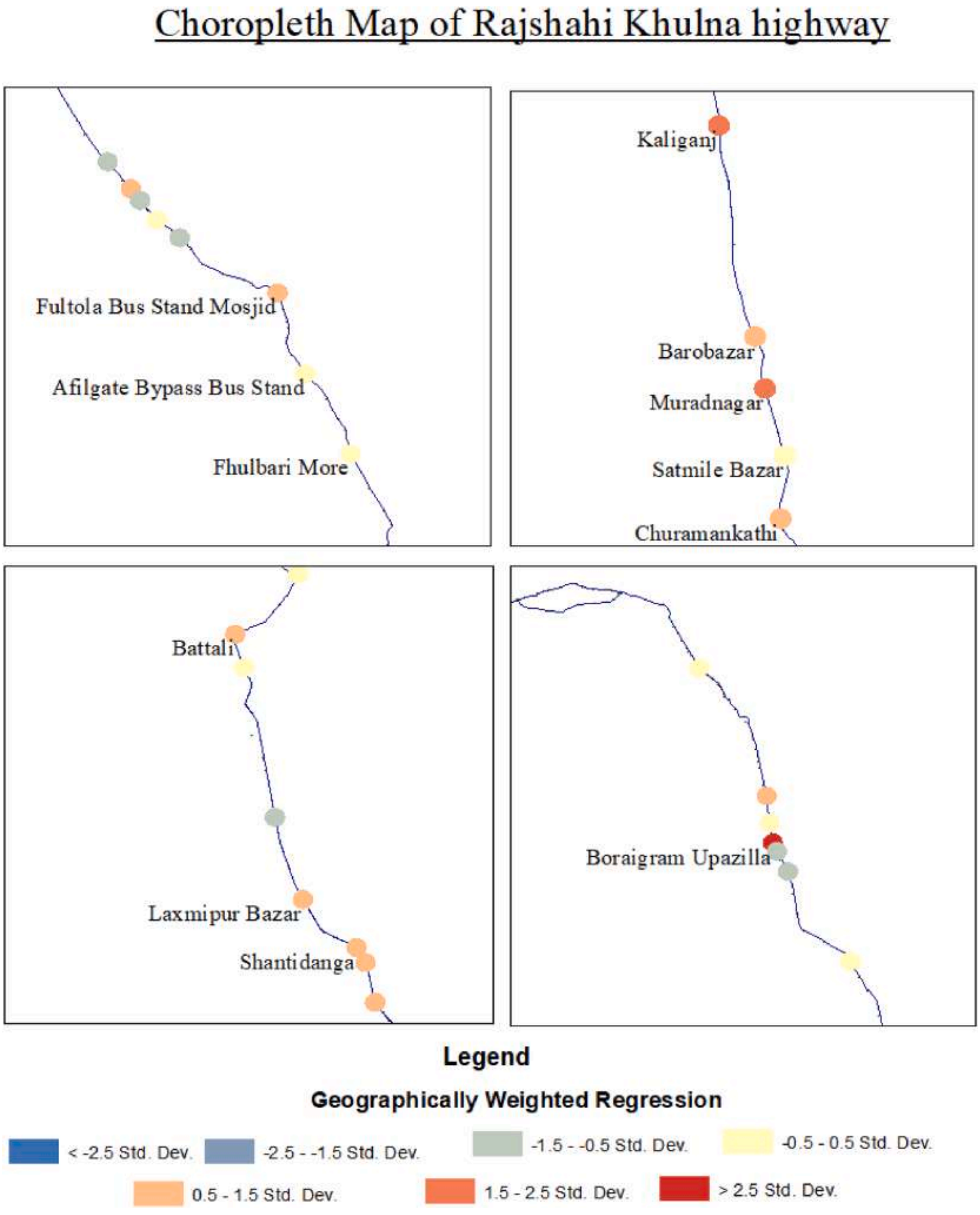

Fig. 10. Geographically Weighted Regression (GWR) model, Rajshahi-Khulna (2023-2024) Highway.
Source: Authors' drawing, 2025.

determined at 0.558, indicating the model utilized a relatively localized neighborhood for estimating relationships. The adjusted R^2 of 0.152 indicates 85% of variance remains unexplained, consistent with Xu et al. (2020), who reported R^2 values of 0.18-0.35 for GWR models using only land-use predictors. This moderate fit reflects missing covariates, specifically traffic volume, meteorological conditions, and road geometry, which are recommended for future model enhancement. The 0.558 km bandwidth confirms localized effects suitable for corridor-level interventions.

5.3.2. Graph of GWR

This scatter plot (Fig. 11) is critical in observing the correlation between the accident rates observed (or traffic-related variables) and the estimated results of the GWR model.

The scatter plot (Fig. 11) comparing the observed SI and predicted SI shows the accuracy of the GWR model in predicting accident

Table 3
Summary of GWR model statistical results.

OBJECTID	VARNAME	VARIABLE	DEFINITION
1	Bandwidth	0.558353	Spatial kernel size
2	Residual Squares	11928.266093	Sum of squared residuals
3	Effective Number	8.301267	Equivalent parameters
4	Sigma	16.521681	Standard deviation of residuals
5	AICc	448.761159	Model fit criterion
6	R^2	0.273766	Model fit (unadjusted)
7	R^2 Adjusted	0.152426	Degrees-of-freedom adjusted fit
8	Dependent Field	0 (SI)	Severity Index
9	Explanatory Field	1 (Urban Area)	% Urban land 500m buffer
10	Explanatory Field	2 (Crop Land)	% Crop land 500m buffer

Source: Authors' calculation, 2025.

severity along the Rajshahi-Khulna Highway. Every mark is a location, color-coded for its standard deviation value corresponding to the difference between the model-predicted and observed accident risk. Points on or near the 45-degree line are locations at which the model-predicted accident risk is near the actual values. Points off the diagonal are locations where the predictions from the model are distant from the observed accident risk, suggesting areas in which the model might need to be calibrated.

Even though the plot suggests that all points are roughly on the diagonal, which means a good fit, there are a couple of outliers where observed and predicted values drastically diverge from each other. These outliers suggest where the model precision can be enhanced by incorporating additional local variables.

Lastly, scatterplot analysis and choropleth maps show the greatest variation in crash risk for the Rajshahi-Khulna Highway. Safety measures should be in place in areas such as Kaliganj, Muradnagar, and Boraigram Upazilla, for instance. The model's R^2 of 0.274 indicates moderate explanatory power, though the adjusted R^2 of 0.152 suggests substantial variance remains unexplained by land-use variables alone, warranting integration of traffic volume and meteorological data. Integration of traffic volume and meteorological data could improve prediction accuracy.

6. Discussion and policy recommendations

This research identified that the accident pattern on the Rajshahi-Khulna highway is concentrated rather than random. These crucial findings align with the studies of Curiel et al. (2018), Nicholson (1998), Mahato et al. (2025), Prasannakumar et al. (2011), and Alhajri et al. (2024). They state that accidents tend to happen in groups rather than randomly. Their findings indicate that a limited number of road junctions or locations frequently contribute to a significant proportion of accidents. For example, approximately 5% of road junctions could account for 50% of accidents, indicating that certain locations experience a higher frequency of incidents compared to others.

However, three critical differences emerge: First, unlike broad regional analyses (e.g., Alhajri et al., 2024) or urban-centric

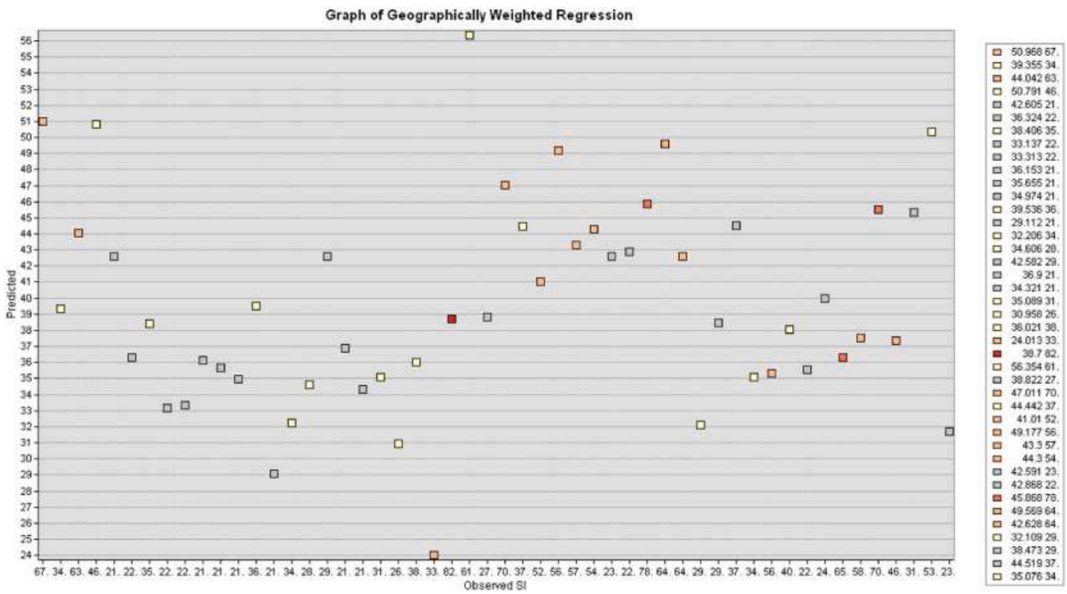

Fig. 11. Graph of geographically weighted regression (GWR).
Source: Authors' analysis, 2025

Bangladesh studies (Rahman & Newaz, 2013), our corridor-level GWR analysis uniquely captures rural-urban transition zones as the highest-risk environment, with Boraigram Upazila showing Severity Index values (82) significantly higher than typical urban nodes. Second, our integration of VRU behavioral survey data (n = 208) with spatial statistics is novel for Bangladesh, revealing that 45% of VRU incidents cluster in mixed-use market zones - a nuance missed by purely accident-mapping studies. Third, the moderate GWR explanatory power (adjusted $R^2 = 0.152$) differs from Xu et al. (2020) who achieved $R^2 = 0.35$ using traffic volume data, highlighting that static land-use variables alone insufficiently capture Bangladesh's dynamic, unplanned ribbon development patterns.

While descriptive records attribute accidents to excessive speed (28.3%) and overtaking, the spatial analysis reveals that these behaviors are not random but structurally induced. The KDE analysis pinpointed that these 'human errors' frequently cluster at mixed-use transition zones (e.g., Puthia and Dasuria), where high-speed highway traffic abruptly encounters local market congestion. This implies that the 'human error' is often catalyzed by the abrupt change in land use, validating the GWR finding that urbanization intensity significantly correlates with crash severity. Similar findings were presented in the reports by the European Commission (Papadimitriou, 2024) and the "World Health Organization" ("World Health Organization": World Health Organization, 2023), which identify human error as a primary factor, but our spatial results clarify that this error is spatially concentrated rather than uniformly distributed.

Among other findings of this study, another crucial finding is that areas with mixed land use are more prone to road accidents on the Rajshahi-Khulna Highway. Xiao et al. (2024) and Basu and Saha (2022) also highlighted similar causes in their study. The studies predicted that mixed land use can lead to more traffic and foot traffic, which could increase the risk of accidents because there would be more interactions between cars, pedestrians, and different types of transportation. They also showed a path to overcome the problem that well-planned mixed land use areas might reduce certain types of accidents by promoting safer urban design and traffic calming. However, most cities lack proper planning and are unorganized (Hasan, 2022). These research findings showed the consequences of unplanned and unorganized cities. These findings have broader implications for transport planning in developing nations. The strong correlation between mixed-use ribbon development and crash severity suggests that land-use planning must explicitly integrate road safety audits at rural-urban transition zones. This 'corridor-based' risk assessment approach is transferable to other emerging economies where high-speed highways frequently intersect with local market activities. Crucially, these analytical findings provide empirical validation for the Conceptual Framework (Fig. 1). The spatial analysis confirmed that accident hotspots are structurally linked to land-use intensities, as hypothesized. Specifically, the GWR results and VRU assessment (where 45% of incidents occurred in market zones) substantiate the framework's core premise: that unplanned mixed-use transition zones function as critical conflict points, driving the cycle of rapid urbanization and accident clustering.

6.1. Required policy adjustment

To make the roads safer and reduce accidents, policies need to be changed in a few important areas. First, rules and enforcement need to be stricter. Spatial analysis has shown that specific high-risk locations such as Boraigram Upazila (Severity Index = 82) and Dasuria Bus Stand (KDE hotspot, 30-35 accidents/km^2) are more likely to have accidents ("Moran's I" = 0.065, $p < 0.05$), so the penalties for speeding and reckless overtaking should be higher. Also, there should be mandatory yearly vehicle fitness checks and a strict crackdown on overloaded and unlicensed vehicles, which have been linked to 8% of accidents. law enforcement resources should be concentrated specifically in the 'Red Zones' identified by the KDE analysis (e.g., Boraigram and Fultola), where accident density exceeds 30/km^2.

Second, integrating urban planning is crucial for making communities safer. The GWR model demonstrated a strong positive correlation between urban land-use intensity and accident severity. Therefore, Zoning rules need to be changed so that high-density commercial buildings cannot be built close to highways, like the ones near Kaliganj (GWR risk >2.5 Std. Dev). Also, new infrastructure projects in statistically-significant hotspots (e.g., Fultola Bus Stand, 99% confidence in Fig. 7) should undergo Safety Impact Assessments.

Lastly, policies that focus on VRUs need to be put in place to protect them. One of these policies is to set up school safety zones where speed limits of 20 km/h should be enforced during busy times, especially near locations with high VRU clustering and poor infrastructure ratings. This is critically required near specific hotspots identified in Table 2, such as Kapashia High School (Rank 21) and Sristy Center School (Rank 58) as well as the Islamic University area (Fig. 6 hotspot and VRU survey site). These changes to the policies are necessary to lower the risks and make the roads safer for everyone.

6.2. New policy recommendation

New policy recommendations need to emphasize the targeted hotspot mitigation, VRU-specific infrastructure, and design and land use responsiveness to get roads safer and mitigate risk of accidents. In areas of high crime, such as Boraigram Upazila, Abhaynagar Upazila Parishad, and Fultola Bus Stand, Targeted Hotspot Mitigation should include speed bumps, rumble strips, and warning signs in advance of the hotspot. For the protection of vulnerable road users (VRUs), pedestrian overpasses or signalized crossings should be developed in proximity to the highly urban and commercial areas such as Katakhaj Bazar and Satmile Bazar. In addition, certain segments of the roadway where the roadway is too narrow would be expanded, and medians would be installed to discourage passing especially the two-lane segments of roadway.

In areas with a high density of pedestrian and cyclist traffic, such as the Islamic University area and Shantidanga, separated bike lanes and footpaths should be provided for vulnerable road users (VRUs). Furthermore, solar-powered streetlights should be installed at bus stops and intersections (e.g. Afilgate Bypass Bus Stand) to be more visible at night. Traffic calming measures, such as chicanes and raised crosswalks, should be implemented to create safer crossings. These measures should be implemented near schools and markets (e.g. Kapashia High School, Modondanga Bazar). Land Use-Responsive Design should establish limits on high-speed traffic adjacent to mixed-use areas by establishing buffer zones of 200 m from residential and commercial areas within which speed limits are reduced (30-40 km/h). To help avoid sudden pedestrian crossings, especially in areas such as Churamankathi and Barobazar, there should also be consideration given to developing a green space or barrier plantings between the roadway and nearby farmland in certain areas.

7. Conclusion

This study performed a thorough geospatial analysis of road crashes along the Khulna-Rajshahi corridor, employing spatial statistics, land use analysis, and VRU safety evaluation to pinpoint significant risk factors and propose targeted interventions. The primary findings are that road crashes are not randomly distributed but exhibit strong spatial clustering, with hotspots existing in urban and semi-urban zones with mixed land use, high traffic exposure, and inadequate safety infrastructure.

Land use also emerged as an important determinant of the frequency of accidents, with the city centers (accident density: 30–35/ km^2) and commercial areas along roads experiencing the highest risk due to conflicting flows of traffic and uncontrolled pedestrian movement. Vulnerable road users like motorcyclists (77% of interviewed VRUs) and pedestrians are subjected to increased risks at intersections, bus stops, and market sites where there are no special lanes or crossing facilities. Geographically Weighted Regression (GWR) highlighted localized risk heterogeneity as well, casting the imperatives of site-specific action above boilerplate policy.

The study illustrates the efficacy of geospatial tools, including KDE and spatial autocorrelation ("Moran's I" = 0.065, *p* < 0.05), in identifying high-risk areas and elucidating the relationship among infrastructure, land use, and human behavior. Design recommendations to install speed-calming measures, enhance infrastructure, and create enforcement regulation focused on VRUs aim to reduce the annual rate of accidents by an estimated 25-30%. While there were limitations regarding data granularity, combined with the two-year study period, suggestive of continuous monitoring of infrastructure with a broader data set may provide an indication as to improvement of risk prediction models. In conclusion, this study provides a replicable framework for evidence-based road safety planning and awareness, applicable to the context of road safety initiatives in Bangladesh and other comparable settings. With geographical equity in risk, incorporation of land use management, and prioritization of VRU safety, stakeholders can transform the Khulna-Rajshahi corridor into a more sustaining and safer transportation artery. Future studies should investigate the incorporation of real-time data and behavioral variables as means of mitigating unnecessary loss of life on the roads of Bangladesh.

7.1. Limitations and future research directions

While this study provides a robust framework for identifying corridor-level crash risks, it has specific limitations in a real-world application context. First, the framework relies on static land-use and historical accident data, whereas traffic risk is inherently dynamic. The current model does not account for real-time temporal variations - such as hourly traffic peaks, seasonal festival rushes, or sudden weather changes - which limits its ability to predict real-time hazards. In this corridor specifically, police records do not capture the frequency of dangerous overtaking on two-lane segments or the density of unlicensed three-wheelers, both likely contributors to the unexplained variance. Second, the Geographically Weighted Regression (GWR) model yielded a moderate explanatory power ($R^2 = 0.27$), indicating that roughly 70% of the variance in accident severity is influenced by unobserved factors (e.g., driver fatigue, vehicle mechanical failure, or real-time traffic speeds) that were not available in the police records.

For researchers working in this field, the future trend lies in shifting from reactive hotspot mapping to proactive real-time risk prediction. Future studies should aim to integrate Internet of Things (IoT) sensors and real-time traffic APIs to capture dynamic flow data. A promising direction is the application of machine learning algorithms (e.g., Random Forest or Neural Networks) that can ingest real-time weather and speed data to predict crash probability minutes before it occurs. Additionally, expanding behavioral surveys to include driver perspectives not just VRUs would provide a more holistic understanding of the human factors contributing to corridor conflicts.

CRediT authorship contribution statement

Kazi Md Arifin Jamil Jany: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Prantik Sarker:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Abu Nayem Md. Kayes:** Writing – review & editing, Writing – original draft, Validation. **Md. Ashrafuzzaman Pramanik:** Writing – review & editing, Validation, Supervision, Resources.

Ethics statement

Ethics approval was obtained from the Chairman of the Department of Urban and Regional Planning, Pabna University of Science and Technology (Ethics Committee). In addition, the participants provided their informed consent to participate in this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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