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SPATIAL AND TEMPORAL ANALYSIS OF TRAFFIC ACCIDENTS IN THE FEDERAL DISTRICT ROAD SYSTEM, BRAZIL (2014–2023)

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ABSTRACT

This study aims to analyze the spatial and temporal patterns of traffic accidents on the Road System of the Federal District, Brazil, between 2014 and 2023, based on 16,865 georeferenced records. The methodology integrates inferential statistical techniques and spatial analysis tools using Geographic Information Systems. Analysis of Variance (ANOVA) and Tukey's post hoc test were applied to daily accident counts, grouped into two-hour time slots and days of the week, in order to assess whether incidence varied significantly across temporal categories. Spatial clustering was examined through Hot Spot Analysis using the Getis-Ord Gi* index to detect areas of high and low accident concentration. Additionally, Geographically Weighted Regression was used to model the localized effects of explanatory variables including elevation, per capita income, and average daily traffic. The results reveal statistically significant spatial patterns and temporal differences, highlighting the relevance of geospatial approaches in evidence-based traffic safety planning and territorial management.

Keywords: Spatial analysis. Traffic safety. Geographically Weighted Regression.

ANÁLISE ESPACIAL E TEMPORAL DOS SINISTROS DE TRÂNSITO NO SISTEMA RODOVIÁRIO DO DISTRITO FEDERAL, BRASIL (2014–2023)

RESUMO

Este estudo tem como objetivo analisar os padrões espaciais e temporais dos sinistros de trânsito no Sistema Rodoviário do Distrito Federal, Brasil, no período de 2014 a 2023, com base em 16.865 registros georreferenciados. A metodologia integra técnicas estatísticas inferenciais e ferramentas de análise espacial por meio de Sistemas de Informação Geográfica. Foram aplicadas a Análise de Variância (ANOVA) e o teste de Tukey para avaliar a influência de variáveis temporais, como o horário do dia e o dia da semana, na gravidade dos sinistros. A aglomeração espacial foi examinada por meio da Análise de Hot Spots, utilizando o índice Getis-Ord Gi*, a fim de identificar áreas de alta e baixa concentração de sinistros. Adicionalmente, foi empregada a Regressão Ponderada Geograficamente para modelar os efeitos localizados de variáveis explicativas, incluindo altimetria, renda per capita e tráfego médio diário. Os resultados revelam padrões espaciais estatisticamente significativos e diferenças temporais relevantes, evidenciando a importância das abordagens geoespaciais para o planejamento da segurança viária com base em evidências e para a gestão territorial.

Palavras-chave: Análise espacial. Segurança viária. Regressão Ponderada Geograficamente.

INTRODUCTION

The growth of the vehicle fleet and the intensified use of road networks have contributed to rising traffic accident rates in various urban and highway areas around the world. According to the World Health Organization (WHO, 2019), traffic accidents are responsible for approximately 1.3 million deaths per year, mainly affecting the most vulnerable users, such as motorcyclists, cyclists, and pedestrians. In Brazil, the scenario is equally alarming, with more than 31,945 deaths recorded in 2019, placing the country among the world leaders in traffic mortality (DENATRAN, 2021).

By December 2023, the Brazilian vehicle fleet had reached 119.2 million vehicles. In the same period, the Federal District, with an estimated population of 2,817,381 inhabitants, had 2.08 million registered vehicles, indicating a high motorization rate per capita (IBGE, 2023). This scenario accentuates the impact of transport accidents on urban mobility, road infrastructure and, above all, public health. Furthermore, the spatial distribution of these events is uneven, with recurrent concentrations on critical segments of the road system. These patterns reinforce the need for geospatial analysis to identify risk zones and propose more effective and targeted public interventions.

The use of Geographic Information Systems (GIS) has proven effective in detecting spatial patterns of traffic accidents, enabling a detailed understanding of accident distribution and the influence of environmental and infrastructural variables (Shafabakhsh et al., 2017; Ma et al., 2021). Among the most widely adopted methods is the Getis-Ord Gi* statistic, which identifies statistically significant spatial clusters—or hot spots—of accidents. This approach has been successfully applied in countries such as Malaysia, Iran, and Chile (Hisam et al., 2022; Truong; Somenahalli, 2011; Blazquez; Celis, 2013).

In addition to cluster analysis, more robust methods such as Geographically Weighted Regression have advanced the understanding of spatial heterogeneity in accident occurrence. These models enable local calibration of explanatory variables—such as traffic volume, road hierarchy, and land use, revealing spatial variability and overcoming the limitations of traditional global models (Jia et al., 2018; Wang et al., 2021).

Moreover, the development of interactive dashboards has emerged as a strategic tool in road safety management. These platforms integrate georeferenced traffic accident data with accessible visualizations and, increasingly, real-time inputs from Internet of Things (IoT) devices—such as sensors and surveillance cameras—facilitating dynamic monitoring and rapid response (Batty et al., 2012; Zanella et al., 2014). In the context of smart cities, this technological integration has transformed the collection, analysis, and management of traffic-related data, promoting safer and more responsive urban mobility systems (Townsend, 2013; Silva et al., 2020).

In this context, the aim of this study was to analyze the spatial and temporal distribution of traffic accidents recorded on the Federal District Road System (FDRS) between 2014 and 2023. The methodological approach integrated temporal trend analysis, inferential statistical tests, spatial cluster analysis using Getis-Ord Gi* and Local Moran's I, and geographically weighted regression to examine local relations between accident frequency and explanatory variables.

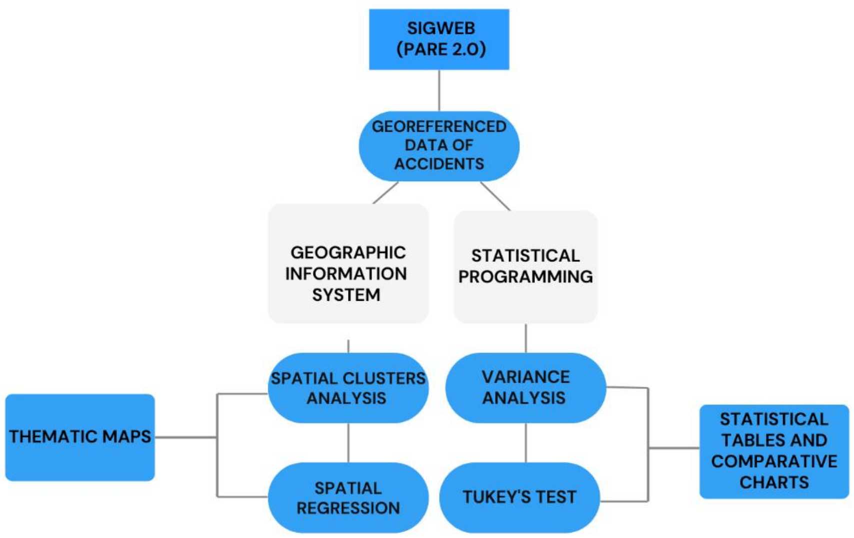
Although the techniques employed are well-established in scientific literature, their systematic application at a regional level offers strategic value for public management. The findings provide timely and spatially explicit evidence for identifying critical segments of the road network and prioritizing interventions.

As a key contribution, this study supports the formulation of public road safety policies, strengthens enforcement and inspection strategies, and guides infrastructure improvements. By integrating advanced spatial analysis methods with high-resolution official data, this research offers technically robust evidence to enhance intelligent, efficient, and territory-based urban mobility planning in the Federal District.

METHODOLOGY

This research was conducted using an integrated approach combining statistical and geospatial methods, with the aim of analyzing the distribution and factors associated with traffic accidents on the FDRS. The methodological steps (Figure 1) were organized sequentially, starting with the collection and structuring of the database, followed by the pre-processing and classification of the information, and culminating with the application of analytical techniques, both statistical and spatial.

Figure 1 - Methodological flowchart of the research

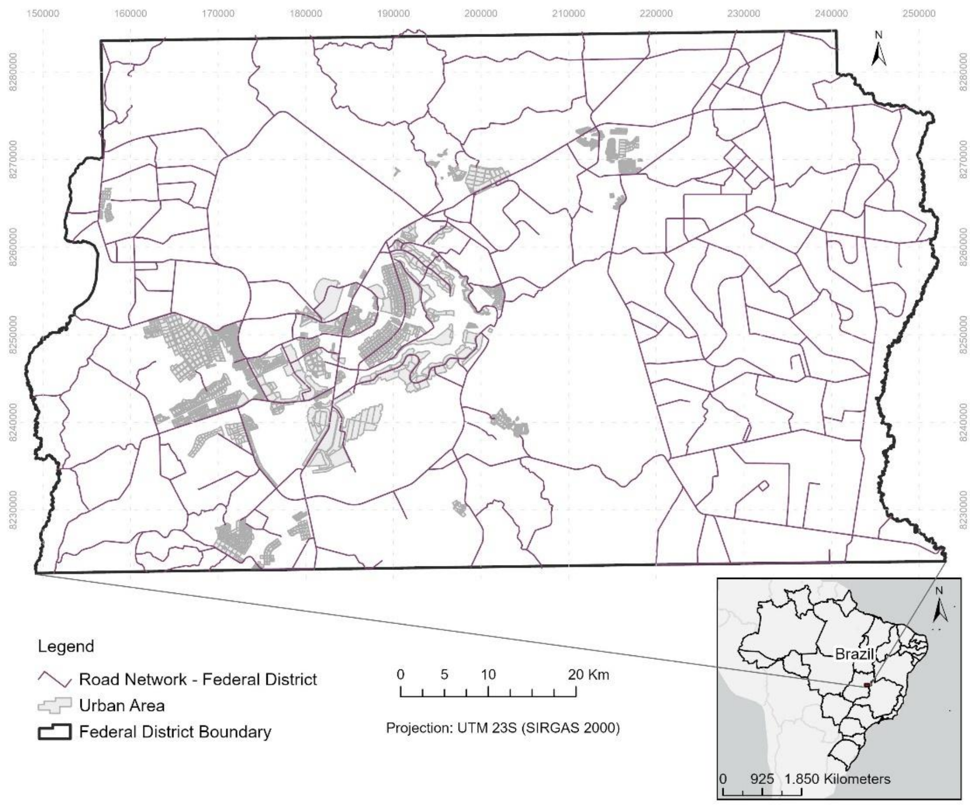


Source: The authors, 2025.

Study area

The Federal District (FD) is situated in the central-western region of Brazil and it has an area of approximately 5,802 km², being the administrative center of Brazil's capital, Brasília (Figure 2). The Federal District has two major urban centers - Brasília (Plano Piloto) and Taguatinga/Ceilândia - which are administrative, commercial and service centers. These hubs play a central role in the spatial organization of the metropolis, acting as vectors for the transport networks that link the other administrative regions.

Figure 2 - Federal District (Brazil): Location



Source: The authors, 2025.

The local Road Plan was conceived in 1960 as part of the establishment of new Brazilian capital and the regional territorial structuring. Currently, the network under district jurisdiction, excluding urban roads and federal highways, totals 1,923.5 kilometers in length. This network covers both paved and unpaved stretches, and it is made up of various elements of road infrastructure, including special structures, access roads, ring roads, and interchanges, which play a fundamental role in the links among the administrative regions of the Federal District (DER-DF, 2023).

Database and pre-processing

The traffic accident data used in this study were obtained through the DERGeo interactive geovisualizer, developed by the Federal District Roads Department (DER-DF), as described by Santos et al. (2023). This platform allows georeferenced access to accident records on the FDRS, offering a structured spatial database that was essential for carrying out the statistical and spatial analyses conducted in this research.

The database includes 16,865 accident records that occurred on the district road system between 2014 and 2023, georeferenced in UTM coordinates, SIRGAS 2000 datum, 23S zone. Each record includes spatial and descriptive attributes such as date, time, type and nature of the traffic accident, vehicles involved and the accurate location of the traffic accident. Before being analyzed, the data underwent a rigorous pre-processing stage, which included tabular verification of incomplete and inconsistent records, identification and correction of discrepant data and standardization of the geocoding of events.

Statistical and spatial analysis of traffic accidents

Data analysis was conducted using a combination of inferential statistical techniques and spatial analysis methods to understand distribution patterns and factors associated with accidents on the FDRS. Analysis of Variance (ANOVA) was applied to test for statistical differences among groups defined by time slots (in 2-hour intervals) and days of the week. Tukey's post hoc test was used to identify pairs of groups with statistically significant differences. The selection of these variables was based on their relevance to traffic patterns and exposure risk, as documented in the literature.

Getis-Ord Gi algorithm*

A hot spot is an area or location within an identifiable boundary that has a concentration of incidents. The main approaches to estimating clusters of incidents include the analysis of georeferenced traffic incidents, the mapping of clusters using Getis-Ord Gi* functions.

$$G_i^* = \frac{\sum_j w_{i,j} x_j - \bar{x} \sum_j w_{i,j}}{S\sqrt{\frac{n\sum_j w_{i,j}^2 - \left(\sum_j w_{i,j}\right)^2}{n-1}}} \tag{1}$$

Where:

$Gi*$ is the index value for location i.

xj is the attribute value at location j.

wi, j is the spatial weight between locations i and j.

x is the average of the attribute values.

S is the standard deviation of the attribute values.

n is the total number of locations.

Geographically Weighted Regression

Geographically Weighted Regression - GWR is a spatial statistical technique used to model the relation between a dependent variable and one or more independent variables, taking spatial variation into account. This technique is especially useful for analyses in which it is assumed that the relations between variables may change over space (ESRI, 2024):

$$y_i = \beta_{0(u_i,v_i)} + \sum_{\{k=1\}}^{K} \beta_{k(u_i,v_i)} x_{\{ki\}} + \epsilon_i \tag{2}$$

Where:

y_i: is the value of the dependent variable in location i.

$\beta_{0(u_i,v_i)}$: Intercept of the regression in location i.

$\beta_{k(u_i,v_i)}$: Coefficient of the explanatory variable x_1 in location i.

$x_{\{ki\}}$: Value of the explanatory variable x_1 in location i.

ϵ_i: Error term at location i.

All operations were performed using ArcGIS Pro version 3.2 (ESRI, 2024). This GIS environment was used to standardize the data and apply the Getis-Ord Gi* and Geographically Weighted Regression tools, in order to identify spatial patterns and correlate the data with variables of interest. Spatial analysis was then implemented in the software, where the Hot Spot Spatial Analysis (Getis-Ord Gi*) techniques were applied to identify statistically significant clusters of accidents, and Geographically Weighted Regression to model the spatially variable influence of explanatory factors on the distribution of traffic accidents.

This integrated approach enables a multi-scalar and spatially sensitive understanding of the analyzed phenomena, providing a solid technical basis to support strategic interventions in road safety planning and management.

RESULTS AND DISCUSSION

Temporal and Statistical Analysis of Traffic Accidents

The data were analyzed to identify temporal trends, severity patterns, and critical traffic-accident hotspots over the study period. Table 1 summarizes the annual evolution in the number of fatalities, injured persons, and fatal and non-fatal pedestrian accidents, as well as the overall total of records per year. Note that, between 2020 and 2023, no records were found for injured persons and non-fatal pedestrian accidents in the available data; these absences are indicated by a specific symbol.

Table 1 - Annual evolution of traffic accident victims on the Federal District Road System (2014-2023)

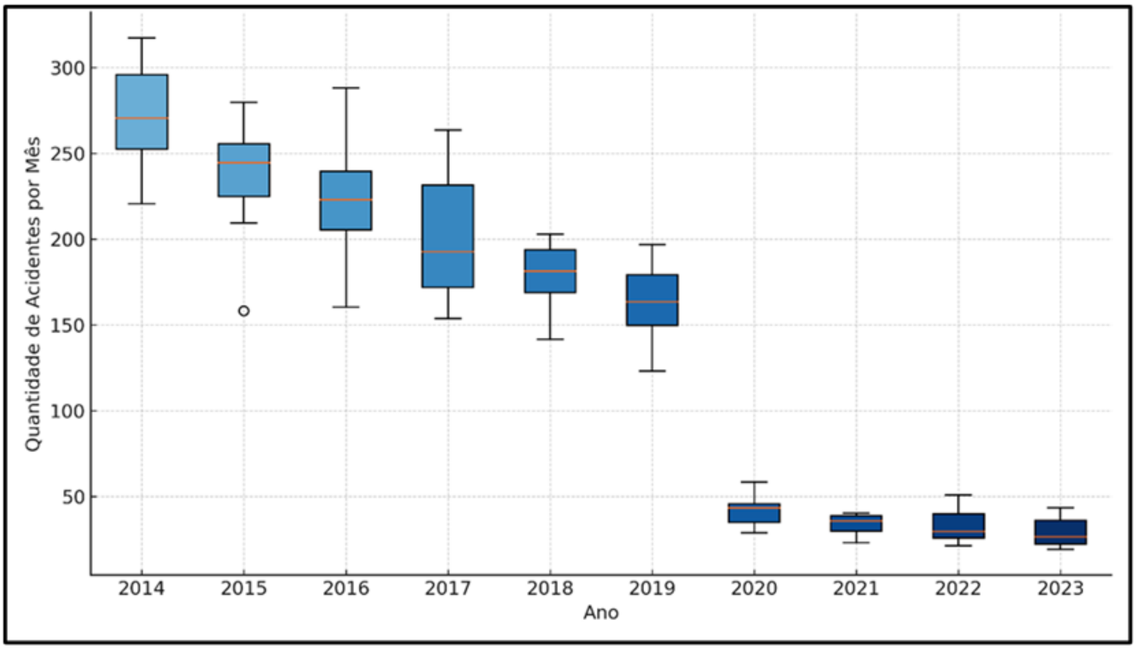
Year	Fatal Victims	Injured Victims	Fatal Pedestrian Accidents	Non-Fatal Pedestrian Accidents	Total
2014	128	2.857	39	259	3.283
2015	98	2.509	35	267	2.909
2016	109	2.339	43	256	2.747
2017	70	2.301	22	221	2.614
2018	78	1.931	38	211	2.258
2019	68	2.293	29	216	2.606
2020	83	-	22	-	105
2021	66	-	23	-	89
2022	91	-	29	-	120
2023	73	-	31	-	104

Source: DER/DF, 2025.

Time-series analysis for 2014–2023 indicates a downward trend in the total number of traffic accidents on the Federal District Road System. However, non-fatal crashes and injured-victim counts are missing for 2020–2023: these variables were not compiled in the database, likely due to COVID-19–era changes in reporting workflows that also altered mobility patterns and risk exposure. Accordingly, the results for those years should be interpreted with caution given the period’s data-collection and administrative constraints.

In order to visually represent the annual variation in traffic accident records in the Federal District, a boxplot graph (Figure 3) synthesizing the statistical distribution of traffic accidents from 2014 to 2023 was drawn up.

Figure 3 - Monthly variation of traffic accidents in the Federal District, 2014–2023



Source: The authors, 2025.

Figure 3 shows the monthly variation in the number of traffic accidents on the Federal District Highway System (2014–2023). From 2020 onward, values are lower and more homogeneous, consistent with pandemic-era changes in mobility and reporting.

In order to evaluate the influence of time variables on the severity of accidents, analysis of variance (ANOVA) tests was applied, considering the Time and Week variables as explanatory factors. Tukey's test was then applied (Table 2) in order to identify which categories, differ significantly from one another.

Table 2 - ANOVA results for the time variables

Factor	GL (between)	GL (residual)	SQ between	SQ residual	Value F	p-value
Time	11	16,823	77	8,427	464,45	< 0.001
Week	6	16,828	27	8,477	10.55	< 0.001

Source: The authors, 2025.

ANOVA revealed statistically significant effects of both time of day and day of the week on accident incidence (Table 2). Multiple-comparison tests (Tukey) showed marked contrasts between early-morning intervals (00:00–05:59) and periods of higher traffic volume, particularly 06:00–07:59 and 16:00–19:59, which displayed the highest mean daily counts. In the weekly profile, Fridays concentrated on the largest average number of crashes, whereas Sundays exhibited the lowest means. These temporal patterns reinforce the existence of distinct risk regimes over the course of the day and the week, consistent with fluctuations in exposure associated with commuting peaks and weekend travel.

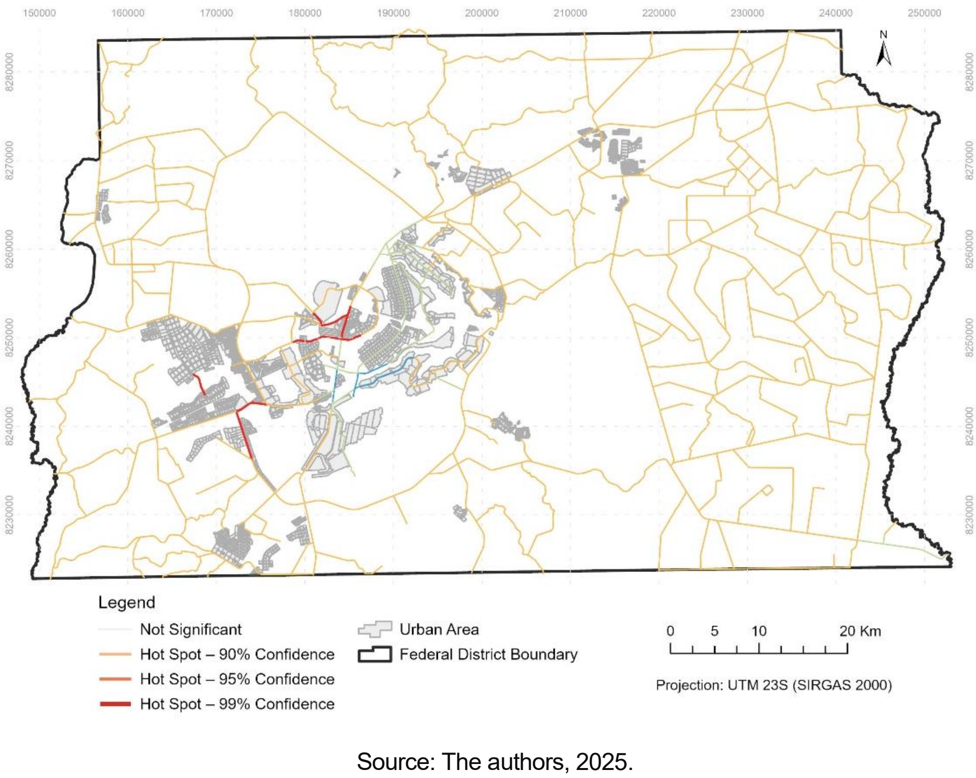
The time series analysis (Table 1) revealed a general declining trend in the total number of traffic accidents on the Federal District Road System (FDRS) between 2014 and 2023. This decline, especially evident after 2020, coincides with pandemic-related mobility restrictions. Similar trends were observed in studies conducted in Spain and the United States, where reductions in accident frequency were attributed to lockdowns and decreased vehicle flow (Qureshi et al., 2020; Saladié et al., 2020). These findings highlight the influence of exogenous shocks—such as health crises—on traffic dynamics.

Spatial analysis of traffic accidents

Analysis of Spatial Agglomerations of Accidents

After the temporal analysis, the investigation of spatial patterns continued. In order to identify the spatial patterns of concentration of traffic accidents on the Federal District Road System, the Hot Spot Analysis technique was applied, based on the Getis-Ord Gi* index. This approach makes it possible to detect statistically significant clusters of events (hot spots) and areas of low concentration (cold spots), based on the spatial distribution of georeferenced records.

Figure 4 - Federal District (Brazil): Hot Spot Map of Traffic Accidents, 2014–2023



Source: The authors, 2025.

Figure 4 maps statistically significant Getis–Ord Gi* clusters of traffic accidents across the Federal District's road system, highlighting high–high concentrations that require priority attention. Table 3 summarizes the number of road segments by significance level and supports the identification of corridors for targeted road-safety interventions.

In addition, Table 3 summarizes the number of road sections classified according to their respective levels of statistical significance. Most of the critical groupings were observed at the 90% confidence level (61 stretches), followed by the 95% (52 stretches) and 99% (38 stretches) levels. There were also 47 stretches identified as cold spots, as well as 120 stretches that were not statistically significant. These results confirm the utility of spatial analysis for identifying priority areas for road safety intervention and planning.

Table 3 - Distribution of stretches according to statistical significance

Confidence Level	Number of Identified Stretches
95%	52
99%	38
90%	61
Cold Spot	47
No Significance	120

Source: The authors, 2025.

The Hot Spot Analysis (Figure 4) identified statistically significant clusters of high accident concentration in key road segments, especially DF-001, DF-085, and the access points to populous administrative regions. These findings are consistent with global evidence that highlights the influence of traffic density and urban centrality on accident clustering (Kim et al., 2006; Quddus, 2008). As observed in studies conducted in South Korea and the United Kingdom, roads with complex intersections and high volumes of mixed traffic are prone to persistent spatial clustering of crashes.

Table 3 shows that the highest number of hot spots occurred at the 90% confidence level, yet a substantial number of clusters reached the 95% and 99% thresholds. This spatial distribution reinforces the necessity for localized interventions, echoing the conclusions drawn by Erdogan et al. (2008), who emphasized the role of spatial targeting in reducing road traffic injuries in Turkey.

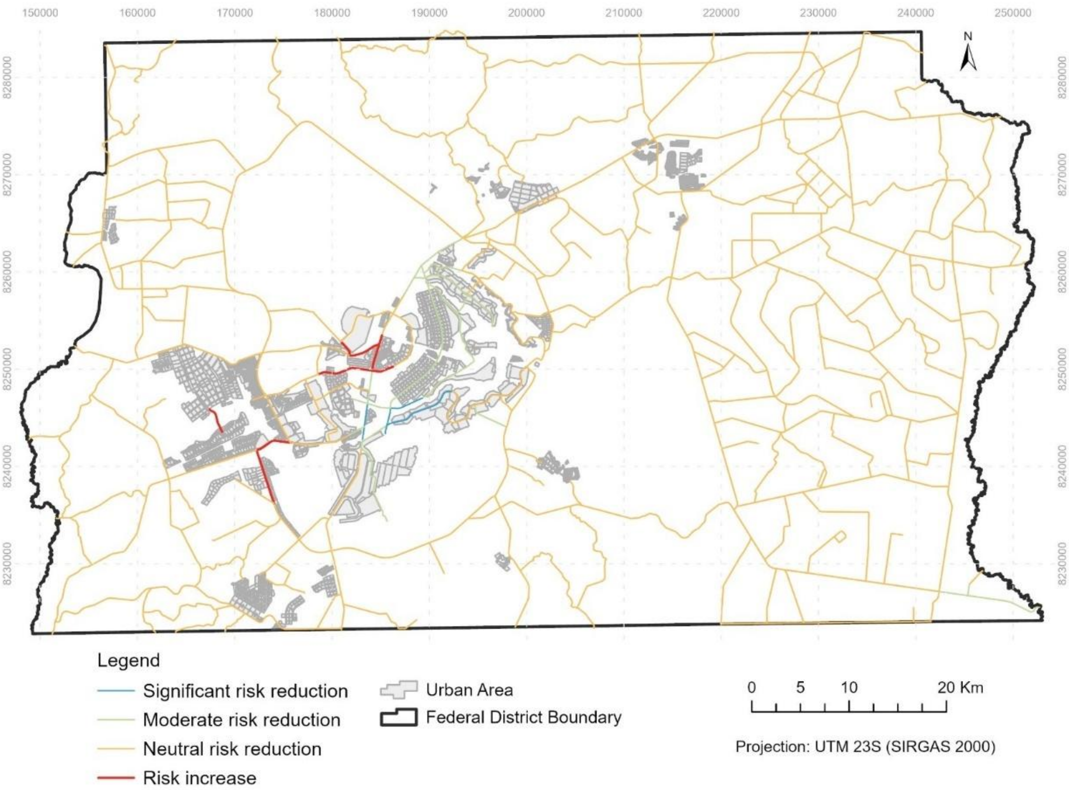
Spatial Modeling of Accident Factors

In addition to identifying agglomerations, we sought to understand the spatially differentiated influence of explanatory variables on the incidence of accidents, using the Geographically Weighted Regression technique. The modeling considered three independent variables: altimetry, per capita income and average daily traffic (ADT), whose local effects were estimated along the stretches of the Federal District's road system. The results are shown in figures 5, 6 and 7.

Depicted in figure 5 is the spatial distribution of regression coefficients for the elevation variable. The highest positive values are observed predominantly in the northern and western portions of the Federal District. These areas are characterized by steeper slopes and greater altimetric variation, which appear positively associated with traffic accident rates. This suggests that topographical features may act as contributing factors to accident occurrence, especially in road segments with sharp curves, limited visibility, and restricted maneuvering space.

Conversely, road segments located in flatter central and eastern areas tend to exhibit neutral or even negative coefficients, indicating that elevation plays a less significant role in those regions. These results reinforce the importance of incorporating geomorphological factors into spatial modeling and traffic safety planning. Targeted interventions—such as slope stabilization, improved signage, and speed control infrastructure—are especially critical in accident-prone areas with complex terrain.

Figure 5 - Federal District (Brazil): Regression Map of the Elevation Variable, 2025



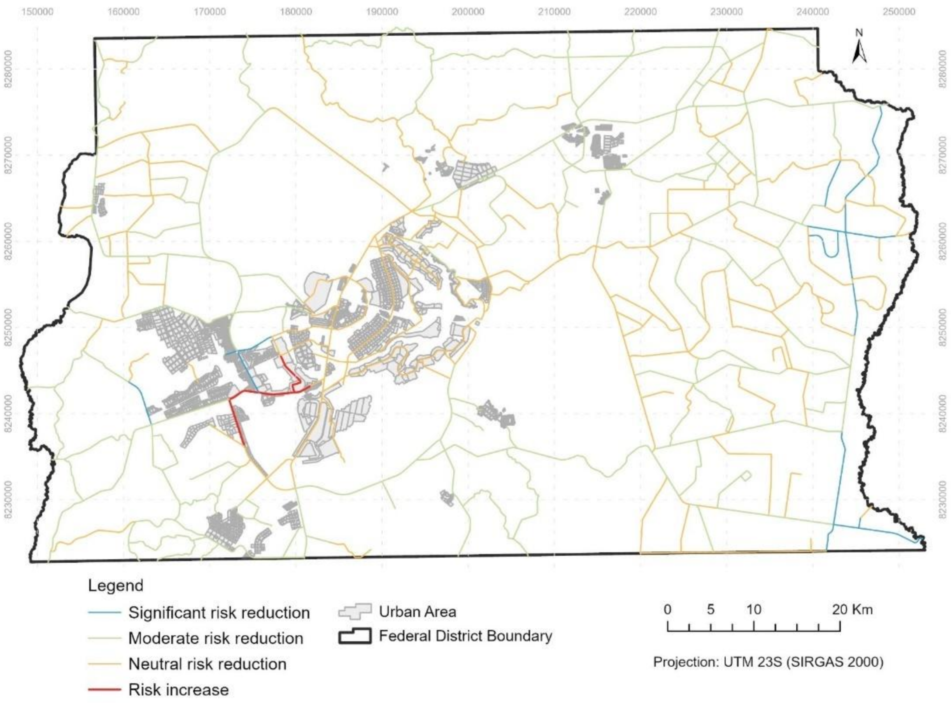
Source: The authors, 2025.

Figure 6 presents the spatial distribution of regression coefficients for the per capita income variable. The segments exhibiting the strongest positive association between income and traffic accidents are concentrated in central and administrative regions of the Federal District, which are characterized by higher socio-economic status. This spatial pattern may reflect increased vehicle ownership, greater mobility demand, and consequently, higher traffic density and exposure to risk in these areas.

In contrast, several peripheral road segments show neutral or even negative coefficients, indicating a weaker or inverse relation between income and accident occurrence. These areas, typically marked by lower socioeconomic indicators, may experience lower traffic volumes and less exposure due to limited access to private vehicles. These findings underscore the relevance of incorporating socioeconomic indicators into spatial regression models and highlight the need for differentiated strategies in traffic safety planning that account for income-related mobility patterns.

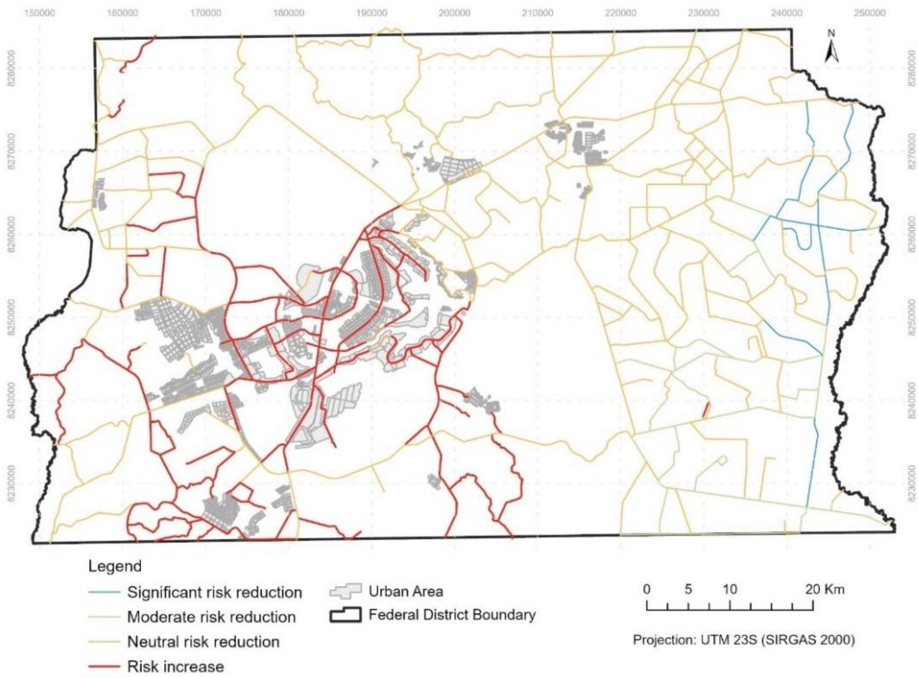
As illustrated in Figure 7, the distribution of the average daily traffic (ADT) coefficients shows that the stretches with the highest daily vehicular flow, especially on the DF-001, DF-003 and DF-085 highways, exhibited a strong association with traffic accidents. These results confirm the relevance of traffic as an explanatory variable for accidents and reinforce the importance of spatial modeling for preventive road safety management.

Figure 6 - Federal District (Brazil): Regression Map of the Per Capita Income Variable, 2025



Source: The authors, 2025.

Figure 7 - Federal District (Brazil): Regression Map of the Average Daily Traffic (ADT) Variable, 2025



Source: The authors, 2025.

In addition to the strong positive association observed in major traffic corridors, Figure 7 also reveals segments where the influence of ADT on accident occurrence is neutral or even negative. Particularly in peripheral areas of the eastern region of the Federal District, certain road segments exhibit moderate or significant reductions in accident risk associated with traffic volume. These patterns suggest that in lower-density regions, increases in daily traffic may not necessarily translate into higher accident rates, possibly due to improved infrastructure conditions or lower conflict points. Such spatial heterogeneity reinforces the importance of localized diagnostics for road safety policies, enabling differentiated strategies that consider the specific dynamics of each road segment.

Figures 5–7 present the GWR outputs for elevation, per capita income, and Average Daily Traffic (ADT). The positive association among elevation and accident rates in hilly western and northern segments of the FDRS reflects findings from mountainous regions in Taiwan and Iran, where slope and road curvature were also identified as contributing risk factors.

The analysis of income (Figure 6) revealed a stronger positive correlation between accidents and higher-income regions, suggesting that vehicle availability and traffic demand play a more significant role than vulnerability per se in those zones. This pattern is corroborated by Hadayeghi et al. (2003), who reported similar trends in Canadian cities, where affluence was linked to higher exposure due to increased car ownership.

GWR results indicate spatially varying associations between accident occurrence and the three covariates. Elevation shows positive coefficients on hilly, curvilinear segments—consistent with sharper geometry, restricted sight distance and maneuvering constraints—while flatter central/eastern corridors tend to display weaker or neutral effects. Per capita income presents higher positive coefficients in central, high-income areas, which are likely to reflect greater vehicle ownership, trip density and exposure—whereas several peripheral segments show neutral or negative effects. Finally, ADT exhibits strong positive coefficients along major central corridors, highlighting volume-driven exposure in high-flow links. These patterns align with international evidence on geometry- and exposure-related risk (Chang & Wang, 2006), underscoring the value of spatial targeting in road-safety policy.

CONCLUSION

This study applied statistical and geospatial techniques to investigate accident patterns on the Federal District Road system between 2014 and 2023, drawing on 16,865 georeferenced accident records. The research proceeded in four stages: (i) database consolidation and pre-processing; (ii) inferential testing (ANOVA and Tukey) to examine how accident severity varies across times of day and days of the week; (iii) identification of critical segments through Hot Spot Analysis (Getis-Ord Gi*); and (iv) local modelling of explanatory factors via Geographically Weighted Regression (GWR).

Evidence indicates a center–periphery gradient that reinforces urban inequalities in the Federal District. High and statistically significant GWR coefficients for per capita income and ADT are concentrated along central corridors, suggesting greater exposure and risk where trip densities, car ownership, and economic activity are highest. In contrast, many peripheral segments display neutral or negative coefficients and fewer statistically significant hot spots, which may reflect lower measured exposure but also possible underreporting and longer emergency response times. Overall, central areas appear to bear a disproportionate crash burden driven by volume and speed dynamics, whereas peripheral areas present distinct vulnerabilities linked to access, enforcement reach, and post-crash care.

The spatial distribution of crashes aligns with prevailing patterns of urban expansion and land-use allocation. Central mixed-use axes concentrate flows and conflicts—consistent with strong positive associations with ADT—while recent peripheral expansions lengthen trip distances and increase radial dependence on major trunk roads, channeling traffic into a limited set of high-flow links. Policy implications include coordinated speed management and traffic calming in central corridors; geometric and visibility treatments at high-risk segments; multimodal strategies (public transport priority, safe cycling infrastructure, and demand management) to curb car-dependent growth at the urban fringe; and the coupling of land-use approvals with network capacity and safety impact assessments to avoid reproducing high-risk corridors.

Statistical results revealed marked variation in accident severity: Sundays and off-peak hours were associated with higher severity levels. Spatial analysis pinpointed significant clusters along high-traffic corridors—especially the DF-085, DF-001 and EPIA highways and the approaches to Taguatinga, Ceilândia and Plano Piloto. GWR showed that elevation, per capita income and average daily traffic (ADT) exert heterogeneous local effects, underscoring the value of spatially targeted policy.

Data coverage limitation (2020–2023): Records for nonfatal injuries and nonfatal pedestrian accidents are unavailable for 2020–2023 in the dataset. Although fatal accident data remain available, the missing injury information reduces temporal comparability and may affect severity estimates for those years. Accordingly, analyses that rely on injury counts exclude 2020–2023, and these years are flagged in sensitivity checks (see Methods). Standardized reporting and automated data transfers would improve continuity in future series.

Based on our findings, we recommend upgrading critical stretches (signage, geometry, lighting); installing speed-control devices; expanding smart enforcement; and running education campaigns focused on vulnerable users such as motorcyclists and pedestrians. These measures must respect local particularities of terrain, traffic load and socioeconomic vulnerability.

Finally, long-term road-safety research in the Federal District will depend on robust data ecosystems. Future studies should (i) integrate vehicle mix, weather and collision-type variables; (ii) link traffic-offence databases to accident registries; and (iii) maintain uninterrupted collection to capture post-pandemic mobility dynamics. Only by coupling high-quality data with advanced spatial analytics can public agencies deliver safer, more sustainable and evidence-based mobility policies.

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