Spatial analysis of traffic accidents on federal highways in the State of Alagoas

João Vítor de Oliveira Santos[1[0009-0008-8440-5545]], Jonhatan Magno Norte da Silva[1[0000-0003-4084-9511]] and Lucas Gomes Miranda Bispo[2[0000-0002-5305-6257]]

[1] Federal University of Alagoas – Campus do Sertão, Highway AL-145, Delmiro Gouveia, Brazil
[2] Federal University of Rio Grande do Sul – Postgraduate Program in Production, Avenue Osvaldo Aranha 99, Porto Alegre, Brazil
jonhatan.silva@delmiro.ufal.br

Abstract. Brazil is among the countries with the highest mortality rates related to traffic accidents. The State of Alagoas, in turn, has seen significant increases in its fleets in recent years, and as a result, traffic problems have intensified. Therefore, this study aims to conduct a spatial analysis of federal highways in the State of Alagoas to identify critical municipalities where traffic accidents occur. Based on records of road accidents between 2014 and 2018, we conducted an exploratory analysis of spatial data and georeferencing using Geographic Information Systems (GIS). In this context, choropleth maps and the Moran index (I) were used, with a significance level of 5%, to observe and associate factors related to accidents, such as causes, phase of the day, and severity. The factors that presented the most significant univariate spatial autocorrelation were total accidents (I=0.345), lack of attention and keeping a safe distance (I=0.339), dangerous overtaking (I=0.336), slippery road (I=0.270), ingestion of alcoholic beverages and psychoactive substances (I=0.268), disobeying traffic rules (I=0.259), late-night (I=0.338) and serious injuries (I=0.300). The maps showed a high incidence in BR-101, BR-104, and BR-316 for georeferencing. Therefore, it is concluded that the northeast region of the State of Alagoas, with the municipalities of Pilar and Rio Largo, are the critical regions and locations for traffic accidents, respectively.

Keywords: Road accident, Georeferencing, Moran index.

1 Introduction

Traffic accidents have become a direct consequence of the significant increase in road transportation. The various variables of society, whether positive or negative, point to a complex system composed of factors that ultimately lead authorities to create policies and measures to reduce the number of accidents [1].

According to the World Health Organization (WHO), over 1.3 million people are killed annually, and between 20 to 50 million are injured due to traffic accidents in low- and middle-income countries [2]. Brazil ranks fifth in the highest number of traffic deaths [3]. Although the traffic system comprises three key elements (vehicle, user, and road), approximately 90% of accidents are linked to driver error through law violations or mistakes. Thus, the driver plays a pivotal role in ensuring safety and preventing accidents [4].

Brazil's social and diplomatic conditions still imply a lack of planning and investment in road maintenance, exacerbating issues with traffic accidents [5]. According to the Institute of Applied Economic Research (IPEA), accidents on Brazilian highways, including state and federal roads, cost approximately R$ 41 billion [6], representing a significant amount for public coffers.

Using spatial statistical tools has gained prominence in addressing and making decisions regarding common issues in the population. Studies related to risk mapping and health [7], agriculture, vegetation, and soils [8,9], socio-economic aspects [10], public safety information, and planning [11] have gained prominence in the current scenario. In the scientific literature, one can find works utilizing tools and techniques for spatial analysis in traffic safety [12-18]. In Brazil, studies focusing on point patterns, networks, and areas stand out [5, 13, 19-21]. However, no road studies were found regarding the state of Alagoas, making the spatial distribution of traffic accidents on federal highways unknown.

In light of this, the quest to understand spatial events occurring at specific positions, with varying incidence levels over a certain period, is one of the approaches responsible agencies utilize to analyze the interrelationships among different types of accidents [22]. The use of data that highlights a potential diagnosis, the dimensions of the accident, and the characteristics of the problem to be addressed are of paramount importance for potential solutions. Accident records serve as the primary sources of information regarding road issues, as the foundation for conducting a study and subsequently implementing measures to reduce these rates [23].

The state of Alagoas has an approximate area of 27,768 km², featuring a road network spanning 30 state highways and 6 federal highways. The federal highways connect the state with the rest of Brazil. In Alagoas, the BR-104, BR-110, BR-316, BR-423, BR-424, and BR-101 are considered highly important as they connect many states in the Northeast region.

According to the State Department of Traffic of Alagoas (DETRAN-AL), the vehicle fleet in Alagoas grew approximately ninefold between 1991 and 2011 [24]. From 2013 to 2017, an average of 41,200 vehicles were added to the fleet yearly, representing an average growth of 20.95% in the state, totaling more than 789,000 vehicles. The cities of Arapiraca and Maceió stand out with the most significant growth. With the increase in the vehicle fleet, the occurrence and possibilities of traffic accidents automatically increase.

Regarding accident costs, in 2012, the state of Alagoas totaled approximately R$ 251.392.800,00, of which accidents on federal highways accounted for around R$ 139.015.680,00, representing 55.29% of the total. According to the DETRAN-AL balance sheet [25], with this amount, it would be possible to build 4 hospitals with Intensive Care Unit (ICU) or even purchase more than 1,680 ambulances with mobile ICU. Therefore, it is important to seek solutions that minimize the occurrence of traffic accidents to make highways safer [20]. However, it is necessary to understand the spatial distribution of accidents and the trends in data behavior to make possible decisions regarding the problem.

Using Geographic Information Systems (GIS) and spatial analysis-related statistical methodologies in transportation areas produces results with a certain level of reliability, making them more accurate than conventional models. As a result, benefits such as cost reduction stem from implementing these tools, contributing to better road transportation planning and control [19]. Queiroz [12] states that reducing the impacts resulting from traffic can be achieved through a set of measures associated with certain elements of the system (human, road, environment, and vehicle). Therefore, identifying critical locations and seeking viable solutions depend on knowledge about these elements.

Furthermore, considering the scarcity of studies in the field regarding the state of Alagoas, analyzing and understanding the registration processes, accident rates, main factors conducive to the occurrence of events, and planning undertaken by responsible agencies will directly contribute to the formulation of prevention policies on the federal road network. In light of the above, the objective of this article was to conduct a spatial analysis of traffic accidents on Brazilian highways in the state of Alagoas to identify the municipalities with the highest incidence of these incidents.

As a state with thirty-six highways, Alagoas experiences a notable number of traffic accidents. In this study, only federal highways will be analyzed because their direct connection with the states of Sergipe, Pernambuco, and Bahia makes road transportation part of a continuous flow, fluctuating considerably at any time of the day and increasing the probability of traffic accidents. Therefore, the highways used for the analysis in this study are divided among BR-104, BR-110, BR-316, BR-423, BR-424, and BR-101.

2 Methods

2.1 Database

For this study, data from 2014, 2015, 2016, 2017, and 2018 (January to October) were utilized, sourced from DETRAN-AL and the Federal Highway Police (PRF). A data cleaning process was carried out to remove duplicates and errors in the accident records in an attempt to increase the reliability of the analyses. The database provided the following information:

- Accident location: includes data such as date, time, geographic coordinates, kilometer marker, municipality, and highway (BR);
- Accident type: brief description of accidents (side collision, rear-end collision, frontal collision, lateral collision, impact, overturning, and rollover);

- Accident cause: describes potential accident causes (animals on the road, tire damage or wear, excessive or improperly secured cargo, driver falling asleep, vehicle mechanical failure, road defects, inadequate vehicle signaling, traffic rule violations, lack of attention, natural phenomena, alcohol consumption, sudden illness, failure to maintain a safe distance, static object on the roadway, slippery road surface, visibility restrictions, insufficient or inadequate road signage, improper passing, and speeding);
- Imposed conditions: time of day (dawn, daytime, dusk, nighttime), weather conditions (clear sky, rain, drizzle, fog, cloudy, sunny, and windy), road type (single, dual carriageway), and road conditions (straight, curved, temporary detour, intersection, bridge, roundabout, tunnel, and overpass);
- Vehicle data: information related to vehicle type (car, moped, motorcycle, minibus, bus, truck, pickup truck, quad bike, wheeled tractor, semi-trailer, or trailer), year of manufacture, and brand;
- Personal identification: age, gender (male or female), individuals involved (driver, passenger, pedestrian, cyclist, or witness);
- Risk classification: the individual's physical condition (uninjured, minor injury, serious injury, or death).

2.2 Data consistency analysis and variable selection

Considering the use of a database about the state of Alagoas, a data consistency analysis was conducted. Teixeira [22] outlines several criteria to avoid potential location errors and consequent analysis errors, including identifying and correcting data with the same name but different spellings, examining the exact locations of the involved roads, and identifying and handling records that do not allow for complete localization. This approach makes it possible to validate inconsistent data.

After completing this process, the variables to be used in the models were defined. The selection was made through a comparison between different years under analysis. Upon observing the database, it is noted that most accident-causing factors used between 2014 and 2016 were related solely to factors considered human, whereas after 2017, additional factors were included. Therefore, the following variables were chosen: Accident cause, time of day, and accident severity.

2.3 Mapping traffic accidents

Accidents in 2017 and 2018 were utilized due to their spatial references (latitude and longitude). After selection, the data was exported to version 3.6.0 of the Quantum GIS (QGIS) software [26], a multifaceted Geographic Information System (GIS) platform providing visualization of georeferenced data.

According to Santos [5], this process aims to associate each accident in the database with its respective locations on the maps, which objects or points can represent. The article added a vector layer of the state of Alagoas and federal highways in shapefile (SHP) format for road map plotting. Subsequently, a delimited text layer was added from a text file extension (.csv) to create a point layer referenced through latitude and longitude later, thus mapping the locations where accidents occurred during this period.

2.4 Statistical procedure

The statistical treatment was performed using version 1.12 of the GeoDa software [27]. Several steps were outlined to facilitate the study. In the first step, critical areas and points of accidents were identified. A natural breaks choropleth map was used to identify natural groups, ensuring maximized variation between accident locations. Additionally, a scatterplot was used to analyze spatial associations (through Moran's Index) of municipalities with distinct values from their neighbors, subsequently represented by a BoxMap [18]. The Moran index (I) can be calculated using the Equation 1:

$$I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \bar{x})}{S_o \sum_{i=1}^{n}(x_i - \bar{x})} \; ; S_o = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \quad (1)$$

- n represents the number of observation locations.
- x_i denotes the observed value in location i.
- x_j denotes the observed value in location j.
- $\bar{x}$ represents the average value of all observations.
- w_{ij} denotes the weighting matrix element between locations i and j.

Thus, Global Moran's Index compares each point to an average value. Values close to 1 and -1 indicate positive and negative correlation, respectively. Therefore, a value close to 1 means that it can contribute to the occurrence of accidents. Values close to -1 reduce the probability of accidents. Values close to 0 indicate no spatial correlation or spatial randomness.

The second step involved using local indicators of spatial association (LisaMap) and significance BoxMap to determine regions and zones where autocorrelation is treated more significantly. Considering each variable individually, a spatial significance of 95% with 99 permutations was used [28].

3 Results

3.1 Descriptive analysis of acidentes

Among the 6,313 records of traffic accidents that occurred during the period (Table 1), 2017 stands out (32.03%). Accidents with uninjured victims (52.60%), occurring on Sundays (16.81%), involving collisions (53.1%), during daylight hours (53.85%), on straight roads (59.78%), with single lanes (82.69%), and in rural areas (74.02%) were the most common events. Analyzing the geographical distribution of accidents, a high predominance is observed on the federal highways BR-101, BR-104, and BR-316 (Fig. 1).

Table 1. Table captions should be placed above the tables.

Variable	n (%)	Variable	n (%)
Nature of Accidents		Registered Accidents	
Rollover	478 (7.6)	2014	1529 (24.22)
Overturn	467 (7.4)	2015	1071 (16.96)
Run-off-road	1063 (16.8)	2016	951 (15.06)
Vehicle fall	220 (3.5)	2017	2022 (32.03)
Cargo spillage	39 (0.6)	2018	740 (11.72)
Collision	3415 (54.1)	Severity	
Run over (animal/person)	563 (8.9)	Uninjured	5068 (52.60)
Fire	35 (0.6)	Slightly Injured	2544 (26.40)
Other damages	11 (0.2)	Severely Injured	1536 (15.94)
Not reported	22 (0.3)	Dead	487 (5.06)
Time of day		Road	
Dawn	350 (5.54)	Intersection	206 (3.26)
Daytime	3399 (53.85)	Straight	3774 (59.78)
Dusk	333 (5.27)	Curve	1862 (29.49)
Nighttime	2231 (35.34)	Others	205 (3.25)
Day of the week		Not reported	266 (4.21)
Sunday	1061 (16.81)	Lane	
Saturday	972 (15.40)	Single	5220 (82.69)
Friday	945 (14.97)	Double	1068 (16.92)
Thursday	833 (13.19)	Multiple	25 (0.39)
Wednesday	828 (13.12)	Environment	
Tuesday	780 (12.36)	Rural	4673 (74.02)
Monday	894 (14.16)	Urban	1640 (25.98)

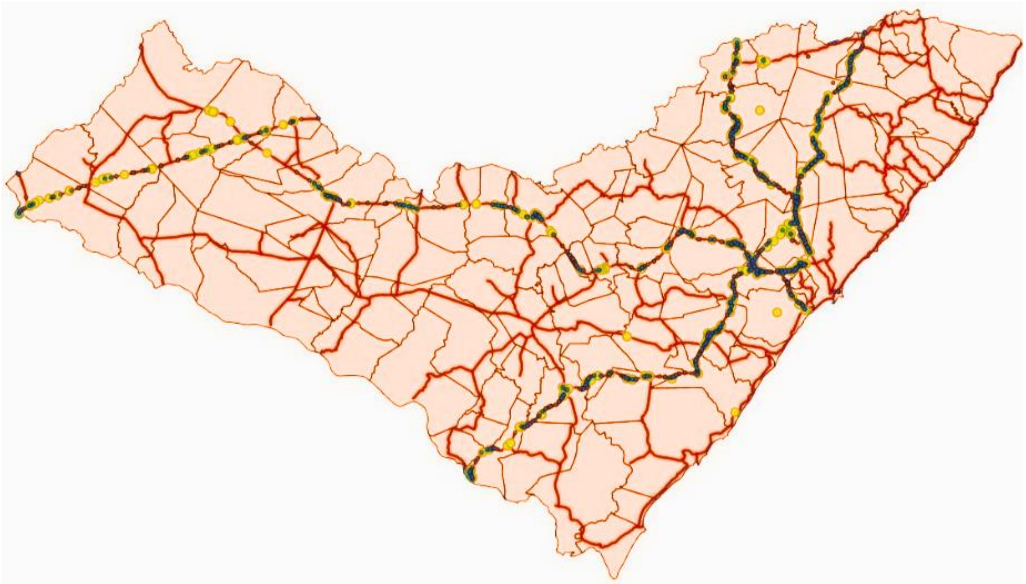

Fig. 1. Georeferencing of accidents in 2017 and 2018. The purple and yellow points indicate the locations where the incidents occurred in 2017 and 2018, respectively.

3.2 Identification of critical areas

To identify the municipalities with the highest incidence of traffic accidents, the choropleth map with absolute values (Fig. 2) highlighted eight cities that fell within high occurrence indices. It was found that areas represented by the brown color are the municipalities of Pilar (n = 660) and São Miguel dos Campos (n = 537). At the same time, those in orange are the municipalities of Satuba (n = 322), Atalaia (n = 382), Rio Largo (n = 531), São Sebastião (n = 249), União dos Palmares (n = 384), and Messias (n = 259). Another 15 municipalities stand out in accident occurrence: Delmiro Gouveia, Canapi, Santana do Ipanema, Palmeira dos Índios, Porto Real do Colégio, Teotônio Vilela, Branquinha, Jequiá da Praia, Joaquim Gomes, Junqueiro, Maceió, Murici, Novo Lino, and São José da Laje.

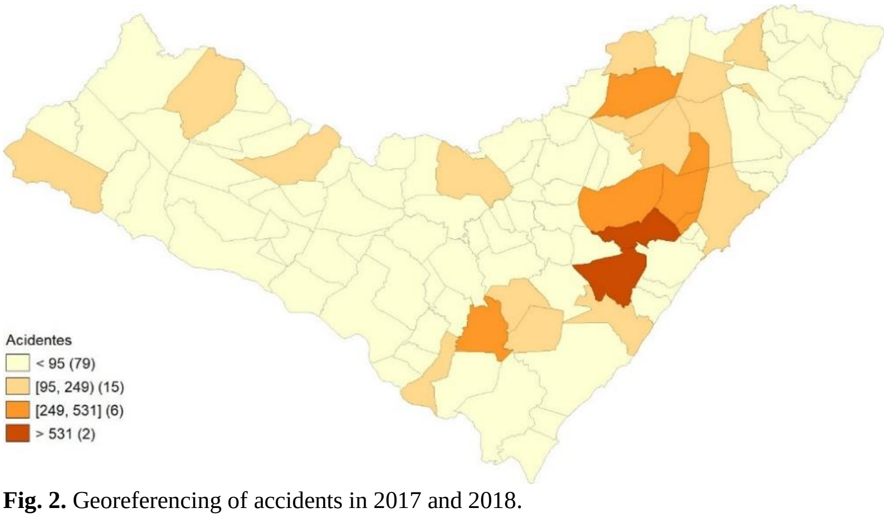

Fig. 2. Georeferencing of accidents in 2017 and 2018.

Regarding spatial associations for the number of accidents (Fig. 3), the scatterplot presented a Global Moran's Index of 0.345 (p-value of 0.001) for the entire state. Through the LisaMap (Fig. 4), it can be observed that the Northeast region of the state, marked in red, presents a High-High index for 8 municipalities and, in light blue, a Low-High index for 2 municipalities. Meanwhile, the Central-West region of the state showed a grouping of 11 municipalities with a Low-Low index, represented by the color blue. No High-Low associations were found.

The map significance (Fig. 5) found that the same Northeast region presented more significant values, with a p-value of 0.01 for six and 0.001 for three municipalities. Meanwhile, the Central-West region showed predominance with p-values slightly lower than 0.05 for eight municipalities. Therefore, these results were considered significant at a significance level of 5%.

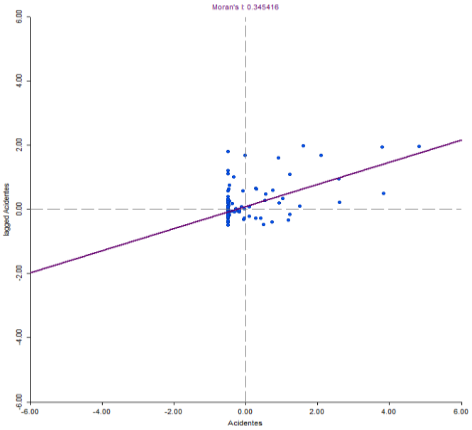

Fig. 3. Scatterplot of accidents.

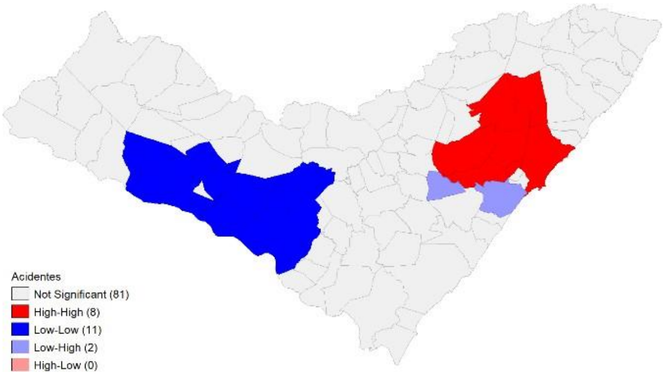

Fig. 4. LisaMap for the number of accidents.

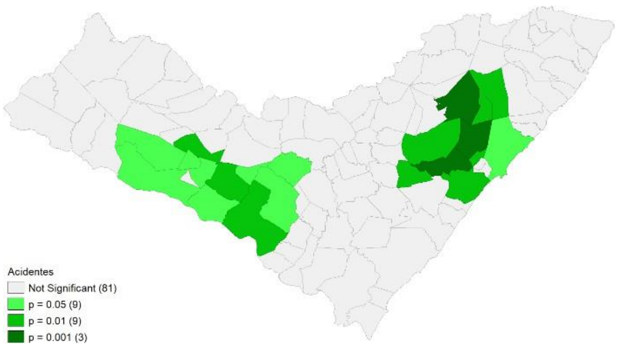

Fig. 5. Significance BoxMap of accidents.

3.3 Moran's Index analysis for associations

Regarding the causes of accidents, the Global Moran's Index (I) was analyzed for 14 contributing factors (Table 2). The vast majority of I values showed a positive association. Among these, factors such as animals on the road, mechanical defects, lack of attention and failure to maintain a safe distance, dangerous overtaking, incompatible speed, driver falling asleep, disobedience to traffic rules, alcohol and psychoactive substance consumption, slippery road, and road defect contributed to traffic accidents in certain municipalities. Regarding the time of day and severity, it is observed that all factors obtained a positive and significant association. Some factors show indices close to 0.30 and 0.34 (daytime, dusk, nighttime, uninjured, and seriously injured), indicating spatial dependence.

Table 2. Results of the Global Moran's Index (I) for the causes of accidents.

Variable	I	p-value	Variable	I	p-value
Cause of Accidents			Time of day		
Animals on the road	0.120	0.04	Dawn	0.192	0.03
Mechanical Defects	0.219	0.01	Daytime	0.337	0.01
Sudden Illness	0.008	0.27	Dusk	0.336	0.01
Dangerous Overtaking	0.336	0.01	Nighttime	0.338	0.01
Incompatible Speed	0.249	0.01	Severity		
Driver Falling Asleep	0.165	0.01	Uninjured	0.333	0.01
Physical Aggression	-0.007	0.31	Slightly Injured	0.289	0.01
Disobeying Traffic Rules	0.259	0.01	Severely Injured	0.300	0.01
Slippery Road	0.270	0.01	Dead	0.256	0.01
Natural Phenomena	0.052	0.18			
Tire Defect	0.022	0.25			
Vehicle Stopped on the Roadway	-0.042	0.29			
Road Defect	0.190	0.03			
Lack of Attention and Failure to Maintain a Safe Distance	0.339	0.01			
Alcohol and Psychoactive Substance Consumption	0.268	0.01			

4 Discussion

Using spatial statistics with highway accident data can generate valuable insights for traffic managers. Through georeferencing, there was an indication of larger clusters of points in the state's northeastern region. This fact, highlighted by Brandão [14], underscores the procedures for identifying critical points, emphasizing the tendency of certain occurrence locations to aggregate despite a widespread spatial distribution of events across the road network.

Previous studies assure that the utilization of Geographic Information Systems for identifying points and areas has proven effective, contributing to the development of plans for accident reduction [29-33]. Thus, the BR-101, BR-104, and BR-316 highways, which encompass this region, become significant when viewed through georeferencing, especially as they are routes leading to neighboring cities and states to the capital of Alagoas, Maceió.

In contrast, BR-424, BR-110, and BR-423, when analyzed in terms of extension and compared to BR-101, BR-104, and BR-316, become less significant. Moreover, two of them are located in one of the least populated regions of the state, the Sertão. However, Bottesini and Nodari [4] emphasize that the causes of accidents are associated with various factors, including driver behavior and performance.

The conditions imposed on drivers, such as the type of road and direction, are relevant aspects when it comes to identifying critical points. According to Salvador [34], single-lane roads with opposite directions are used as main traffic routes for tourist or mountainous regions, requiring highly complex operations. These factors characterize the northeastern region of Alagoas. In this region, a high index was observed in cities like Pilar, São Miguel dos Campos, and Rio Largo.

The city of Pilar, in turn, is crossed by three federal highways (BR-101, BR-316, and BR-424), triggering a continuous and high flow of cars. According to IPEA [6], the higher the traffic volume, the greater the existing conflicts in the area, consequently increasing accident rates. Therefore, the possibility of the municipality being in a critical zone increases. The municipalities of São Miguel dos Campos and Rio Largo follow the same model as Pilar; being border cities, their highways complement each other, resulting in a high flow of vehicular traffic.

However, when analyzing the High-High indices, it is observed that the city of São Miguel dos Campos does not present significant values to be included in the grouping, justified by a more discrepant value than its neighbors and possibly situated in a transition zone. The cities of Atalaia, Flexeiras, Maceió, Murici, Messias, and Satuba present values above the average, characterized as positive clusters.

For the Low-High index, spatial dependence grouped the Marechal Deodoro and Boca da Mata municipalities, showing a negative average for accident values. However, neighboring municipalities have positive averages, and the cities are possible risk areas. Regarding Boca da Mata, federal highways are nonexistent, but it has road networks connecting state highways, such as AL-105 to BR-101 and AL-215 to BR-316.

The Low-Low indices for the Central-West region of the State, with a negative global Moran's index, reveal that the occurrence of accidents in this area is unlikely due to the absence of federal highways passing through the cities. Therefore, the municipalities of Batalha, Belo Monte, Craíbas, Girau do Ponciano, Jacaré dos Homens, Jaramataia, Monteirópolis, Olho D'Água das Flores, Pão de Açúcar, São José da Tapera, and Traipu are exempt from statistics related to the national traffic road network.

The other municipalities did not show significance when only the overall accident factor was analyzed. For example, the city of São Miguel dos Campos presents transition areas where it is impossible to identify whether critical zones exist. However, this does not mean that some of these cities are not critical locations when other factors are analyzed. Thus, it is specified that there is a need not only to understand the behavior of these processes but also to seek the relationship with other spatial phenomena in these areas.

In terms of Moran's Index, it was observed that factors associated with human actions showed the best indices for spatial dependence, such as driver inattention and failure to maintain a safe distance, unsafe/overtaking, and alcohol and psychoactive substance consumption. However, the institutional factor, non-compliance with traffic regulations, and the roadway factor, slippery road surface, are also part of this group.

The factor of driver inattention and failure to maintain a safe distance stands out among the other factors, as it has the most significant result. Previous studies have shown that inattention is one of the main causes of accidents in Brazilian territory [1, 35]. According to Balbinot et al. [36], various factors can distract a driver's attention and performance, so understanding their psychological and cognitive functions while driving is essential to reduce these events. The driver's proactivity is crucial in deciding which movements, spaces, and times are necessary to avoid an accident. Andrade et al. [37], note the need for studies evaluating the fundamental causes of distractions in traffic, raising numerous questions about measures to take. However, they point out that the lack of basic safety requirements within the vehicle and fewer traffic enforcement points contribute to increased traffic accidents.

It is important to highlight that in previous studies [4], it is suggested that safety measures associated with restrictions on rights and those that offer the possibility of being caught by authorities influence drivers to commit fewer infractions. In the study by Rueda and Gurgel [38], when applying a Test of Concentrated Attention (TEACO-FF) for drivers, it was observed that the level of education and the type of driver's license sought by users (paid and unpaid) showed significant results. That is, these are factors that, due to the lack of norms ensuring control, directly impact driver inattention and subsequently lead to traffic accidents. Chagas [23] shows that the attention factor not only requires demands from drivers but also from pedestrians, as improper positioning, careless movement, and haste can lead to accidents. Therefore, safety measures taken for this factor should be relevant enough to ensure the occurrence of traffic problems for both drivers and pedestrians.

The factor of dangerous/improper overtaking and the consumption of alcoholic beverages and psychoactive substances being closely linked to driver attention, the rates found for this type of accident become significant. Authors like Marín and Queiroz [39] discuss the relationship between these factors and their potential social problems. The scarcity of exploratory works addressing data related to the factor of dangerous/improper overtaking is still high. However, Almeida et al. [35] establish associations to identify how critical federal highways in the state of Mato Grosso were in 2004 and show, through results, that the relationship of this factor with imposed conditions and other factors exhibits some significance.

Damacena et al. [40] present a set of sociodemographic factors that, when linked to abusive and frequent alcohol consumption, become significant for the occurrence of traffic accidents. Campos et al. [41] point out that Brazilian studies indicate that male students aged 25 to 34 are the group with the highest frequency of drinking and driving after consumption. Alves and Gomes [42] highlight principles of psychology in which driving is a basic condition that requires maintaining proper health and dispensing with alcoholic beverages or substances, as they ensure organization in the road system, compliance with traffic rules, and a natural driver behavior. In other words, there is a dependence between natural and psychological factors, and when treated correctly, they can reduce social problems, including traffic accidents. However, identification and treatment are variables that require specific studies to be conducted.

Understanding what leads the driver to violate them becomes complex due to disobedience to traffic laws. Bottesini [43] analyzes the relationship of behaviors related to traffic safety regulations, revealing that the human element is the main contributing factor to traffic accidents, with a significant portion due to violations and infractions of traffic laws. Additionally, it highlights that factors such as the driver's age and gender are determinants to understanding the profile of individuals fitting into this context. Disregarding traffic laws has been significant for motorcycle riders, especially for couriers [44,45], justified by the short delivery time. This aspect can be extrapolated to the current reality, where people have less time to complete their tasks and, feeling overwhelmed, end up disregarding traffic signals. Queiroz and Oliveira [46] emphasize in their work with drivers that it is not enough to have strict laws if they are not applied to everyone and if there is no efficient enforcement. A previous study [47] also reveals critical zones in the city of Vitória – ES, with the main cause being the disregard for traffic safety regulations, both by drivers and pedestrians. That is, the influencing characteristics are associated with anyone, regardless of their societal position.

Regarding slippery roads, they are associated with issues where the road surfaces are exposed. Andersson and Chapman [48], in their analysis of the impact of temperature on traffic accidents in the UK, observed that winter weather directly affects this index, increasing incidents related to slippery roads. When it comes to weather, rains are the main contributors to traffic problems, as they, through various physical effects, create disruptions on road networks, including loss of friction between the tire and the road [49]. Other factors include road maintenance. Eisenberg [50] specifies that after long periods of drought followed by rain, accumulated oil on the roads can lead to potential traffic accidents. Therefore, monitoring and oversight by transportation departments regarding road maintenance are essential to prevent events that contribute to worsening traffic casualties. In Brazil, studies highlighting the cause of slippery roads were not found.

For the different times of day, significance was found for all cases, with the highest spatial index for nighttime, daytime, dusk, and dawn, respectively. In these areas, there are no decisive phases for accidents, but somewhat inherent characteristics of the locations that facilitate the occurrence of events. Studies by Brazilian agencies (CNT, 2018) show a disparity in results accumulated between 2007 and 2017, with daytime (53.4%) and nighttime (35.0%) periods being more conducive to traffic problems. Cabral [51] explains that the low frequency of accidents at dawn is linked to the driver's bodily and mental restoration; low levels of fatigue, hunger, and sleepiness promote ideal behavior in traffic. Oliveira and Sousa [52], on the other hand, highlight that the reason for the higher occurrences during late afternoon stems from contributions related to various physical conditions, including pressure, anxiety, and stress.

Regarding severity, the values found indicated spatial correlation for all classes: uninjured ($I=0.333$), seriously injured ($I=0.300$), lightly injured ($I=0.289$), and dead (0.256). Studies evaluating accident severity in many countries can be found in the literature [53-56]. This reveals an eminent concern with this factor, as it is directly linked to the citizen's life. It is important to highlight that the category of people involved in this type of event is crucial for the greater severity, as those involved in an accident may be in a motor vehicle, on foot, or even on an animal, and due to safety mechanisms, it is known that pedestrians, motorcyclists, and cyclists are in vulnerable groups [57]. Works seeking to understand the variables associated with this group are more common than for other types of vehicles. Ramos [58] further states that many other factors contribute to the severity of a traffic accident, and their identifications are necessary.

The northeastern region of the state of Alagoas and the Zona da Mata showed significant values for the factors of dangerous overtaking, disregard for traffic rules, lack of attention, and failure to maintain a safe distance. When analyzing the Agreste and Sertão regions, the city of Delmiro Gouveia showed significant values for more than one factor, including disregard for traffic rules and slippery road conditions.

It is worth noting that accidents generate consequences for public health, economic costs, and impacts on social well-being. Accidents can leave visible consequences (various injuries, disabilities, and deaths) but also invisible ones related to post-traumatic stress disorders, travelphobic anxiety, and depression [59]. Although the value of human life cannot be quantified in monetary value, it is estimated that the costs of such accidents amount to R$41 billion [6]. The accident also impacts the family and friends of those involved, reducing many people's quality of life and ability to work [59, 60]. Furthermore, safe and inclusive transport provides access to socioeconomic and life-enhancing opportunities [61], promoting better social well-being. Therefore, accident prevention has gained in different spheres of society.

This article has limitations. The first was using secondary data, which increases the likelihood of errors. Another significant area for improvement was the use of univariate models. Bivariate models better explain the causes of accidents on highways. Future studies can perform Bivariate analyses by crossing information from this study with other information related to road conditions, weather patterns, and traffic density. Another limitation of this research is that the data comes exclusively from road records. Multiple sources (police reports, hospital records, and insurance claims, for example) could complement and validate the data collected. Future studies may also identify significant predictors of accidents through regression models. In the same way, they could consult public managers, pedestrians, and drivers about the proposed interventions to ensure or increase their effectiveness.

5 Conclusion

This article analyzed traffic accidents on the federal highways of the state of Alagoas through georeferencing and spatial autocorrelation to identify critical regions. Georeferencing indicated a concentration of accidents on highways BR-101, BR-104, and BR-316. The northeast region of Alagoas demonstrated that factors such as lack of attention and failure to maintain a safe distance, alcohol and psychoactive substance consumption, dangerous overtaking, disobedience to traffic rules, and slippery roads contribute to a higher number of traffic accidents in the region, and consequently, in the state.

The most critical cities during the analysis were Pilar and Rio Largo. However, each city has its peculiarities. The danger drivers face in the northeast region of Alagoas is real because, in addition to factors related to the time of day, the region is crossed by highways BR-101, BR-104, and BR-316.

The pursuit of new methods and solutions to achieve a reduction in traffic accident rates becomes essential for state authorities. Establishing stringent policies that encourage drivers to perform basic safety procedures, adhere to enforcement regulations, and undergo behavioral assessment tests in traffic ensures improvements in factors such as lack of attention and failure to maintain a safe distance, dangerous overtaking, and disregard for traffic signals. Programs aimed at eliminating the use of alcohol and psychoactive substances, coupled with new laws, increase public awareness and decrease accident statistics. Other factors like road maintenance are also crucial, making traffic accidents less likely. Therefore, knowledge of critical regions and locations prompts drivers to act with greater prudence and responsibility. At the same time, authorities heavily monitor the analyzed area, fostering a harmony that promotes traffic safety, reduces casualties, and enhances social well-being. Thus, the results reinforce, in a certain way, the need for public managers to seek alternatives that combine methods of calming traffic, improving road infrastructure, increasing the application of traffic laws, and improving public awareness campaigns. Public about safe driving practices.

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