

IDENTIFYING THE HAZARDOUS LOCATIONS USING GEOGRAPHIC INFORMATION SYSTEM NETWORK ANALYSIS: A CASE STUDY OF BUENG KAN PROVINCE, THAILAND

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Abstract

This study aims to identify high - crash - risk locations on local roads in Bueng Kan province, Thailand, using Geographic Information System (GIS) - based spatial analysis. Despite being Thailand's newest and one of its least populated provinces, Bueng Kan consistently reports one of the highest fatality rates per capita, highlighting the urgency of evidence-based road safety planning. The study employed Kernel Density Estimation (KDE) to detect spatial concentrations of road crashes and a Chi-square test to assess whether crash severity proportions differed significantly across districts. Crash data from 2018 to 2020 were collected, georeferenced using linear referencing techniques, and analyzed in ArcMap. KDE was applied to generate crash density surfaces. The KDE results revealed spatially distinct crash hotspots in five districts, with Seka district showing the highest crash density despite Mueang Bueng Kan recording the highest number of incidents. This underscores the importance of considering spatial overlap-not just frequency-in identifying hazardous areas. Chi-square test found no statistically significant difference in the proportion of fatal versus non-fatal crashes among districts ($p = 0.403$), suggesting that crash severity is spatially uniform. This supports the need for province-wide interventions rather than district-specific responses. The integrated use of KDE and statistical testing provides a robust analytical framework for supporting local traffic safety strategies. Recommendations include incorporating exposure data and advanced modeling techniques in future studies to improve risk prediction and policy development.

Keywords: Spatial analysis; Kernel Density Estimation; Chi-square test; Local policy; Practical implications

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Introduction

Background

Road traffic accidents remain a major public health and infrastructure safety issue in Thailand, particularly on local roads that often lack the design standards and monitoring seen on national highways. In recent years, northeastern provinces have reported increasing trends in road accidents, many of which occur on rural and district - level roads. Bueng Kan province, located in the upper northeastern region of Thailand, is no exception. Despite its relatively low population density, it faces persistent challenges in managing road safety. Since its establishment in 2011, Bueng Kan has been Thailand's newest province, having been administratively separated from Nong Khai. Despite its relatively small population compared to other provinces, Bueng Kan has consistently experienced a high and rising number of road traffic fatalities (Figure 1). Consequently, the province's fatality rate-measured as deaths per 100,000 population-has escalated to rank among the highest in the country (Division of Injury Prevention, 2025).

Understanding the spatial patterns of road crashes is crucial for designing effective prevention strategies. However, conventional statistical methods often overlook the spatial distribution and network structure of road crashes, making it difficult for policymakers to pinpoint hazardous segments that require urgent attention.

Road Safety in Bueng Kan

Bueng Kan province, situated along the Mekong River and sharing a border with Laos (Figure 2), spans an area of approximately 4,000 square kilometers and is composed of eight administrative districts (Provincial Labour Office Buengkan, 2025). They contain a diverse mix of

local administrative roads, district roads, and rural village roads, many of which traverse agricultural landscapes with varying levels of infrastructure development. Such diversity in terrain and road conditions presents a valuable context for localized road safety analysis.

As Thailand's newest province, officially established in 2011 following its separation from Nong Khai, Bueng Kan is still in the process of developing and institutionalizing its road safety management systems. This transitional phase offers opportunities to evaluate how emerging provinces structure their traffic safety policies, infrastructure investments, and enforcement strategies from the ground up. Bueng Kan's status as a medium-sized province makes it particularly suitable for the implementation and evaluation of road safety measures. It is not too small to generate meaningful data or pilot large-scale interventions, nor too large to pose challenges in resource allocation or logistical feasibility. This balance enhances its suitability for experimentation with scalable policy interventions and infrastructure improvements.

Despite having one of the smallest populations among Thai provinces, Bueng Kan ranks in the upper half of the nation in terms of road traffic deaths per 100,000 population (Division of Injury Prevention, 2025). Current trends indicate a continued rise in fatality rates, with projections suggesting that the province could enter the top ten nationally within the next decade. This alarming trajectory underscores the urgency of targeted interventions and further supports Bueng Kan as a strategic and appropriate setting for studying spatial patterns of road crashes and implementing network-based safety solutions.

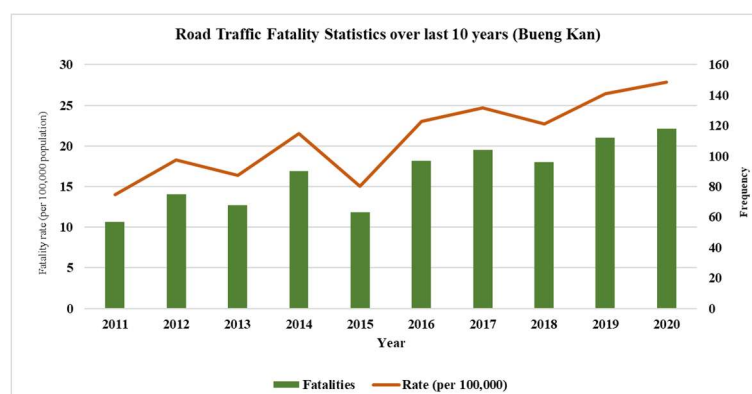


Figure 1. Overview statistics of road fatality trend in Bueng Kan Province

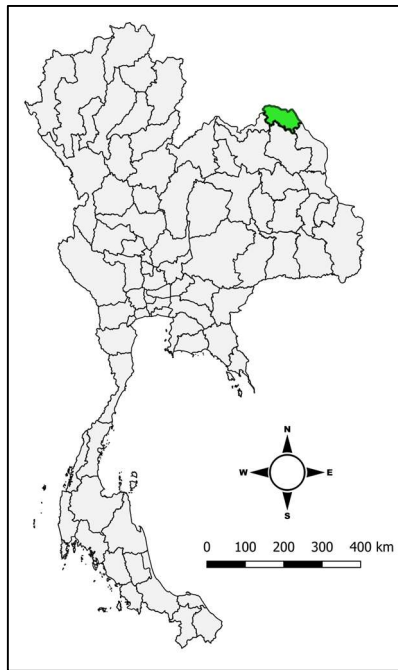


Figure 2. Location of the Study Area

Objectives

This study aims to apply a Geographic Information System (GIS) - based approach utilizing Kernel Density Estimation (KDE) to identify high - crash-risk area on local roads in Bueng Kan province. The research is designed to achieve the following specific objectives:

- To analyze the spatial distribution of road traffic crashes between 2018 and 2020 using KDE techniques.
- To identify the most hazardous areas across the five districts with the highest crash frequencies.
- To examine the relationship between crash severity levels and crash locations through the application of Chi-square statistical testing.
- To propose evidence - based policy recommendations aimed at improving local road safety, and to evaluate the effectiveness of KDE as a decision-support tool in traffic safety analysis.

The remainder of this paper is structured as follows: Section 2 presents a review of relevant literature and theoretical frameworks. Section 3 describes the data sources, collection procedures, and analytical tools employed in the study. Section 4 outlines the key findings and provides a discussion of the results. Finally, Section 5 offers conclusions and practical recommendations based on the study's outcomes.

Literature Review

Spatial Analysis in Road Safety

The application of spatial analysis in traffic safety research has grown significantly, offering tools to understand the geographic distribution and clustering of traffic crashes. Unlike traditional statistical models that focus on numeric trends, spatial analysis considers the location of crashes, enabling researchers and decision-makers to detect patterns not immediately evident in tabular data. Point pattern analysis, spatial autocorrelation, and hotspot mapping are commonly used approaches for visualizing and interpreting crash occurrences in relation to their environment (Harirforoush and Bellalite, 2019; Gedamu *et al.*, 2024).

In road safety, spatial heterogeneity and autocorrelation are critical considerations. For example, one crash may increase the probability of nearby incidents due to shared environmental risk factors such as poor road design or limited visibility. Tools such as KDE have been widely employed to detect clustering and hotspot zones.

Kernel Density Estimation (KDE) in Road Safety

KDE is a non-parametric spatial analysis technique commonly used to estimate the intensity or concentration of discrete events across a continuous surface (Harirforoush and Bellalite, 2019). In the context of road safety, KDE is particularly effective for identifying crash hotspots by transforming individual crash locations into a smoothed density surface. This approach allows for the visualization of spatial patterns and the detection of high-risk areas, even when crash data are aggregated or imprecisely geocoded.

The KDE method assigns weights to crash events based on their proximity to a specified location, using a mathematical function called a kernel and a bandwidth parameter that controls the radius of influence. As a result, KDE enables researchers and traffic authorities to observe where crashes are most concentrated and to prioritize interventions accordingly. Unlike traditional frequency - based methods, KDE provides a more nuanced understanding of spatial distribution by accounting for the surrounding context of each event.

KDE has been widely employed in road safety studies globally. For instance, Anderson (2009) used KDE and K-means clustering to profile road accident hotspots in the United States, while Pulugurtha *et al.* (2007) applied KDE to identify high pedestrian crash zones in urban settings.

Amiri *et al.* (2021) compared KDE to four five various types of hotspot identification techniques to assess hazardous segments the risk associated with road crashes and, as a result, help them to propose more effective countermeasures in order to reduce the annual crash rate. Thakali *et al.* (2015) conducted KDE-based analysis for identifying crash hotspots in a road network in the Hennepin County of Minnesota. Similarly, Le *et al.* (2022) developed KDE algorithm and spatial autocorrelation analysis, which helped to determine traffic accident hotspot locations and simultaneously evaluate the statistical significance of the hotspot clusters in Hanoi, Vietnam. Similar applications in other countries have validated KDE as a robust tool for analyzing road crash distribution, especially in areas where exact GPS locations are unavailable and crashes are recorded by reference points or kilometer markers. These studies demonstrate the robustness and adaptability of KDE in various geographic and road contexts. Its flexibility and visual output make it an essential tool in the spatial analysis of crash data and a valuable component of traffic safety management strategies.

In Thailand, GIS-based studies have typically focused on urban crash mapping or municipal areas. For example, studies in Bangkok and metropolitan areas have used KDE and spatial regression to explore the influence of road design and land use on crash frequency (Chayphong and Iamtrakul, 2023; Iamtrakul *et al.*, 2025). However, there remains a gap in spatial analysis focused specifically on local or rural roads, especially in less urbanized provinces like Bueng Kan.

In recent years, researchers have highlighted the importance of integrating GIS tools with local administrative data to support decentralized road safety planning. For example, the Department of Rural Roads and local municipalities have begun using GIS for asset management, but not yet fully exploited its use in accident hotspot prediction. This leaves room for introducing methods like KDE to support decision-making at the local level, especially when crash data are limited to descriptive reports and lack geocoded precision.

While spatial hotspot detection methods have been widely used internationally, their application to local road networks in Thai rural settings remains scarce. Most current methods either ignore the network nature of roads or lack multiple district assessments. Given the availability of multi-year crash data and digitized local road networks in Bueng Kan, this study aims to fill this gap by applying KDE to uncover stable high-risk areas that warrant targeted safety improvements.

Methods and Materials

Data Collection

This study uses two primary datasets: 1) Local road accident data (2018-2020): Road accident records for local roads in Bueng Kan province were obtained from Ministry of Transport (2022). The dataset includes accident date, location reference (in kilometer post format), severity level (fatal, injury, and property damage), crash characteristics (e.g., collision type, weather, lighting condition), as well as coordinate of each crash for analyzing with road network data. And 2) Geospatial Road Network Data: The provincial road network of Bueng Kan province, including highway roads, rural roads, and local roads, was acquired from the Department of Highways. The road network was digitized and classified into types as shown in the KDE map, as presented in Figure 3

Data Preprocessing and Spatial Analysis (using KDE)

Due to the lack of precise GPS coordinates in the crash reports, linear referencing was employed to spatially map accident locations. Each crash was georeferenced to a specific road segment using the reported distance marker, with the process executed in QGIS 3.36.2 utilizing the Heatmap (Kernel Density Estimation) tool. This method generated point features that accurately represent crash locations along the digitized road network of Bueng Kan province.

The crash dataset underwent a series of preprocessing steps to ensure consistency and reliability. These included:

- Removal of duplicate records,
- Standardization of severity level codes, and
- Filtering to include only crashes occurring on highways and local roads across all districts of Bueng Kan province.

To identify hazardous locations, KDE was applied to model the intensity of crashes along the road network. The analysis was performed using QGIS 3.36.2, with an equal - split continuous kernel function chosen for computational efficiency. A bandwidth of 1 kilometer was selected to appropriately balance the sensitivity of spatial variation with the clarity of hotspot identification.

As a result, raster - based crash density maps were generated for each of the three study years (2018-2020). The density values were subsequently classified into discrete hazard levels - ranging from very low to very high-to facilitate interpretation and support spatial decision-making for road safety interventions.

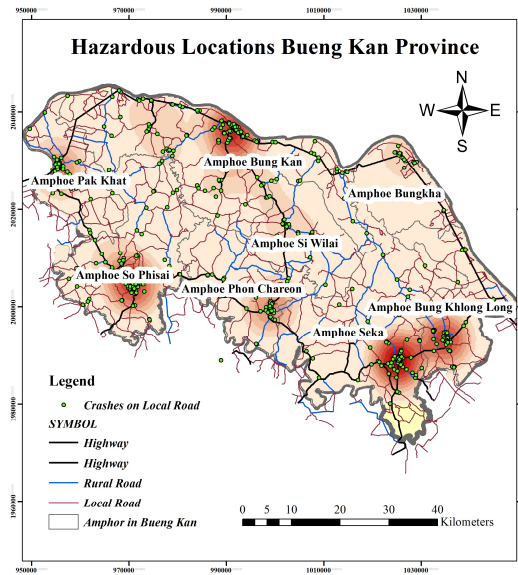


Figure 3. Road network and district visualization

Chi-Square Test

The Chi-square (χ^2) test for independence is a non-parametric statistical method used to determine whether there is a significant association between two categorical variables (King, 1997). In road safety research, it is frequently applied to analyze the distribution of crash outcomes—such as fatal versus non-fatal injuries—across different crash-related factors, including crash locations, road types, and environmental conditions (Karacasu and Er, 2011). When used for difference in proportion analysis, the Chi-square test compares observed frequencies of events (e.g., fatal vs. non-fatal crashes) across different categories (e.g., crash locations or road segments) against expected frequencies under the assumption of independence. If the observed frequencies deviate significantly from the expected ones, the test indicates a statistically significant association between injury severity and location.

In this study, the Chi-square test is employed to evaluate whether the proportion of fatal versus non-fatal crashes differs significantly across crash-prone areas identified by KDE. This approach helps to reveal whether specific districts are disproportionately associated with fatal outcomes, thereby informing more targeted road safety interventions.

Several previous studies have used the Chi-square test in road safety research. For instance, Karacasu and Er (2011) analyzed the distribution of traffic faults in accidents, based on driver's age and gender: Eskisehir case. Oluwadiya *et al.* (2016) used odds ratio and chi-square tests to assess the

relative vulnerability of motorcyclists and passenger injury severity in southwest Nigeria. Similarly, Agyemang *et al.* (2021) used the Chi-square analysis to compare crash severity between urban and rural areas in Ghana. These studies demonstrate the value of Chi-square testing in uncovering spatial and behavioral patterns associated with crash outcomes, particularly when examining categorical variables without assuming normal distribution.

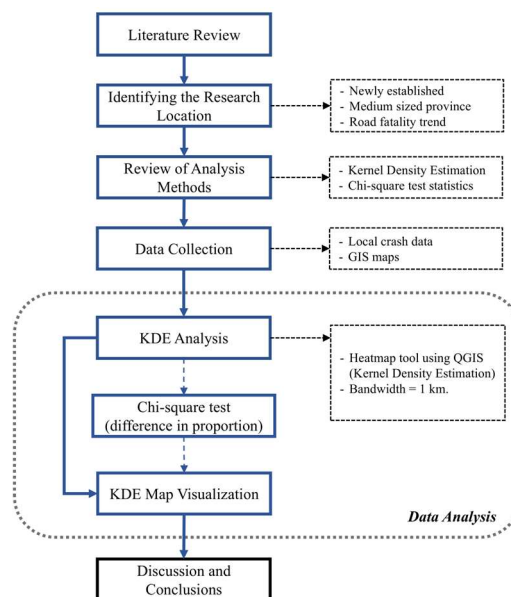


Figure 4. Research framework

Research Procedure

This study followed a systematic research procedure composed of eight key steps (Figure 4), from preliminary review to spatial analysis and interpretation. Each step is described as follows:

1) Literature Review: The research process began with an extensive review of academic literature, technical reports, and policy documents related to road safety, crash analysis, and spatial methods such as KDE. This helped establish the background, identify the research gap, and formulate the objectives of the study.

2) Identifying the Research Location: Bueng Kan province in northeastern Thailand was selected as the study area due to its emerging road safety challenges and unique characteristics as a newly established and medium-sized province. Five districts with the highest crash incidence were identified for focused analysis.

3) Review of Analysis Methods: A review of relevant spatial analysis techniques was conducted, particularly focusing on KDE for crash hotspot detection and the Chi-square test for statistical comparison. This step helped justify the selection of tools and guide the integration of spatial and statistical methods in the research design.

4) Data Collection: Local Crash Data and GIS Map Data: Crash data for the years 2018 to 2020 were obtained from relevant local and national authorities. The data included location references, severity levels, and crash characteristics. Additionally, GIS-based road network data of Bueng Kan province were collected and prepared for spatial analysis using linear referencing and geocoding.

5) KDE Analysis: KDE was applied using GIS tools to identify spatial concentrations of crash incidents along the road network. A bandwidth of 1 km was selected to generate smoothed density surfaces that highlight high-risk locations.

6) Chi-square Test: To statistically assess whether the proportions of fatal versus non-fatal crashes differed significantly across various crash locations, the Chi-square test was applied. This allowed for quantitative validation of hotspot severity and the association between crash type and location.

7) KDE Map Visualization: The results of the KDE analysis were visualized through thematic maps showing crash density distributions. These maps facilitated clearer understanding of spatial patterns and supported the identification of priority intervention areas.

8) Discussion and Conclusions: Finally, the findings were synthesized and interpreted in light of the study's objectives. The implications for road safety policy, infrastructure planning, and the utility

of KDE and Chi-square analysis were discussed. Conclusions were drawn, and recommendations were proposed for local road safety improvements and future research.

Results and Discussion

Overview of Local Road Accidents (2018-2020)

During the three-year study period (2018-2020), a total of 513 road accidents were recorded on local roads in Bueng Kan province. Among these, 66 resulted in fatalities, 441 involved injuries and property damage (as Figure 5). During that period, the highest number of crashes were clearly found in districts such as Mueang Bueng Kan District and Seka District. Crash characteristics showed that the most common collision types included [e.g., rear-end, head-on, side-swipe], and were often associated with poor visibility, rainy weather, or lack of traffic control infrastructure.

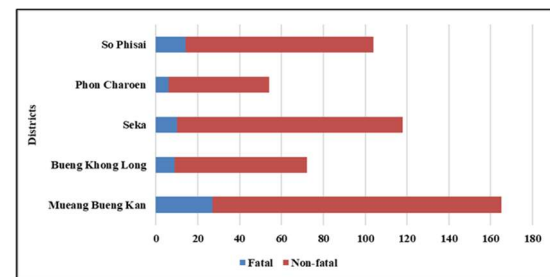


Figure 5. Overview of distribution proportion of crash severity

Spatial Patterns of Crash Density using KDE

The results of the KDE revealed several high-density crash locations concentrated in five key districts: Mueang Bueng Kan, Bueng Khong Long, Seka, Phon Charoen, and So Phisai. The spatial distribution of crash density is visualized in Figure 3 KDE map, where darker shaded areas indicate higher crash risk. It can be seen that all accidents occur in the central business districts of each district, which are densely populated, have a large network of roads, and are located next to large main intersections. Some consistent high-risk locations include:

- Intersections near local market areas in Mueang Bueng Kan.
- Road segments adjacent to schools or community centers in So Phisai.
- Curved or hilly rural segments in Seka, especially in rainy months.

These findings suggest a strong association between crash-prone areas and surrounding land - use characteristics.

When the KDE analysis was stratified by severity level, different spatial patterns emerged: Fatal crash hotspots were more concentrated in rural and high-speed road sections, particularly in Phon Charoen and Seka. Minor injury and property damage crashes clustered around urbanized subdistricts and busy community roads.

These patterns highlight the importance of targeted interventions - for example, speed management in rural areas and pedestrian safety enhancements in semi-urban zones.

Chi-Square Test for Severity Proportion Differences

An analysis of crash severity proportions was conducted to examine the distribution of fatal and non-fatal crashes across the five districts with the highest crash frequencies in Bueng Kan province: Mueang Bueng Kan, Bueng Khong Long, Seka, Phon Charoen, and So Phisai. Among a total of 513 reported crashes from 2018 to 2020, 66 were classified as fatal and 447 as non-fatal (Table 1). Mueang Bueng Kan recorded the highest number of fatal crashes (n=27), followed by So Phisai (n=14), while Phon Charoen reported the lowest number (n=6). Despite these variations in raw counts, it is essential to determine whether the differences in severity proportions are statistically significant across districts.

To assess this, a Chi - square test of independence was performed (Table 2), with the null hypothesis stating that there is no significant difference in the proportion of fatal crashes among the five districts. The calculated Chi-square statistic was 4.020, which is below the critical value of 9.488 at the 0.05 significance level, and the associated p-value was 0.403. Since the p-value exceeds 0.05, the null hypothesis was not rejected.

These results suggest that, although there are observable differences in the number of fatal crashes among the districts, these differences are not statistically significant when adjusted for total crashes. In other words, the proportion of fatal to non-fatal crashes does not differ significantly across the five districts. This implies that fatal crashes are likely distributed evenly relative to the total number of incidents and are not disproportionately concentrated in any single district. From a policy perspective, this finding supports the need for province-wide road safety interventions rather than focusing resources solely on specific districts.

Discussion and Implications for Road Safety

The spatial analysis of crash heatmap using KDE, supported by the descriptive data in Table 1, reveals important insights for local road safety management in Bueng Kan province. While Mueang Bueng Kan district recorded the highest number of crashes in absolute terms, the KDE map visualization (Figure 3) indicates that Seka district may be the most hazardous area in terms of spatial crash concentration. This is evidenced by the highest degree of crash point overlap and the darkest density shading on the map. These findings suggest that crash frequency alone may not fully capture the spatial risk landscape. Therefore, local authorities and policymakers should carefully consider their operational objectives - whether to prioritize total crash volume or spatial intensity - when selecting intervention areas.

Moreover, the Chi - square test results provide additional perspective by indicating no statistically significant difference in the proportion of fatal versus non-fatal crashes among the five districts. This suggests that road crash severity is distributed relatively evenly across the province, and that fatalities are not disproportionately concentrated in any one location. Consequently, policy interventions and safety measures should be

Table 1. Observed frequencies of local crashes

Severity	Districts					Total
	Mueang Bueng Kan	Bueng Khong Long	Seka	Phon Charoen	So Phisai	
Fatal	27	9	10	6	14	66
Non-fatal	138	63	108	48	90	447
Total	165	72	118	54	104	513

Table 2. Chi-square test statistic results

	Value	df	Significance (2-sided)
Pearson Chi-Square	4.020 ^a	4	0.403
Likelihood Ratio	4.144	4	0.387
Number of Valid Cases	513		

implemented province-wide, rather than focusing solely on high-frequency districts. However, it is worth noting that if future studies detect statistically significant differences in severity proportions across districts, such findings could help refine resource allocation by enabling district - level prioritization based on severity risk, not just crash count.

The combined use of KDE and the Chi-square test in this study demonstrates the value of integrating spatial and statistical analytical tools in road safety research. KDE offers an effective method for visualizing crash hotspots, particularly in regions where precise GPS data may be limited, while the Chi-square test provides a quantitative assessment of distribution patterns. Together, these tools enable a more comprehensive understanding of both the frequency and severity dimensions of traffic crashes. Future road safety research is encouraged to adopt such integrated approaches, incorporating appropriate statistical techniques that align with the structure of the data and the specific policy questions being addressed.

Conclusion and Limitations

Overall Summary

This study applied a GIS - based method using KDE and Chi-square statistical analysis to identify hazardous locations on local roads in Bueng Kan province, Thailand. The research responded to the pressing issue of rising road fatalities in this newly established and developing province, which - despite its relatively small population - has one of the highest fatality rates per capita in the country.

The KDE analysis effectively identified spatial patterns of crash concentrations across five key districts. While Mueang Bueng Kan had the highest crash frequency, the KDE map indicated that Seka district exhibited the highest spatial crash density, suggesting a greater concentration of overlapping crash incidents. This distinction emphasizes the importance of differentiating between absolute crash counts and spatial intensity when determining priority intervention areas.

Additionally, the Chi-square test revealed no statistically significant difference in the proportion of fatal versus non-fatal crashes among the five districts, indicating that crash severity is relatively evenly distributed across the study area. This finding supports the implementation of province-wide road safety policies, rather than focusing resources solely on specific districts. Nonetheless, the combination of spatial and statistical techniques used in this study illustrates the value of an integrated analytical approach in road safety

research. The KDE technique supports visualization and hotspot detection, while the Chi - square test provides a statistical foundation for evaluating severity-related disparities.

Limitations and Future Directions

While the study provides meaningful insights, several limitations should be acknowledged:

- **Data Precision:** Some crash data lacked accurate GPS coordinates and relied on kilometer-post references, which required geocoding through linear referencing. This process may introduce location inaccuracies, particularly for crashes occurring near administrative boundaries or overlapping network segments.
- **Limited Variables:** The analysis focused on spatial distribution and severity, without incorporating other potential influencing factors such as traffic volume, driver behavior, vehicle types, or road design characteristics. These factors may help explain underlying crash patterns and risk (Loo *et al.*, 2011).
- **Temporal Scope:** The study covered a three-year period (2018-2020). While sufficient for spatial trend identification, a longer timeframe could enhance the ability to detect temporal stability or emerging trends in crash severity and density (Mohaymany *et al.*, 2013).
- **Analytical Scope:** While KDE and Chi-square tests are suitable for hotspot and proportion analysis, other advanced statistical models - such as spatial regression, time-series clustering, or machine learning-based classification - may provide deeper insights into crash prediction and risk profiling.

For future studies, researchers are encouraged to: 1) Incorporate traffic exposure data (e.g., AADT) to calculate crash risk ratios, 2) Use multi-level spatial models to account for nested geographic or road hierarchy structures, 3) Extend the analysis to compare rural vs. urban road settings or integrate socioeconomic and environmental variables, and 4) Explore temporal patterns of crashes using spatiotemporal KDE or time-series-based methods.

This study examined hazardous locations at the provincial level, which may limit its applicability for district-specific interventions. Future research should conduct district-level analyses to identify hazardous locations within each district, enabling more targeted and localized road safety measures. Such granular analysis would better support district administrators in prioritizing resources and implementing location-specific safety improvements.

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