UNCOVERING THE DANGER ZONES: SPATIAL AND STATISTICAL INSIGHTS INTO ROAD ACCIDENT HOTSPOTS IN KHULNA

Nusrat Jahan*[1], Bishal Chaklader Swadin[2], Mofasser Bin Hossain Maruf[3], Hasnat Or Rashid Hamim[4], Md Eastiak Hossain[5]

[1] *Graduate Student, Urban and Rural Planning Discipline, Khulna University, Khulna 9208, Bangladesh, e-mail: nusratmimjahan123@gmail.com*
[2] *Graduate Student, Urban and Rural Planning Discipline, Khulna University, Khulna 9208, Bangladesh, e-mail: chakladerbishal@gmail.com*
[3] *Urban and Rural Planning Discipline, Khulna University, Khulna 9208, Bangladesh, e-mail: mofasserbinhossain2002@gmail.com*
[4] *Urban and Rural Planning Discipline, Khulna University, Khulna 9208, Bangladesh, e-mail: hasnathamim7395@gmail.com*
[5] *Graduate Student, Urban and Rural Planning Discipline, Khulna University, Khulna 9208, Bangladesh, e-mail: eastiakbin@gmail.com*

***Corresponding Author**

ABSTRACT

Road traffic accidents (RTAs) are one of the leading causes of mortality and morbidity throughout the world and in low and middle-income countries such as Bangladesh in particular where roads are being developed faster, additional infrastructures are inadequate and necessary actions have been established to reduce the vice to ensure that it escalates even more. In this paper, I analyze the spatial and statistical features of RTAs in Khulna City, Bangladesh, over the period of 2010 to 2019 and identify the areas likely to experience the accidents as well as those factors influencing the building up. The analysis provides a detailed examination that combines the spatial modeling of Geographic Information System (GIS) with more complex statistical analysis to provide the entire picture of dynamics of accidents in the urban environment. Accident data were analysed using Kernel Density Estimation (KDE) and Getis-Ord Gi star statistic over a period of 9 years in order to determine how data clustered spatially and statistically significant areas of greatest occurrence. These spatial results were supplemented by chi-square tests and binary logistic regression models in establishing the existence of a correlation between the accident hotspots and the factors that impacted them which include a vehicle type, time of the day, driver age, conditions of the road, the consequences of the crash. The result indicated that the spatial clustering of RTAs was higher around Khulna Sadar, Khan Jahan Ali and Sonadanga thanas (high density of traffic, the geometries of roads, and mixed modes of travel). The statistical results coincided with the preliminary results that time of day ($p = 0.035$), age group of the driver ($p = 0.041$), and the result of the accident ($p = 0.004$) showed significant results in the development of hotspots, but the type and speed of the vehicle was also weak or meaningless. The logistic regression equation (Nagelkerke R2 = 0.462) established that the blend of spatial, temporal and human variables to clarify the fluctuation in the incidence of the hotspots clarifies nearly fifty percent of the fluctuation. This spatial analysis and statistical analysis demonstrate that RTAs in Khulna are not scattered everywhere statistically, but they are very clustered in certain permanent clusters that have been intensified over time. The study reveals that local solutions of safety interventions (enhancing light into roads, more vigilance during rush time and certain driver education) are urgently required. The results provide a practical conceptual framework that may be utilized by policy makers and urban planners in implementing evidence-based policies in reducing the risks of accidents and enhancing sustainable urbanism in Khulna and other urban areas in Bangladesh.

Keywords: *Road traffic accident; Getis-Ord Gi*; Kernel density; Hotspot analysis; regression model*

1. INTRODUCTION

Road accidents are regarded as one of the biggest social and economic problems across the globe. In the year 20-50 million non-fatal injuries are experienced worldwide annually and more than 1.24 million succumb to death. According to World Health Organization (WHO), road traffic accidents are estimated to be the fifth leading cause of death by 2030 due to the incessantly increasing road traffic injuries epidemic. Moreover, the WHO notes that among the people between the age of 15 and 29. The first leading cause of mortality through injuries is caused by traffic accidents (Kaygisiz et al., 2015). It has been reported that in low and middle-income countries (LMICs), more than 90% of deaths and injuries were witnessed (World Health Organization, 2015, 2018), and up to 5% of GDP loss was reported, which is compared with 3% in other countries of the world (Maggi et al., 2019). The major causes of the growth of RTAs in LMICs include rapid economic development, motorization, and urbanization (Maggi et al., 2019). Despite lower rates, LMICs such as Bangladesh have to deal with a disproportionate number of crashes (WHO, 2015; WHO, 2018; Hasan et al., 2024). The problem of road traffic accident (RTA) has also been made worse in Bangladesh than in other developing South Asian nations. This is due to a number of factors such as poor maintenance of roads which is portrayed in the shape of potholes, bad surfaces and lack of lighting. Such risks infringe on visibility and control of the drivers and increase the number of fatalities in the traffic disproportionately. Not to mention that, due to unroadworthy cars, which include worn tires, broken steering, and ineffective brakes, there is a greater chance of an accident occurring and a severe road safety issue at stake. Moreover, the lack of awareness of road traffic accidents among drivers and the non-informed population, the insufficient quality of roads, the overpopulation, the lack of trainers and proper education of drivers, excessive speed limit, and drinking have complicated the situation. The combination of these factors in Bangladesh results in harsh social and economic cries, such as property loss and loss of lives. Although the number of RTAs grows, there is still a blind spot concerning road safety despite the fact that the country lacks the necessary resources to mitigate the situation, and the ignorance about the causes of serious traffic deaths is still alarming (Paul et al., 2024; Hasan et al., 2024; Maggi et al., 2019). In Bangladesh, every 10,000 vehicles has approximately 86 deaths. This is a very disturbing figure especially in the cities. Nearly 20 percent of the total road accidents happen in large urban areas such as Dhaka, Rajshahi, Chittagong and Khulna (Hossain et al., 2005). Khulna is a divisional and an industrial city, located on 45.65 km2 in Bangladesh. It also has 243km of road network which includes 18 km of earthen road, 67km of HBB (Herring Bone Bond) roads, and 158km of bituminous roads. The total population of cars in use in the city in 2005 was more than 20,990 cars; there were almost 13360 non-motorized vehicles and 7630 powered vehicles. Practically non-motorized transportation constitutes approximately 60 percent of the traffic in Khulna with non-motorized traffic including the rickshaw. Overall, most vehicles in the city are motorized, at 36.4% with 63.6% being non-motorized, with the proportion of motorized vehicles rising by an average of 15% every year (Hossain et al., 2005). Road traffic accidents (RTAs) have become a critical problem of the community safety in Khulna, Bangladesh because of a group of circumstances which influence the harshness of the accidents and increase the death toll and injuries. Some of the studies have identified the key parameters, which determine the severity of RTAs and they include vehicle speed, the type of collision, and the time of the accident. Indicatively, Hossain and Zaman (2021) have used logistic regression analysis to study 266 events in 2010 through 2019 and they found that rear-end crash, high-speed collision and incidents involving a vehicle with a speed exceeding 40 km/h were more probable to be fatal. Similarly, Islam et al. (2018) have discovered that social-demographic factors such as occupation and level of education influence traffic safety significantly. Although the less educated classes were connected with less safety knowledge as opposed to farming work and labor, more educated individuals were more knowledgeable on the traffic regulation laws and hence the possibility of accidents were less. Hossain et al. (2005) further found out that pedestrians were the most vulnerable road users and that motorized transport more so buses and trucks, contributed to a high percentage of road deaths. This highlights the importance of enhancing road pedestrian safety and the need to bring in the element of non-motor mobility in designing of a road. The paper fills an important gap in the research of road traffic accidents in Khulna city, because it directly employs the identification of the locations of the hotspots of accidents, and the spatial and temporal characteristics of their formation. Although some research studies have been conducted previously on general patterns of accidents, none of them have considered spatial dynamics or what variables contribute to the development of hotspots over time. Through Getis-Ord Gi, Chi-square tests, and binary logistic regression, this paper gets to explore the major factors of interest, which include the vehicle type, road conditions, the volume of traffic, and the speed limits. The results will seek to offer specific policy implications to policy makers and city planners to reduce high-risk areas and enhance road safety generally in Khulna.

2. STUDY AREA

Khulna is the divisional and industrial center of Bangladesh. Khulna's population density is 26287 people per km², and its land area is 45.65 km² (Hossain et al., 2005). Khulna City Corporation has 243 kilometers of roads, which is a suitable length for this study, according to BBS (2013). thus, having a high number of accidents is a beneficial indicator Khulna's roads and highways are crucial for activities associated with the economy, society, politics, environment, and public health. Thus, increased traffic and traffic accidents are frequent occurrences in this urban area (Hossain & Zaman, 2021).

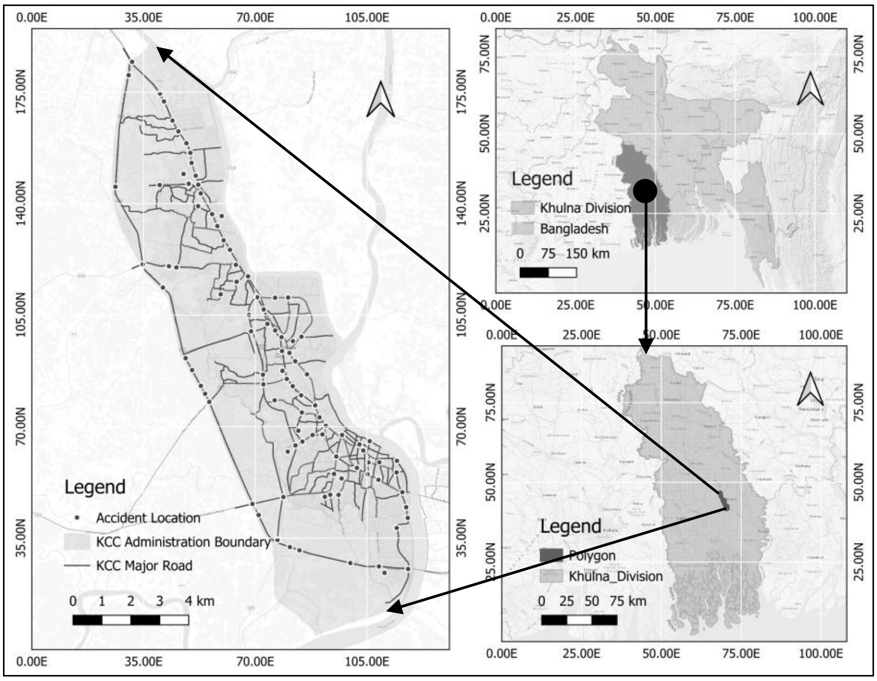

Figure 1: Study Area Map

3. METHODOLOGY

3.1 Severity Index

The Accident Severity Index (SI) can be used to determine the severity of an accident. When it comes to hotspots assessment, it is possible that the determination of a high or low cluster is hard or unimportant without weighted data. The severity of the accidents will produce different results depending on the various weighting schemes. Nevertheless, by doing so, heavier weights are allocated to more serious accidents. It ensures that the figures do not make too high, which may make the total cost of the accidents skewed. The system of weighting the types of accidents that the Belgian government has adopted gives specific weight on the accidents in the country in terms of minor, serious, and fatal accidents as 1, 3, and 5, respectively. It is applicable in this study, due to nine years of information on accidents (Khatun et al., 2024; Choudhary *et al.*, 2015). Equation is:

$$SI = 5D + 3S + L \quad (1)$$

where SI is the severity index for each location,
D is the total number of deaths,
S is the total number of serious injuries,
L is the total amount of slight injuries.

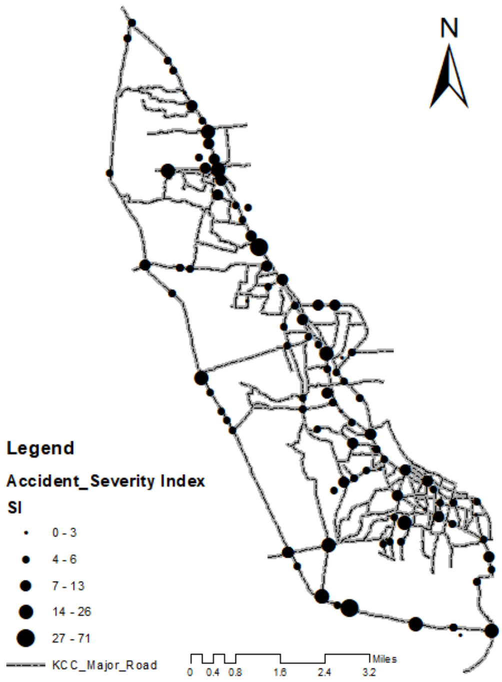

Figure 2: Severity Index Map

3.2 Kernel Density

Kernel density estimation (KDE) is a nonparametric approach to estimating the density of a phenomenon at any point in the study region, not just the location of the phenomenon, in one dimensional space. In terms of road safety, it is possible with NKDE to extract and visualise the accident density on the roads. It is anchored on the theory that, the density of the pattern of points is not only at the point but also at any other location within the area of research. The location of some incident or presentation. It is an intelligent attribute that enables KDE to investigate discrete data, such crashes, particularly where only rough positions are aware of them. This will assist in giving a better picture of the crash distributions. The density estimation technique is followed to define the density surface at each point separately. The density levels end up decreasing to zero as one moves far away off any accident site. The different density surfaces are combined to form a continuous density surface that is integrated to cover the entire area (Mohaymany et al., 2013). It was performed in this paper to generate a subjective heat map, which demonstrated the varying statistics of traffic accidents relative to high and low. The metric is used to calculate the rate of accidents that are most likely to occur at a specific point on the map (Srikanth & Srikanth, 2020). It was estimated using the following formula: the kernel density (Khatun et al., 2024).

$$f(x,y) = \frac{1}{nh^2}\sum_{i=1}^{n} K(\frac{d}{h})$$

f (x, y) = The density estimate of the location (x, y)
n = The number of observations
h = Bandwidth
K = The kernel function
di = Distance between the location (x, y) and the location of the observation.

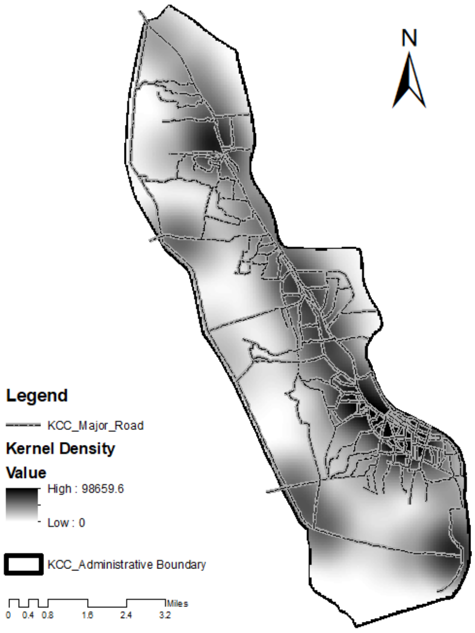

Figure 3: Kernel Density Map

3.3 Getis-Ord Gi* statistic

Hotspot Analysis (Getis-Ord Gi*) is used to obtain the highly significant accident areas, and the statistic of Gi is called Gi. To determine whether the cluster of accidents is significant, the output of Gi* will give Z score, and the p value of each location of an accident (Srikanth and Srikanth, 2020). Hotspot analysis Hotspot analysis is a form of mapping and statistical analysis technique that identifies clusters of the spatial occurrences based on the Getis-Ord Gi+ statistic. This statistic is used to identify statistically significant hotspots and coldspots, as well as computes the extent of suggestion which results due to the concentration of weighted points. In the case where positive Z values depict hot regions, high datum values are more concentrated. Similar to statistically significant negative z-scores, small values close to zero indicate that significant clusters are randomly distributed, and as the z- score decreases, the cluster of low scores gets increasingly concentrated (Khatun et al., 2024). The recommended formula of the Getis-Ord local statistic is as given below (Srikanth and Srikanth, 2020),

$$G^*i = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{X}\sum_{j=1}^{n} w_{i,j}}{s\sqrt{\frac{[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2]}{n-1}}}$$

Where n is the number of features
X_j is the attribute value for feature j,
$W_{i,j}$ is the spatial weights between the feature i and j,

and S is the standard deviation of all features.

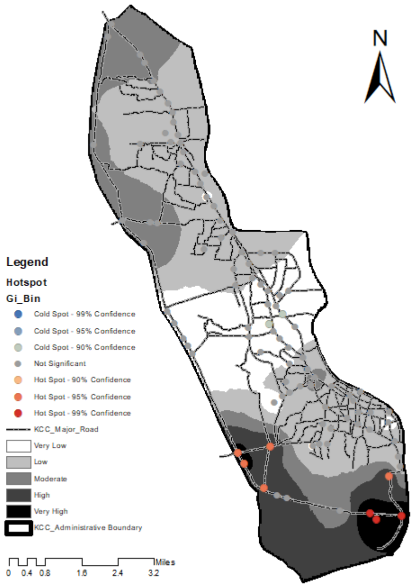

Figure 4: Getis Ord G*I Hotspot Map

c) 2010, 11, 12 **b)2013, 14, 15** **a) 2016, 17, 18, 19**

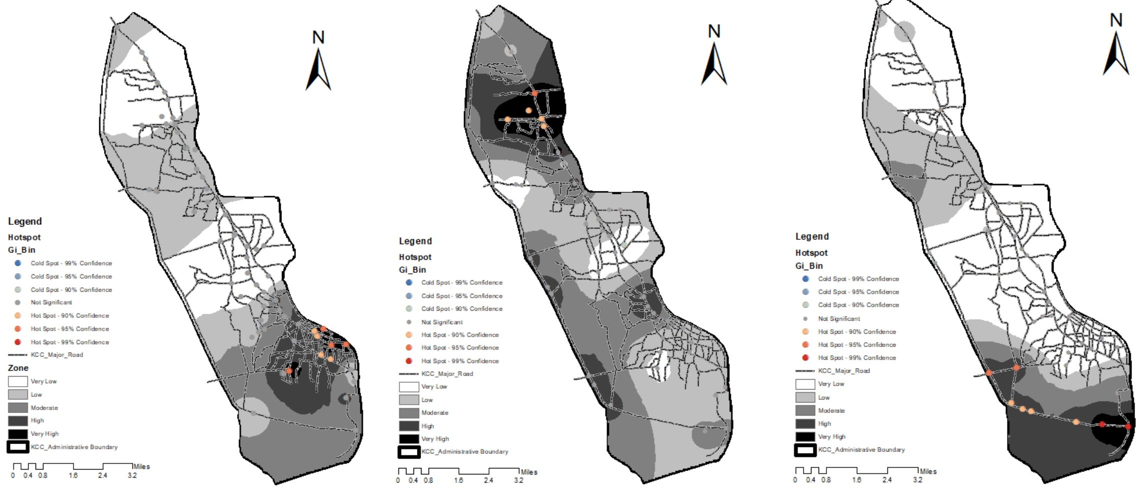

Figure 5: Year-wise Getis-Ord G*I Hotspot Analysis

Table 01: Chi-square Test

Variable Tested	p-Value (Sig.)	Phi / Cramer's V	Significance	Interpretation
Season of Accident	0.531	0.125	Not Significant	Hotspot occurrence does not significantly vary with season.
Time of Day	**0.035****	**0.191**	**Significant ($p < 0.05$)**	Accidents occurring during afternoon and night hours are more likely to form hotspots.

Vehicle Type	0.962	0.074	Not Significant	No significant relationship between vehicle type and hotspot occurrence.
Vehicle Speed Category	0.945	0.021	Not Significant	Hotspot formation is independent of vehicle speed category.
Driver Age Group	**0.041****	**0.104**	**Significant**	No meaningful relationship between driver age and hotspot occurrence.
Accident Location (Police Thana)	**0.000*****	**0.302**	**Highly Significant**	Strong spatial association — certain thanas show higher hotspot tendency.
Type of Accident (Event)	0.055*	0.122	Marginal (Weak)	Weak association; type of accident slightly linked with hotspot formation.
Collision Type	0.250	0.158	Not Significant	Collision pattern not significantly influencing hotspot distribution.
Injury Severity	0.825	0.058	Not Significant	Injury severity not associated with hotspot areas.
Accident Outcome (Fatality/Injury Status)	**0.004*****	**0.269**	**Significant**	A moderate positive relationship; fatal or severe-injury crashes cluster in hotspots.

** Significant at 10% level, ** Significant at 5% level, *** Significant at 1% level.*

The table indicates that among all tested variables, time of day (p = 0.035), driver age group (p = 0.041), accident location (p = 0.000), and accident outcome (p = 0.004) have significant effects on hotspot formation. Accidents are more likely to cluster during afternoon and night hours, and certain police stations show consistently higher hotspot tendencies. In contrast, variables such as season, vehicle type, speed, collision type, and injury severity are not significantly related to hotspot occurrence. This indicates that reduced visibility and higher traffic congestion contribute to accident clustering.

Table 02: Collinearity statistics

Variable	**Collinearity statistics**	
	Tolerance	**VIF**
Season of Accident	0.854	1.171
Time of Day	0.890	1.123
Vehicle Type	0.804	1.244
Vehicle Speed Category	0.822	1.217
Driver Age Group	0.897	1.115
Accident Location (Police Thana)	0.864	1.157
Type of Accident (Event)	0.584	1.711
Collision Type	0.644	1.552
Injury Severity	0.560	1.787
Accident Outcome (Fatality/Injury Status)	0.652	1.533

The collinearity statistics indicate that all variables have tolerance values above 0.5 and VIF values below 2, confirming the absence of multicollinearity among predictors. This means no variable in the regression model is highly correlated with another, ensuring the stability and reliability of coefficient estimates. The Type of Accident (VIF = 1.711), Collision Type (1.552), Injury Severity (1.787) and Accident Outcome (1.533) show slightly higher multicollinearity but remain within acceptable limits. Overall, the data satisfy the assumption of independent predictors, validating the suitability of the variables for logistic regression analysis.

-2 Log Likelihood	Cox & Snell R^2	Nagelkerke R^2
161.991[a]	0.308	0.462

Chi-square	df	Sig. (p-value)
3.236	8	0.919

Table 03: Binary logistic model

Indicators	Category of Indicators	Coefficient β	S.E.	Exp(B)	95% Confidence Interval for Exp(B)	
					Upper	Lower
Season of Accident	Autumn	-0.302	0.803	0.739	0.153	3.569
	Late Autumn	-0.302	0.803	0.739	0.153	3.569
	Rainy Season	0.405	0.847	1.500	0.285	7.893
	Spring	0.050	0.836	1.051	0.204	5.410
	Summer	0.622	0.958	1.862	0.285	12.174
	Winter	1.588	1.107	4.892	0.559	42.850
Time of Day	Afternoon Rush	-0.305	0.699	0.738	0.187	2.906
	Afternoon Working	24.325	55.61	36651	0.000	∞
	Midnight to Dawn	-0.305	0.699	0.738	0.187	2.906
	Morning Rush	0.441	0.819	1.554	0.312	7.734
	Morning Working	0.779	0.761	2.179	0.490	9.681
	Night Time	0.401	0.761	1.554	0.312	7.734
Vehicle Type	Bus	1.588	1.107	4.892	0.559	42.850
	Easy Bike	-0.302	0.803	0.739	0.153	3.569
	Motor Cycle	0.405	0.847	1.500	0.285	7.893
	Pickup	0.050	0.836	1.051	0.204	5.410
	Private Car	0.622	0.958	1.862	0.285	12.174
	Truck	1.588	1.107	4.892	0.559	42.850
Vehicle Speed	Above 40 km/h	0.622	0.958	1.862	0.285	12.174
	Below 40 km/h	-0.302	0.803	0.739	0.153	3.569
Driver Age Group	25 Year to 55 Year	0.405	0.847	1.500	0.285	7.893
	Above 55 Year	0.622	0.958	1.862	0.285	12.174
	Below 25 Year	-0.302	0.803	0.739	0.153	3.569
Accident Location	Aranghata	-0.302	0.803	0.739	0.153	3.569
	Daulotpur	0.405	0.847	1.500	0.285	7.893
	Khalishpur	0.050	0.836	1.051	0.204	5.410
	Khan Jahan Ali Thana	0.622	0.958	1.862	0.285	12.174
	Khulna Sadar Thana	1.588	1.107	4.892	0.559	42.850
	Labonchora	0.405	0.847	1.500	0.285	7.893

	Sonadanga	0.622	0.958	1.862	0.285	12.174
Type of Accident	Motor Cycle Accident	-0.302	0.803	0.739	0.153	3.569
	Losing Balance Through Speed	0.405	0.847	1.500	0.285	7.893
	Crossing Collision	0.050	0.836	1.051	0.204	5.410
	Pedestrian Accident	0.622	0.958	1.862	0.285	12.174
	Truck Driving at Higher Speed	1.588	1.107	4.892	0.559	42.850
Collision Type	Head-On Collision	0.622	0.958	1.862	0.285	12.174
	High-Speed Collision	-0.302	0.803	0.739	0.153	3.569
	Rear-End Collision	0.405	0.847	1.500	0.285	7.893
	Road-Cross Accident	0.050	0.836	1.051	0.204	5.410
	Side-Swipe	0.622	0.958	1.862	0.285	12.174
Injury Severity	Grievous	0.405	0.847	1.500	0.285	7.893
	Minor Injury	0.622	0.958	1.862	0.285	12.174
	No Injury	-0.302	0.803	0.739	0.153	3.569
Accident Outcome	Died on the Spot	-0.302	0.803	0.739	0.153	3.569
	Died on the Spot & Seriously Injured	0.405	0.847	1.500	0.285	7.893
	Died Under Treatment	0.050	0.836	1.051	0.204	5.410
	Minor Injury	0.622	0.958	1.862	0.285	12.174
	No Injury	1.588	1.107	4.892	0.559	42.850
	Seriously Injured	0.405	0.847	1.500	0.285	7.893

The logistic regression results show that season, time of day, vehicle type, and location influence accident hotspot likelihood at varying levels. Higher coefficients and Exp(B) values for winter, night-time, and heavy vehicles (buses and trucks) indicate stronger associations with severe accident clustering. Locations like Khulna Sadar and Khan Jahan Ali Thana exhibit the highest odds ratios, confirming these as critical hotspot zones. Overall, the model highlights that temporal, spatial, and vehicle-related factors significantly determine accident intensity and spatial concentration in Khulna.

4. RESULT & DISCUSSION

The Getis- Ord Gi analysis showed statistically significant concentrations of road traffic accident (RTA) hot spots in Khulna City. The figure of the Z-score and p-value indicated that high-intensity accident zones were basically clustered around the Khulna Sadar, Khan Jahan Ali, and Sonadanga thanas. The major spatial clustering of fatal and serious-injury accidents was found in these areas that can be considered critical risk areas that need specific safety measures. Aranghata and Daulatpur, in contrast, showed relatively lower hotspot intensity, which corresponded to the relatively safer traffic conditions, as it was more concentrated in the major arterial streets and the intersection with high traffic flow, particularly during peak working hours. These findings were supported by the Kernel Density Estimation (KDE) heatmap, which revealed high density of crash concentrations along major arterial streets and intersections with high traffic flow, especially at peak working hours. Data were analyzed in three different periods, i.e., 2010-2012, 2013-2015, and 2016-2019, to determine the temporal change of hotspots of accidents. These maps clearly indicate that there was a significant variation in the intensity of accidents and spatial clustering during these periods. The hotspots of 2010-2012 (a) were widely scattered, with comparatively moderate values in the areas of Khulna Sadar and Sonadanga thanas, and it is possible to assume that the early phase of urban traffic jam can be observed. But in 2013-2015 (b), the trend has become more dense with several clusters along the areas of Khan Jahan Ali and Daulatpur indicating the growth of vehicular flow and urbanization during that time. The hotspot distribution further increased by 2016-2019 (c) with the Khulna Sadar, Khalishpur, and Sonadanga zones becoming the most critical areas of accidents with the highest frequency and severity along the principal transport routes in the city. The temporal variations between 2010 and 2019 could be explained by the urbanization and development of Khulna as the strengthening economy and cities in the country meant that development and traffic were concentrated at the center. The growth of economic activities in the regions of core areas caused an increased number of accidents within central zones as the density of vehicles and movement of people increased. These spatial observations are supplemented by the statistical results. The Chi-square test revealed that the time of a day is a significant factor on the formation of a hot spot ($p = 0.035$), where most of the accidents are experienced during the afternoons and at night. This implies that low visibility, fatigue by the driver and congestion are all factors that enhance the clustering of accidents at such moments. A very strong association was also revealed to exist between the accident location (police thana) [$p = 0.000$] as well supporting the notion that the occurrence of accident is not due to chance but rather dependent on the location of certain urban traffic areas. Conversely, vehicle type ($p = 0.962$) and vehicle speed ($p = 0.945$) did not have any significant statistical value and hence the spatial environment and driving behavior have a greater influence than types or speed of vehicles involved. In addition, driver age group ($p = 0.041$) and the outcome of an accident ($p = 0.004$) were also identified to be significant predictors of the intensity of hotspots. Severe accidents were more often related to younger drivers and with the age group of between 25 years to 55 years, the fatal and serious-injury accidents were more localized in the various hotspots displaying a moderate positive spatial relationship (Cramer V = 0.269).

The logistic regression model (with Nagelkeke r^2 of 0.462) states that the Agence of spatial, temporal, and human factors can explain almost half of changes in hot spot occurrence. It was found that buses and trucks have a higher coefficient, which indicates that the crashes are more serious in case of buses and trucks, as it is indicated by Hossain and Zaman (2021) and Khatun et al. (2024). The combination of the maps and the statistical outputs indicate that hot spot areas are concentrated mostly in highly populated areas, poor road geometry and mixed types of vehicles whereas those areas which are at the edge like Aranghata are at relatively lower levels of accidents.

In general, the fact that spatial and statistical analyses are integrated shows that the seasonal locations of accidents in Khulna are not only persistent but also increasingly intense with time (2010-2012), which speaks of an increasing urban mobility crisis. The results highlight the necessity of having localized road safety measures such as better lighting, road signs and traffic control in high-risk zones and better-driving awareness program involving night-time and congested-hour driving. KDE + Gi techniques combination, therefore, offers a strong platform in the determination and dealing of critical parts of accidents prone areas in order to promote the sustainable urban traffic safety planning of the Khulna City.

5. CONCLUSIONS

The research indicates that the hotspots of road traffic accidents clearly concentrate in major urban centres of Khulna, and there is an urgent necessity of strategic interventions in terms of the safety issues. The results support the need to have policy-based planning which involves incorporation of spatial data in the management of the urban areas. The government must focus on bettering the infrastructure, controlling night time traffic, and social sensitization of high risk areas. Monitoring systems based on GIS implemented in the city planning can facilitate the decision-making beforehand and the appropriate management of mobility. Improving the liaisons between transport planning, law enforcement, and communal education will be key towards having safer roads and attaining the national and global objectives of road safety.

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