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Spatial-Temporal Analysis of the Relationship Between Fatal Road Accidents and Environmental Factors in order to Improve RCS Rescue & Relief Operations (Study Area: Mazandaran and Alborz Provinces)

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Original Article

Abstract

INTRODUCTION: Road traffic accidents are a critical global issue, especially in developing countries such as Iran. Mazandaran and Alborz provinces, due to their diverse climatic and topographic characteristics, experience a high rate of fatal accidents, especially on mountainous roads that are often affected by weather and traffic conditions. Therefore, in this study, a spatiotemporal analysis of the relationship between fatal road accidents and environmental factors was conducted to improve RCS rescue and relief operations in the two provinces of Mazandaran and Alborz.

METHODS: This study analyzed fatal road accidents from March 2017 to January 2024 using data from the Red Crescent Society (RCS) and the Road Maintenance and Transportation Organization. Accident data were converted into monthly raster files via Kernel Density Estimation and examined using the Space-Time Cube model and Hot Spot Analysis in ArcGIS Pro to identify spatial-temporal accident patterns and their relation to environmental and traffic factors.

FINDINGS: Four hot spots and three cold spots patterns were detected across 83 months. Rainfall and flooding significantly affected 16.04% of oscillating and sporadic hot spots. Smooth and semi-heavy traffic conditions were associated with the highest accident percentages (19.45% & 14.01%), while blocked and heavy traffic showed lower accident intensity. Major accident hotspots appeared along the Chalous and Haraz roads and in specific rural districts. Emerging hot spots revealed new risk areas, demonstrating the dynamic nature of accident patterns.

CONCLUSION: The Spatio-temporal analysis highlights high-risk areas and provides important insights for improving road safety. These findings can help the Red Crescent Society optimize rescue and relief operations and inform policymakers on infrastructure and traffic management strategies to reduce casualties.

Keywords: Fatal Road accidents; Environmental factors; Space-time cube analysis; Hot spot analysis; RCS Rescue & Relief Operations.

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Introduction

Road traffic accidents resulted in 17.4 deaths per 100,000 people globally, primarily affecting low-income countries (1). Fatalities dropped in high-income regions, but gaps remain due to infrastructure, emergency response, and culture (2). In Iran, RTAs are the second leading hazard after earthquakes, highlighting the need for strategic action. (3) According to WHO, RTAs are a top cause of death in children and young adults and create heavy economic burdens (4). Recognizing the urgency, the UN included road safety in its SDGs, aiming to cut traffic deaths by 2030 (5). Iran's mountainous roads, especially Haraz and Chalous, are vulnerable due to complex terrain, climate variability, and weak infrastructure (6). Natural factors like frost, landslides, low

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visibility, and avalanches in winter increase accident risks (7). Weather isn't always the main cause, but it is a major factor (8). Studying RTAs' spatial-temporal patterns helps identify high-risk zones and improve response and planning (9). Few studies analyze fatal accidents' space-time patterns with the environment and traffic. This study uses Space-Time Cube and hot spot analysis over 83 months to find high-risk areas and guide safety improvements in Iran's mountains.

Given the importance of road accidents, identifying hazardous sites is key to reducing casualties. Many studies, including Alsahfi (2024), used GIS and methods like DBSCAN and KDE to find hotspots linked to population density in California (10). Soltani et al. (2024) examined accident trends and hotspots in Greater Melbourne over 15 years using cluster analysis (9) .Mesic et al. (2024) found rising injury hotspots in Ghana despite safety gains (11). Ahern et al. (2024) showed rumble strips reduce accidents on slopes (12). Khatun et al. (2024) noted fewer accidents but more fatalities in 2021 linked to driver errors (13). Eltemasi and Behtooiey (2024) reported that weather affects accident types, with rollovers common in Qazvin (14). Elvik and Høye (2023) found that traffic volume predicts accidents in Norway; urban speed limits matter less, and highways are safer (15).

However, Mohammed et al. (2023) linked Qatar hotspots to driver behavior, with more weekday clusters in 2019 (16). Kim and Lee (2023) studied wildlife-related crashes in South Korea, identifying new hotspots (17). Ullah Khan et al. (2023) used spatial methods to find hazardous rural roads (18). Alkaabi (2023) pinpointed accident factors and high-risk zones in Abu Dhabi (19). Berhanu et al. (2023) applied predictive models for hazards (20) . Alam and Tabassum (2023) ranked Ohio hotspots by severity (21). Babaei and Kunt (2023) introduced DBSCAN with temporal clustering (22). Kumar et al. (2023) forecasted rising road deaths in India via ARIMA (23). Qalb (2023) identified high-risk times (24). Dovic et al. (2022) analyzed fatality clusters in Serbia (25). Gheisari (2022) ranked hotspot factors in India (26).Kalantari and Alyan (2022) found road curvature to be a key factor (27). Hamami and Matisziw (2021) developed a GIS framework to track hotspot changes (28). Tola et al. (2021) ranked hotspots in Addis Ababa (29). Manap et al. (2021) identified heavy vehicle accident clusters (30). Mohammadian et al. (2021) compared hotspot detection methods (31).

Moreover, Feng and Zhu (2020) proposed automatic hotspot detection (32). Naseer et al. (2020) developed deep learning models for hotspot prediction (33). Shahzad (2020) introduced GIS techniques for accident simulation (34). Niranjan Kumar et al. (2019) created an automated accident rescue system (35). Bhatti et al. (2019) developed an IoT-based accident reporting system (36). Malin et al. (2019) showed increased accident risk in adverse weather (37). Le et al. (2019) analyzed seasonal effects on hotspots (38). Jamal et al. (2019) linked accident severity in Saudi Arabia to driver traits and weather using logistic regression (1). Yazdani et al. (2019) found that Ardabil urban accidents mostly occur at intersections on warm days due to human errors (39). Liu et al. (2019) identified road geometry factors like elevation and curve radius as key (40). Zahran (2019) recommended STAA for consistent hotspot prioritization and cost reduction (41). Kang et al. (2018) studied elderly-related accidents in Seoul, finding seasonal and location variations (42). Cheng et al. (2018) used multiple spatial methods to analyze evolving accident patterns in China (43).Vakilalroya and Zargar (2018) identified human factors as leading causes via the Analytic Network Process (44).Vatanparast et al. (2018) reported over 90% of accidents due to human factors, with high-risk zones near city entrances/exits (45). Chen et al. (2018) identified intersections as primary accident sites in Shanghai (46). Potoglou et al. (2018) linked non-fatal accident severity to speeding, driver age, and seasonality (47). Pourgholami et al. (2017) showed that climate strongly impacts accidents, especially in winter and autumn (48). Bay et al. (2015) identified population, culture, and road design as key accident hotspot factors (49). Mousavi-Fooladi (2013) highlighted elevation and climate anomalies as key risks on mountain roads (50). Ahadi et al. (2010) identified heavy vehicle factors in Haraz route accidents (51). Karami and Farajzadeh (2005) confirmed higher accident risks in snowy/icy weather (52).

Previous studies have extensively examined environmental and traffic factors to identify dangerous areas and guide safety measures, however, this study seeks to go deeper by connecting environmental and traffic conditions with spatiotemporal patterns of accidents to pinpoint high-risk zones, support policymakers,

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planners, and emergency teams in increasing road safety and reducing fatalities.

Methods

This study focuses on the mountainous regions of Alborz and Mazandaran provinces in northern Iran, specifically the Haraz and Chalous road corridors, which are known for high traffic volumes and a high incidence of fatal road accidents. Alborz province, covering approximately 5,121.694 square kilometers, serves as a critical transit hub connecting 17 populous provinces (53). Mazandaran province, with an area of approximately 24,091.3 square kilometers, extends along the Alborz Mountain Range and the Caspian Sea (54). These regions experience complex topography and diverse climatic conditions, including snowfall, landslides, and floods, which significantly contribute to increased road accident risks. The combination of high population density, heavy tourism traffic, and challenging environmental factors makes road safety analysis in these areas especially important. (Figure 1)

According to the study objectives, the spatial patterns of road traffic accidents over six years were analyzed. Accident data were obtained from the Emergency Management Organization and the RCS Rescue and Relief Organization of the two provinces. Environmental and climatic data—including snow and blizzards, rain and flooding, clouds and fog, landslides and slips—along with traffic conditions (smooth flow, moderately heavy, blocked, heavy, and unclear) were acquired from the Road Maintenance and Transportation Organization. The accident data, originally in Excel format, were converted into point files using ArcGIS software, then 83 monthly raster files were generated using Kernel Density Estimation and used as inputs for the Space-Time Cube model in ArcGIS Pro for further analysis.

To analyze the spatiotemporal patterns of fatal road accidents in Mazandaran and Alborz provinces, 83 monthly raster layers were created using Kernel Density Estimation (KDE) in ArcGIS Pro. These layers were organized into mosaic datasets by season and year, forming multidimensional raster layers. A Space-Time Cube was constructed to identify spatial and temporal trends based on accident data, and Time Series Clustering was applied to group locations with similar temporal accident trends across the two provinces, allowing for the examination of environmental impacts over time. Emerging Hot Spot Analysis was conducted for 83 months (March 2017 to January 2024) and revealed four hot spot patterns and three cold spot patterns (55). These patterns, based on RCS mission data, provide insights for targeted road safety interventions (Figures 2 & 3).

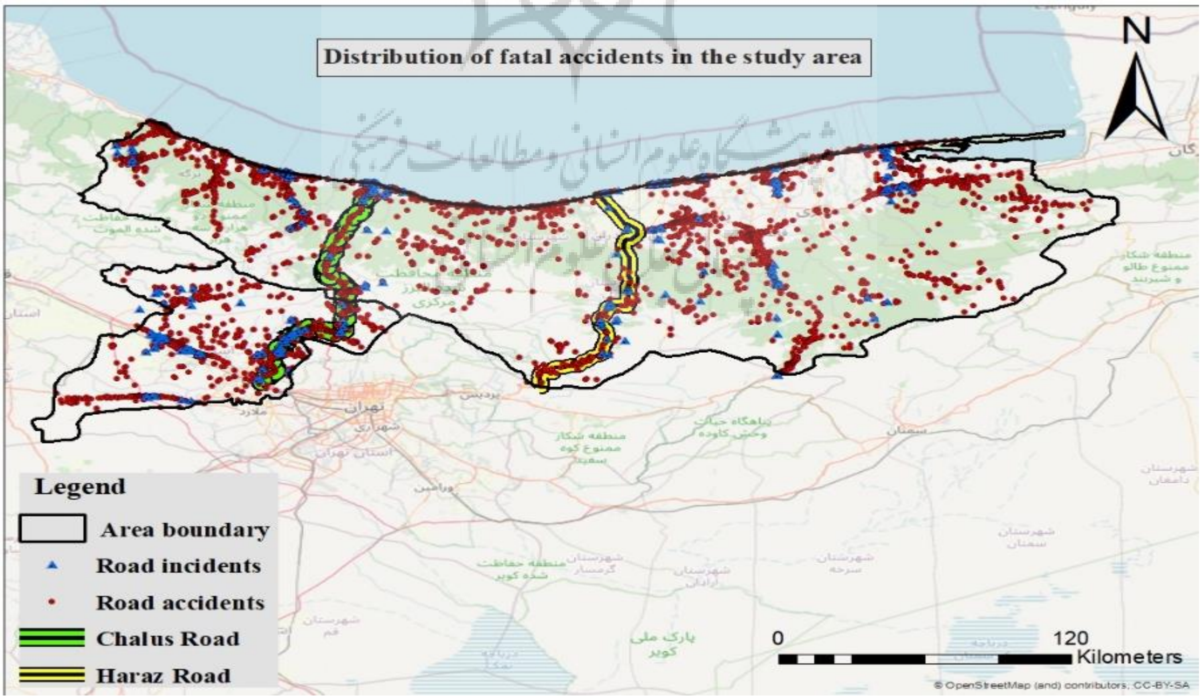

Figure 1. Distribution of road accidents in the study area from 2017 to 2024

Table 1. Definition of patterns and clusters of hot and cold spots (emerging hot spot analysis)

Label	Pattern name	Definition
	New Hot Spot	Previously never was a hot spot but recently has been identified as a hotspot.
	Consecutive Hot Spot	Less than 90% of the study period was a hot spot, except in final time-step intervals, was never a significant hot spot
	Intensifying Hot Spot	In 90% of the study period was a hot spot and its intensity has increased in time-steps generally
	Persistent Hot Spot	In 90% of the study period was a hot spot, but there was not any increasing or decreasing in it intensity in time-steps
	Diminishing Hot Spot	In 90% of the study period was a hot spot and its intensity has decreased in time-steps generally
	Sporadic Hot Spot	Less than 90% of the study period was a hot spot and there was not any cold spot in the time-steps
	Oscillating Hot Spot	Less than 90% of the study period was a hot spot, but there was a cold spot in the time-steps
	Consecutive Cold Spot	Less than 90% of the study period was a cold spot and except in the final time-step intervals, was never a significant cold spot
	Sporadic Cold Spot	Less than 90% of the study period was a cold spot and there was not any hot spot in the time-steps
	Oscillating Cold Spot	Less than 90% of the study period was a cold spot, but there was a hot spot in the time-steps
	No pattern detected	No specific pattern was found

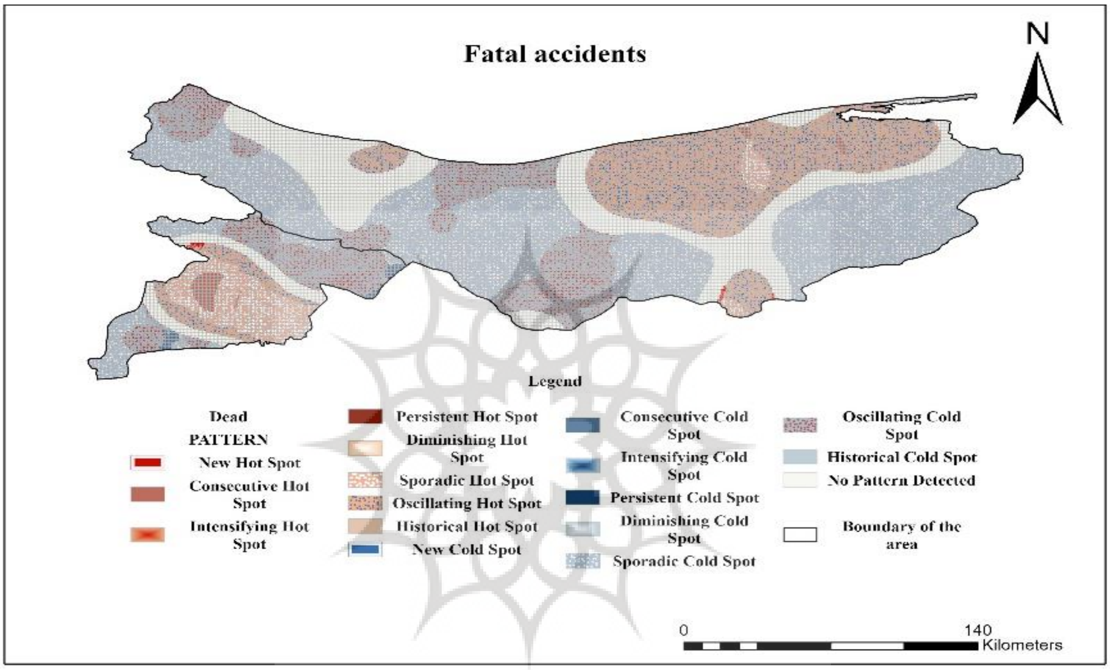

Figure 2. Analysis of hot and cold spots of the space-time cube (emerging hot spot analysis) in fatal accidents

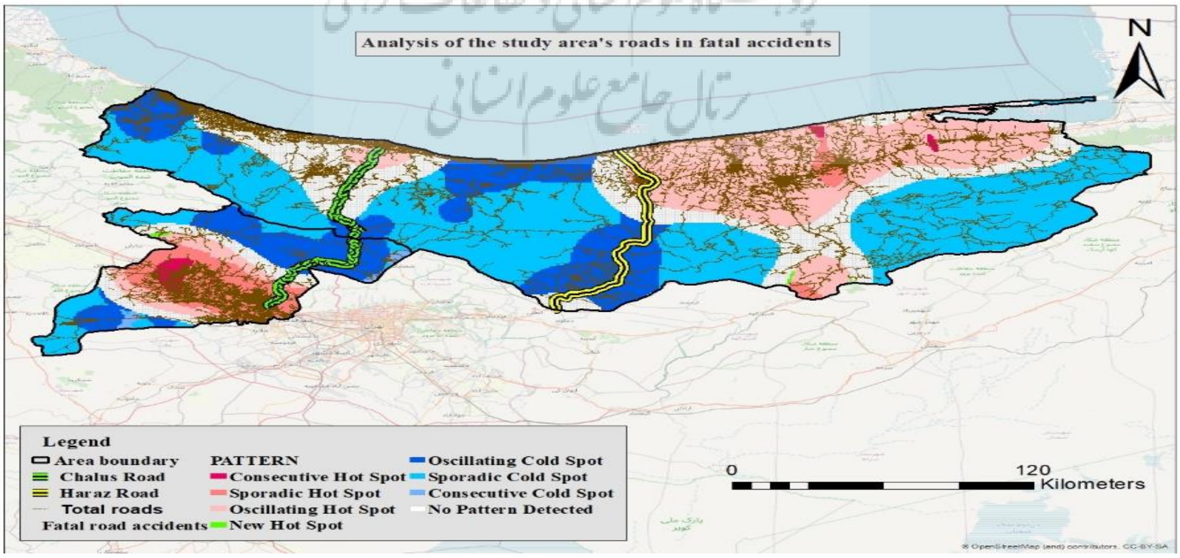

Figure 3. Hot and cold spot analysis of fatal accidents in the study area's axes

Findings

The spatiotemporal analysis of fatal accidents in Mazandaran and Alborz provinces between 2017 and 2023 revealed significant patterns across urban and rural areas. Accidents were predominantly concentrated in densely populated urban centers and major connecting roads to suburban regions. Using the Emerging Hot Spot Analysis based on 83 months of RCS mission and fatal accident data, 17 clusters of spatial-temporal patterns were identified, including eight types of hot spots, eight types of cold spots, and one with no clear pattern. The analysis, performed with ArcGIS Pro, categorized these patterns into seven distinct types: four hot spot patterns (Consecutive, Sporadic, Oscillating, and New Hot Spots) and three cold spot patterns (Oscillating, Sporadic, and Consecutive Cold Spots). The most accident-prone areas corresponded to Consecutive Hot Spots, followed by Sporadic, Oscillating, and Emerging Hot Spots. Conversely, cold spots exhibited opposite trends. These findings highlight dynamic spatial and temporal changes in accident risk, enabling targeted interventions in high-risk locations.

The total area covered by the identified patterns amounts to 6,249 square kilometers out of 35,804. Among cold spots, the Sporadic Cold Spot pattern occupies the largest portion, accounting for 37.26% of this area. For hot spots, the Oscillating Hot Spot pattern covers the highest percentage at 21.19% (Figure 3). Table 2 details the area percentages of each pattern relative to the total patterned area.

Table 2. Areas of cold and hot spots for fatal accidents

Patterns	Cold spots Area%	Hot Spots Area%
Consecutive Hot Spot	0.00	0.79
Oscillating Hot Spot	0.00	21.19
Sporadic Hot Spot	0.00	5.50
New Hot Spot	0.00	0.09
Sporadic Cold Spot	37.26	0.00
Consecutive Cold Spot	0.36	0.00
Oscillating Cold Spot	16.87	0.00

The New Hot Spot pattern represents the smallest coverage at 0.09%, while the Consecutive Cold Spot pattern has the lowest percentage among cold spots at 0.36%. Analysis of environmental impacts on fatal accidents showed that snow and blizzard conditions dominate the Oscillating Cold Spot pattern, covering 21.03% of the total area. In the Sporadic Cold Spot pattern, rain and flooding affect 16.61% of the area. These adverse weather conditions appear to reduce accident severity by lowering vehicle speeds, thus decreasing fatalities. The highest risk area under normal (no snow or rain) conditions accounts for 12.02% of the Oscillating Hot Spot pattern. Following this, rain and flooding contribute 8.54% within the Oscillating Hot Spot pattern and 7.86% in the Sporadic Hot Spot pattern. Overall, rain and flooding have the most significant influence on fatal accidents, covering 16.04% of the total 6,027.80 square kilometers in hazardous Oscillating and Sporadic Hot Spot areas (Table 3).

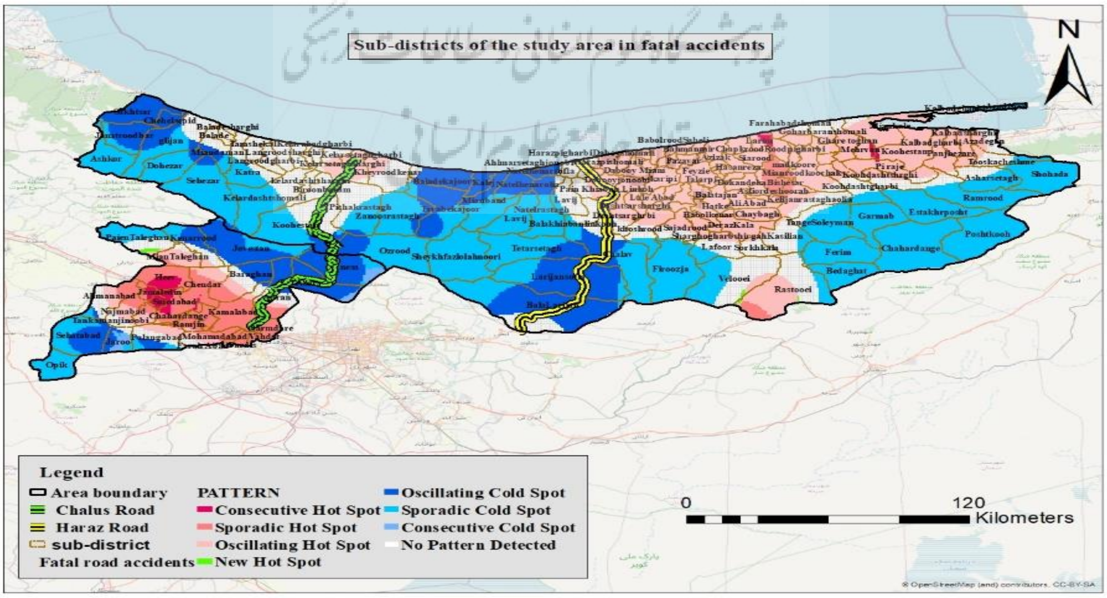

Figure 4. Relationship between identified patterns of fatal accidents and sub-districts

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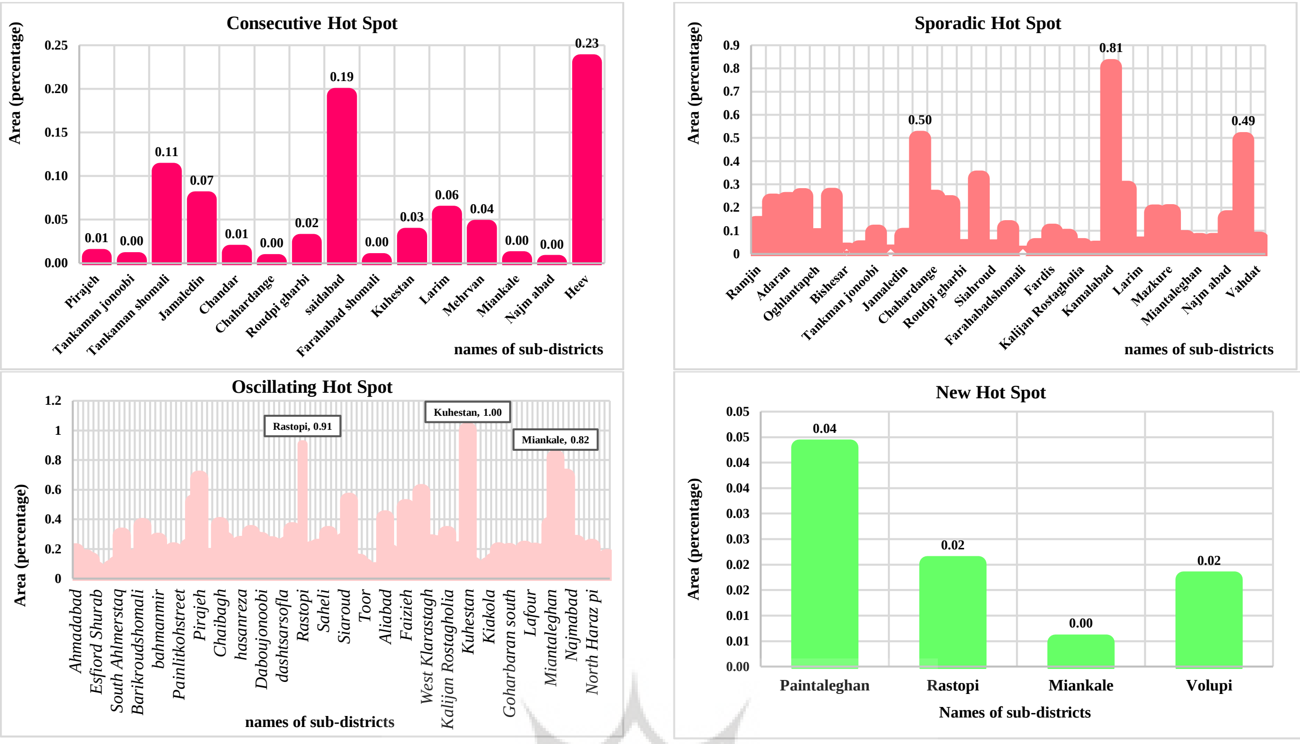

Figure 5. Relationship between the area of hazardous points in fatal accidents and sub-districts

Table 3. Relationship between the area of fatal accident patterns and environmental features

Patterns of fatal accidents	Snow & blizzard	Rain & flooding	Cloud & fog	Landslide & rockfall	Normal	Total Area
Consecutive Hot Spot	0.05	0.04	0.01	0.0014	0.02	60427.80
Oscillating Hot Spot	1.86	8.54	0.59	0	12.02	
Sporadic Hot Spot	3.39	7.86	0.01	0.0014	1.65	
New Hot Spot	0.14	0	0.00	0	0.05	
Sporadic Cold Spot	0.18	16.61	0.49	0	1.18	
Consecutive Cold Spot	0	0	0.00	0	0.21	
Oscillating Cold Spot	21.03	0	2.49	0	17.96	

Results from Figures 4 and 5 analyzing hazardous sub-districts in the study area showed that Heev sub-district has the highest area percentage in the Consecutive Hot Spot pattern at 0.23%, followed by Sa'id Abad and Northern Tankaman sub-districts at 0.19% and 0.11%, respectively, relative to the total 62,358 square kilometers. Kamal Abad leads in the Sporadic Hot Spot pattern with 0.81%, followed by Chandar and Heev at 0.50% and 0.49%. In the Oscillating Hot Spot pattern, Kuhestan holds the largest area at 1.00%, followed by Rastopi and Miyan Kaleh at 0.91% and 0.82%.

For Emerging Hot Spots, Paein Taleghan and Lu'i sub-districts have the highest fatal accident rates at 0.04% and 0.02%, respectively. Since these areas are newly classified as Emerging Hot Spots, not previously showing other hazardous patterns, this indicates a rise in future fatal accident risks. Consequently, targeted interventions are necessary to mitigate hazards and prevent these zones from becoming Consecutive Hot Spots (Figure 4).

The results of the analysis of the relationship between fatal accident patterns and the axes of the study area (Table 4) showed that the oscillating hot spot pattern covers the largest area, accounting for 21.19% of the total area (6249 out of 35804 square kilometers). In contrast, the Emerging Hot Spot pattern covers the smallest area at 0.09%. The Oscillating Hot Spots include the beginning and end of the Chalous axis, specifically Takhteh Boulevard and roads such as Barghan, Malard, Nozan, and Meshkinabad in Mazandaran province, as well as the Amol-Mahmoudabad highway and the cities of Amol and Babol along the Haraz axis. The Sporadic Hot Spot pattern covers 5.50% of the area, including the Lashkari Highway and the entrance to Chalous Road in Alborz province. The

Consecutive Hot Spot pattern accounts for 0.79% of the total area and 2.22% of the total axis length but does not cover the Chalous and Haraz axes. Overall, Oscillating and Sporadic Hot Spot patterns dominate, with significant presence along key highways and urban regions.

The analysis of the relationship between the lengths of axes and identified fatal accident patterns showed that, out of the total 22,700.3 kilometers of axes in the study area, 26.97% correspond to scattered cold spots. The Haraz and Chalous roads have the longest accident-prone segments, with oscillating hot spots covering 18.17% of the total axis length. Additionally, the entrance to the Chalous road in Alborz province and the Lashgari highway account for 7.61% of the axis length within the sporadic hot spot pattern. Figure 6 illustrates the spatial distribution of these accident-prone axes based on the Space-Time Cube model. Further details on the relationship between the length and area of identified patterns relative to the total area and axis length are summarized in Table 4.

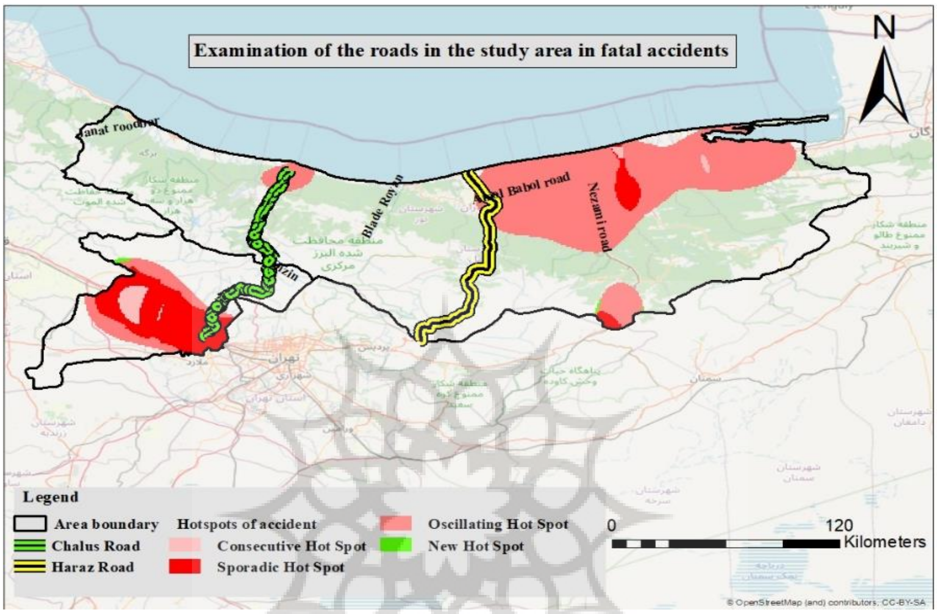

Figure 6. Hazardous axes in the study area

Table 4. Relationship between length and area of identified patterns of fatal road accidents

Patterns of fatal accidents	Axis length as a percentage of total length	Percentage of axis area to total area	Total length of the axes (Km^2)	Total area (Km^2)
Consecutive Hot Spot	2.22	0.79	7003.22	60427.80
Oscillating Hot Spot	18.17	21.19		
Sporadic Hot Spot	7.61	5.50		
New Hot Spot	0.9	0.09		
Sporadic Cold Spot	26.97	37.26		
Consecutive Cold Spot	1.74	87.36		
Oscillating Cold Spot	16.59	16.87		

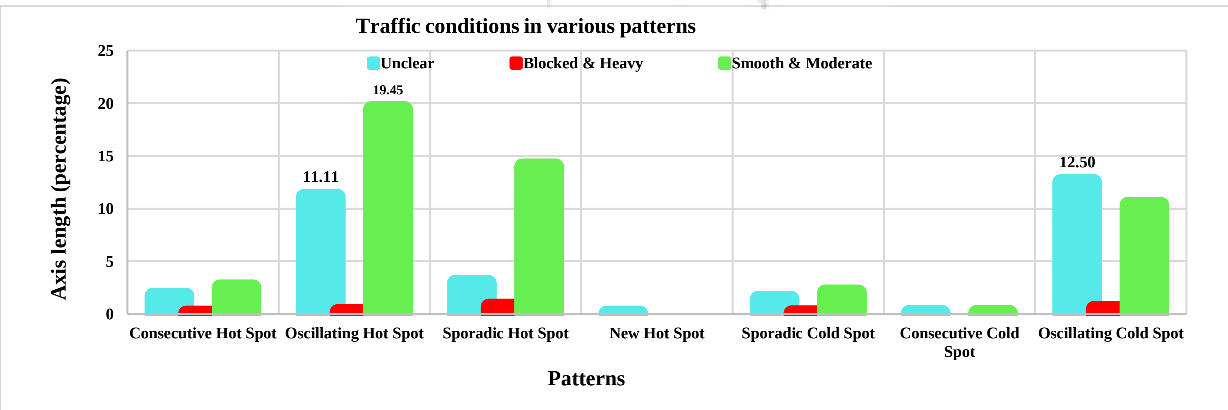

Figure 7. Relationship between the area of identified patterns of fatal accidents and traffic conditions

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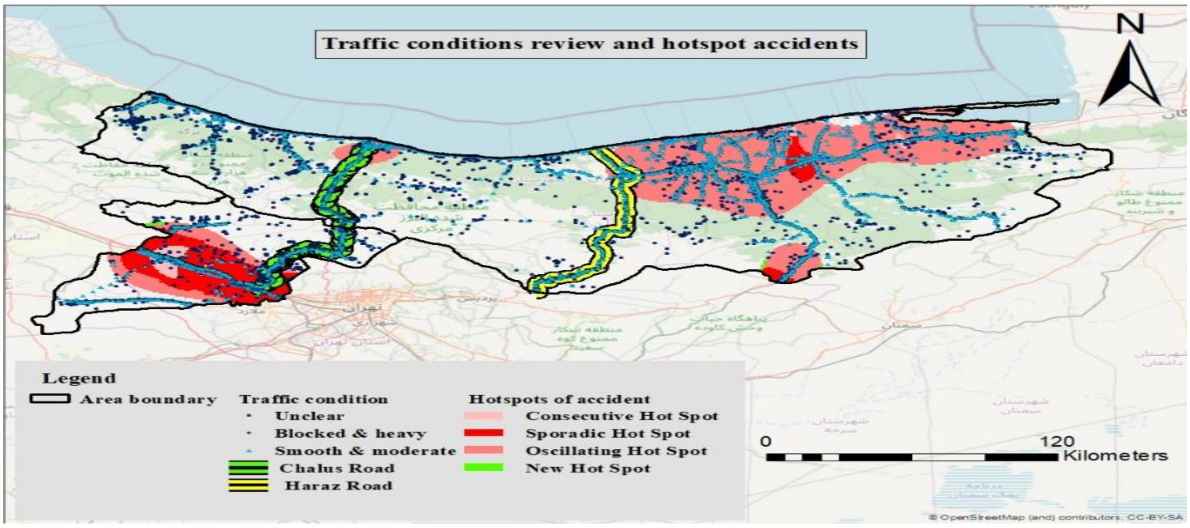

Figure 8. Relationship between identified hot spot patterns of fatal accidents and traffic conditions

The analysis of the relationship between identified fatal accident patterns and traffic conditions revealed that the highest percentages of accidents occur under smooth and moderately heavy traffic, covering 19.45% and 14.01% of the area within Oscillating and Sporadic Hot Spots, respectively. Conversely, the lowest accident severity is observed during blocked and heavy traffic conditions, likely due to reduced vehicle speeds that decrease accident intensity. Notably, 0% of the area classified as Consecutive Cold Spots corresponds to blocked and heavy traffic conditions. These findings are illustrated in Figure 7, which highlights the distribution of fatal accidents across varying traffic conditions.

Additionally, results from Figure 8 show that most smooth and moderately heavy traffic conditions (represented by light blue triangular points) are concentrated in high-risk hotspots, underscoring the greater impact of these traffic conditions on fatal accidents. The space-time cube analysis further revealed that emerging hotspots can become high-risk areas during specific spatiotemporal intervals. The observed upward and downward trends in these regions provide valuable insights into underlying factors influencing accident patterns, such as variations in traffic flow or weather conditions.

Discussion and Conclusion

This study analyzed fatal accidents over 83 months using the Space-Time Cube model and Emerging Hot Spot Analysis, identifying four hot spots and three cold spot patterns. Environmental factors, particularly rain and flooding, significantly influenced fatal accidents, covering 16.04% of the total area in oscillating and sporadic hot spots. Traffic conditions showed that smooth and semi-heavy traffic corresponded to the highest accident rates (19.45% and 14.01%), while blocked and heavy traffic had the lowest accident severity, likely due to reduced vehicle speeds. Spatial analysis revealed that the oscillating hot spot pattern covered the largest area (21.19%), including key roads such as Chalous axis, Takhti Boulevard, and several roads in Mazandaran and Alborz provinces. Sporadic hot spots accounted for 5.50%, mainly along Lashgari highway and Chalous entrance, while sequential hot spots covered the smallest area (0.79%) and were absent from major axes. Lengthwise, oscillating hot spots accounted for 17.18% of accident-prone axes, with notable hotspots on the Haraz and Chalous roads. Rural district analysis highlighted areas like Heev, Kamalabad, Kohestan, and Paein Taleghan as significant hot spots, with emerging hot spots indicating new high-risk zones likely to become future accident hotspots.

These trends reveal the dynamic nature of accident risk influenced by environmental and traffic changes. The study emphasizes the importance of addressing risk factors and implementing targeted interventions to reduce fatalities and prevent hotspot recurrence. The methodology is adaptable internationally, providing valuable insights for traffic safety strategies, emergency response optimization, and policy-making.

This research is among the first in Iran to apply the Space-Time Cube model for fatal accident analysis on challenging roads like Haraz and Chalous, offering a novel framework for both static and dynamic hotspot identification to enhance road safety and emergency planning.

Compliance with Ethical Guidelines

There were no ethical considerations in this research.

Funding/Support

This research has not received any financial support.

Author's Contributions

This article is based on the doctoral dissertation of Bahare Sadat Mousavi, titled "spatial-temporal analysis of the relationship between fatal road accidents and environmental factors to improve RCS rescue & relief operations (Mazandaran and Alborz provinces)". Also, Bahareh Sadat Mousavi was responsible for idea generation, methodological design, data collection and analysis, manuscript writing and editing, and correspondence. Dr. Meysam Argany and Dr. Najme Neysani Samany supervised the research and reviewed the manuscript. Dr. Ahmad Soltani advised on data preparation and rescue-related issues.

Conflict of Interests

The authors declare no conflict of interest.

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