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ORIGINAL RESEARCH

Contribution of a Geographic Information System to the Prevention of Crashes Among Vulnerable Road Users in the City of Cotonou: Exploratory Study

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Purpose: The aim of this study was to determine, using geographic information system (GIS), the spatial characteristics and factors associated with injury crashes among vulnerable road users (VRUs) in Cotonou, Benin.

Patients and Methods: This study was based on road crash data collected by the police in Cotonou from 2008 to 2017. Spatial analyses were performed using density method of QGIS cartography software to identify road crash hotspot for VRUs. Logistic regression analysis was conducted using Stata 15 software. Finally, field observations were used to assess the physical characteristics of the road environment at each hotspot.

Results: From 2008 to 2017, six main crash hotspots involving VRUs were identified on the roads of Cotonou. The majority were located at intersections of main roads. These sites did not meet the standards for traffic safety for VRUs. Factors associated with injury crashes among VRUs were intersections (adjusted odds ratio (aOR) = 3.3; 95% CI: 1.8–6.1) and pavement condition (aOR = 7; 95% CI: 2.9–17.1).

Conclusion: The present study has made it possible to identify the locations on Cotonou's road network where road safety interventions could be implemented to protect VRUs.

Keywords: vulnerable road users, injury crash, hotspots, road environment

Introduction

Road traffic crashes are a public health problem, particularly in low- and middle-income countries. They are responsible for more than 1.35 million deaths each year worldwide and are the leading cause of death among people aged 15–29 years.[1] More than half of these deaths are among vulnerable road users (VRUs) such as cyclists, motorcyclists and pedestrians.[1,2] In Africa, VRUs bear a high burden of road morbidity and mortality. A study conducted in Burkina Faso found that they accounted for 95% of road crash victims.[3]

In Benin, according to a study based on police statistics, pedestrians accounted for more than 25% of road fatalities, or 27.74% (95% CI: 26.31 to 29.20).[4]

In low- and middle-income countries, the effectiveness of road safety measures is often compromised by the contrast between the high number of crash sites on the road network and the limited resources invested in road safety.[5] Risk factors identified in road crashes involving VRUs in their cities were roadway design, curbside parking, road dividers, absence of safe crosswalks, and proximity of roads to schools, markets or drinking establishments.[6,7] The risk of traffic crashes involving children near schools has been described in research as a public health problem.[8] Similarly, proximity to establishments selling alcohol has been identified as a risk factor for VRUs.[9]

In recent years, the use of a Geographic Information System (GIS) has improved understanding of the spatio-temporal distribution of crashes by mapping the most dangerous segments of the road network.[10–18] The tool offers the opportunity to retrospectively process large amounts of spatial and temporal information and is effective for identifying areas of high

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crash concentration, known as hotspots.[17,19–22] A GIS is considered a tool to help prioritize interventions and efficiently allocate resources to improve road safety.[11–15,23,24] The corrective measures for the causes of road crashes then involve changes in the built environment.[25,26]

In Benin, since 2008, financial investments have been made to acquire Global Positioning System (GPS) receivers and train police officers in charge of road crash reports. The geographical coordinates of crashes were integrated into the crash analysis report form, the Bulletin d'Analyse des Accidents Constatés (BAAC), in a pilot phase to improve collection of information on road crashes. After more than a decade of implementation of this pilot phase, the data collected have not yet been subjected to a thorough spatio-temporal analysis for the implementation of corrective measures or recommendations for crash prevention.

The objective of this study was to determine, using GIS, the spatial characteristics of injury crash among vulnerable road users and then to identify their associated factors in Cotonou, Benin.

Materials and Methods

Type of Study

This is a secondary analysis of road crash data with field observation.

Study Area

Benin, a West African country, covers an area of 114,763 km^2 with nearly 11,190,000 inhabitants across 12 departments in 2016.[27] The country's asphalt road network extends over 2685 km with a continuously declining pavement condition index (pavement deterioration indicator), which dropped from 75% in 2013 to 46% in 2016.[28] According to police statistics, road crashes are more frequent in large cities such as Cotonou, which is the country's most populous metropolis with an average population density estimated at more than 7000 inhabitants per square kilometer (Figure 1). It covers 79 km^2 between lake Nokoué in the north and the atlantic ocean in the south, and is the location of almost all public, private, national, and international institutions. It has the largest number of cars in the country, with a predominance of motorized 2–3 wheelers, which are the users most involved in road crashes in Benin.[29]

Data Source

The data studied came from the BAAC database. These data were collected on a paper form during crash reports by the police between 01/01/2008 and 31/12/2017. They were then transmitted to the national road safety center, the Centre National de Sécurité Routière, where they were compiled in a national database.

From 2008 to 2017, the police in Cotonou recorded a number of 21,854 road crashes. Of this number, 1394 had correct GPS coordinates, 665 of which involved vulnerable road users (Figure 2).

Variables

Dependent Variable

The dependent variable is crash involving vulnerable road users (cyclists, motorcyclists and pedestrians). It has two modalities: injury crashes, those that resulted in injury or death, and material crashes, those that occurred without injury. Each road traffic crash point used in the analysis was described by its coordinates (latitude, longitude).

Independent Variables

Independent variables are: road type (national inter state road (RNIE), urban road, side street), intersection (yes, no), pavement condition (good, poor), road geometry (straight line, curve, narrowed pavement), brightness (daytime, night without street lighting, night with street lighting), type of day (weekend, holiday/market day, ordinary day) and marking on the road (yes, no).

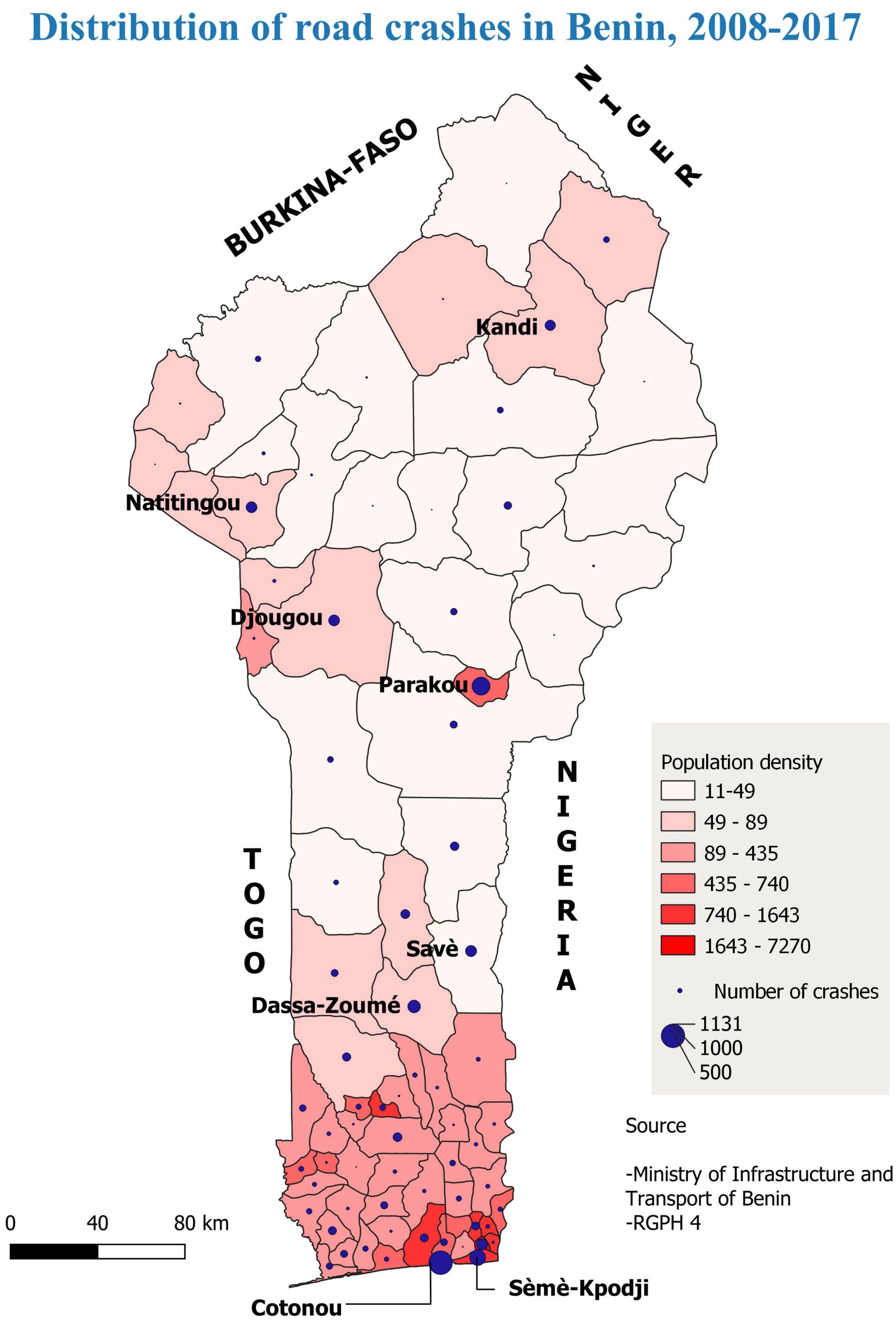

Figure 1 Distribution of road accidents and population density per municipality in Benin, 01/01/2008–31/12/2017.
Notes: Unpublished data; 2017; Bulletin d'Analyse des Accidents Constatés (BAAC), 2008-2017, Ministére des Infrastructures et des Transports, Centre National de Sécurité Routière, Cotonou, Bénin. French.

Analysis

Spatial Analysis

Mapping and spatial analyses were performed using the open-source GIS software QGIS 3.16. Road traffic crashes were mapped using latitude and longitude coordinates. Next, the incorrectly encoded GPS coordinates were eliminated using the geoprocessing tool by excluding observations located outside of Cotonou.

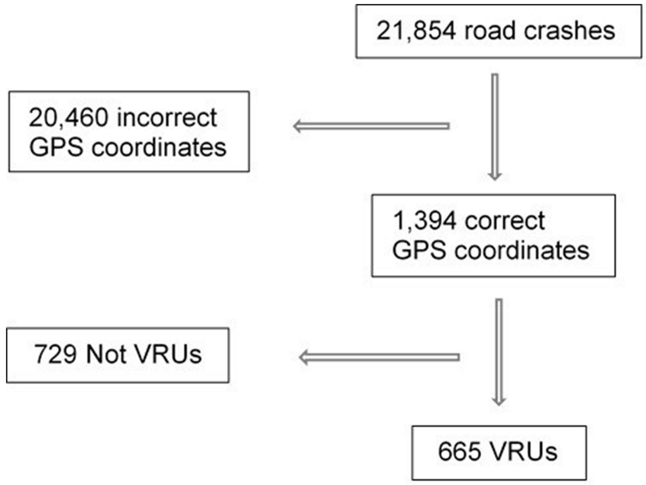

Figure 2 Selection process of crashes involving vulnerable road users (VRUs) in Cotonou, 2008–2017.

Then, using the QGIS heatmap extension, density maps were generated in raster mode to accurately identify hotspots in a road network.[30–32] The spatial resolution of this map was set to 10 m corresponding to the average accuracy of the GPS surveys performed. A radius of 100 m was chosen to avoid identifying multiple hotspots for a location, such as the "Place de l'étoile rouge", which is the largest intersection in Cotonou. This choice is congruent with Porta and his co-authors who, based on the average length of arcs in the road network, suggest a range of values between 100 and 300 m in urban.[33] Hotspots of road crashes (Hotspots) were determined as locations where more than one injury crash (fatal, serious, or minor) were recorded during the period. Hotspots were then ranked according to the number of recorded crashes.

Environmental Observations

The physical characteristics of the roadway environment were observed at each of the hotspots by two researchers who conducted independent field observations of the sites to determine the potential contribution of these factors to VRUs injuries. The factors evaluated were: Traffic light functionality, presence of no-turn signal, presence of visual obstruction, parking along the sidewalk, presence of a safe pedestrian crosswalk, presence of speed bumps at intersection, existence of businesses at intersection, separate lane for VRUs, pedestrian medians, overcrowding of the sidewalk by neighbors, good pavement condition, number of access roads and number of schools within a 2 km radius of the hotspot.

Quantitative Analysis

Data were processed and analyzed using Stata 15 software. Qualitative data were presented as a percentage. Factors associated with the injury crash were identified by performing a multiple logistic regression. The analysis first consisted of cross-tabulating the variable injury crash with each of the independent variables. Simple logistical regression was also used at this stage. Thus, all covariates were examined for inclusion in the multiple regression model based on a threshold of $P < 0.1$. The multiple regression used a top-down stepwise strategy. Variables with p-values greater than 0.05 were gradually removed from the initial model. Co-linearity between variables was sought. The final results were presented in adjusted odd ratio (aOR) form with the 95% confidence interval. Goodness-of-fit and specification tests were performed on the final model.

Results

Description of Road Crashes in Cotonou

During the period 2008–2017, the mapping of road crashes in Cotonou city showed that almost all road crashes occurred on major roads such as the national inter state road 1 (RNIE 1) or urban roads rather than on secondary streets, with a high concentration in city center (Figure 3).

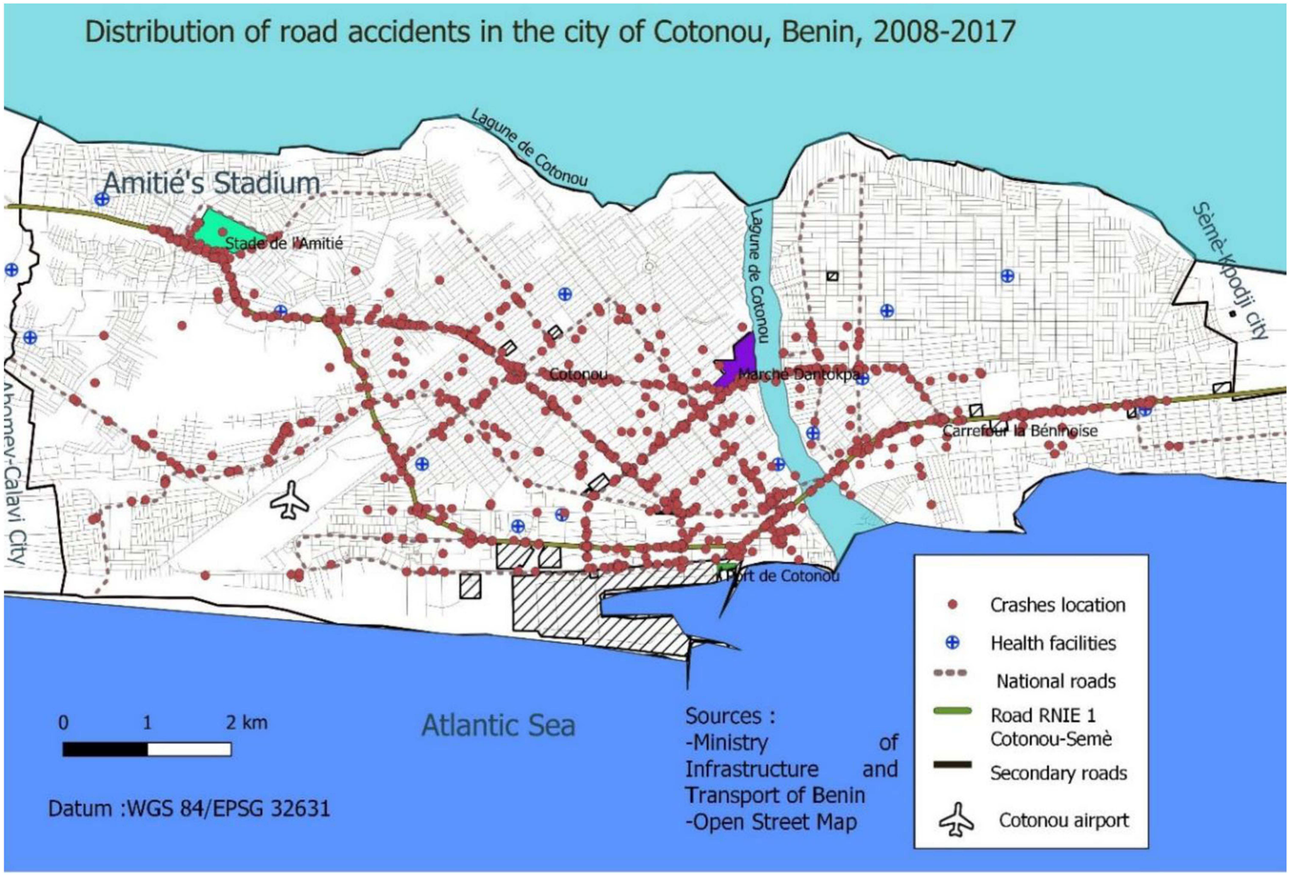

Figure 3 Spatial distribution of road crashes in the City of Cotonou, 2008–2017.

Crashes Involving Vulnerable Road Users in Cotonou: Estimation by Road Crash Density Using QGIS Software

During this period, six main crash hotspots involving VRUs were identified on the roads of Cotonou, five of which were located at intersections and one off intersection (Figure 4).

The intensity of the color of the hotspots was proportional to the number of crashes recorded at that location.

Of the six main road crash hotspots, three were located on the RNIE1 (Figure 4: hotspots 1, 4 and 6), which is the Benin portion of the Abidjan-Lagos West African corridor. This is the busiest road in the country. One hotspot was located on a side street bypassing the city (Figure 4: hotspot 2). This road is also very busy on weekends as it is one of the main access roads to the beach. The last two were located on urban roads serving the Cotonou international market (Figure 4: hotspots 3 and 5). All of them are located on roads serving areas of high human activity such as administrative centers, business centers, markets, large schools and the seaport of Benin.

Hotspots 1 and 6, both located on the RNIE1, recorded the highest number of injuries among vulnerable road users in Cotonou.

Environmental Characteristics of Road Crash Hotspots

The environmental characteristics of the hotspots are summarized in Table 1. In total, two of the six main road crash hotspots had functioning traffic signals (hotspots 3 and 5), and none had a no-turn signal. Visual obstructions such as shrubs existed at one of the hotspots (hotspots 2). No vehicle parking was noted along the roads at these sites. None had safe pedestrian crosswalks or traffic calming devices on the access roads except hotspots 5 where there was a traffic calming device before the intersection. Four hotspots had businesses and five did not have a separate lane for cyclists and motorcyclists (Table 1).

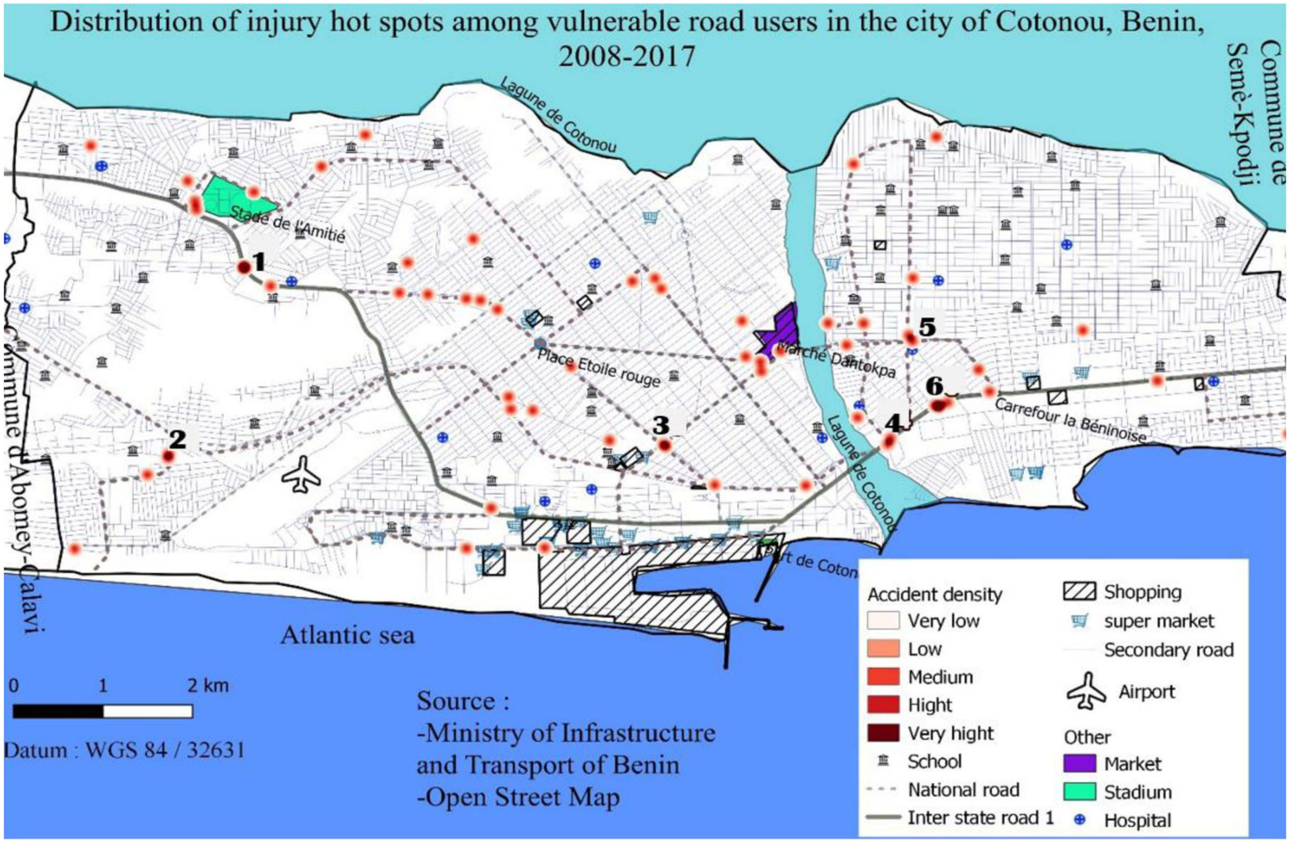

Figure 4 Spatial distribution of injury road crash hotspot among vulnerable road users in Cotonou, Benin, 2008–2017.

In addition, four hotspots did not have pedestrian medians. The number of access roads to these hotspots ranged from 2 to 6 and the number of schools within a 2 km radius ranged from 6 to 15 (Table 1).

Factors common to these hotspots were lack of a safe pedestrian crosswalk, lack of no-turn signal, lack of pedestrian medians, lack of speed bumps at intersection, lack of separate lane for VRUs, non-functional traffic signals, and existence of businesses at intersection.

The lack of dedicated lanes for vulnerable road users is the cause of many fatal crashes.

Factors Associated with Injury Crash Among Vulnerable Road Users

At the simple logistical regression, the factors associated with injury among VRUs were intersections (crude odds ratio (cOR): 3.2, 95% CI: 1.8–5.8), pavement condition (cOR: 8.2, CI95%: 3.5–19.1), and road geometry type: straight line (cOR: 17.2, CI 95%: 2–192) or curve (cOR: 16.9, CI 95%: 1.4–205) (Table 2).

At multiple logistic regression, the associated factors were intersections (adjusted odd ratio (aOR): 3.3, CI 95%: 1.8–6.1) and pavement condition (aOR: 7, CI 95%: 2.9–17.1). The final model was adequate and specific: Goodness-of-fit test (p= 0.691); Linktest (p <0.001) (Table 3).

Discussion

Six main hotspots were identified in the city of Cotonou, five of which are located at intersections on main roads and one on a side street: (i) hotspot 1: intersection "Agla haute-tension", (ii) hotspot 2: intersection "Fidjrossè calvaire",[34] hotspot 3: intersection "Unafrica", (iv) hotspot 4: intersection "Akpakpa Dodomey", (v) hotspot 5: intersection "Eglise du Sacré-Coeur" and (vi) hotspot 6: on the RNIE1 at the roadway "stade René-Pleven". All these points were located on busy roads in the city center. These points do not have all the necessary facilities to ensure road traffic safety, such as separation between road users, functional traffic lights, the existence of safe crossings for pedestrians or traffic calming

Table 1 Environmental Characteristics of Hotspots for Vulnerable Users in the City of Cotonou, 2008–2017

Environmental Characteristics	Hotspot 1	Hotspot 2	Hotspot 3	Hotspot 4	Hotspot 5	Hotspot 6	Number of Risk Factors Identified
Name	"Agla haute-tension"	"Fidjrossè Calvaire"	"Unafrica"	"Akpakpa Dodomey"	"Eglise Sacré-cœur"	"stade René-Pleven"	-
Classe of road	RNIE1	Side street	Urban Road	RNIE1	Urban Road	RNIE 1	-
Intersection	Yes	Yes	Yes	Yes	Yes	No	-
Traffic light functionality	No	No	Yes	No	Yes	No	4
Presence of no-turn signal	No	No	No	No	No	No	6
Presence of visual obstruction	No	Yes	No	No	No	No	1
Parking along the sidewalk	No	No	No	No	No	No	0
Presence of a safe pedestrian crosswalk	No	No	No	No	No	No	6
Presence of speed bumps at intersection	No	No	No	No	Yes	No	5
Existence of businesses at intersection	Yes	Yes	No	Yes	Yes	No	4
Separate lane for VRUs before intersection	Yes	No	No	No	No	No	5
Pedestrian medians	No	Yes	No	Yes	No	No	4
Overcrowding of the sidewalk by neighbors.	No	No	No	Yes	Yes	No	2
Good pavement condition	Yes	Yes	Yes	Yes	Yes	Yes	0
Number of access roads	6	3	4	2	4	2	-
Number of schools	14	8	11	6	15	9	-

Abbreviation: RNIE1, national inter-state road 1.

devices, among others. Similar results were also reported in studies in Rwanda, Malawi, Tanzania and Canada, where the hotspots were located along main roads and in the city centre.[18,21,35,36] The same observation was made in Italy where hotspots were located on major roadways.[37]

A meta-analysis showed that the number of crashes tends to be higher on large, separate roads with high traffic volumes.[38] This is the case for the hotspots in the present study, which were mostly found on the RNIE1, a portion of the Abidjan-Lagos West African corridor, and on access roads to the Cotonou international market. Another study using the same density estimation method found that crashes were more frequent in areas of high human activity such as airports, ferry terminals, and business districts.[39] Comparable results were obtained in the present study where four hotspots (Figure 4: hotspots 3, 4, 5, and 6) serve the seaport, the international market, and the administrative and business centers of Cotonou. The other two hotspots see large daily flows of users between their residences in the suburbs of Cotonou or in neighboring towns and their workplaces in Cotonou (Figure 4: hotspots 1 and 2). The road through the "Fidjrossè calvaire" intersection (Figure 4: hotspot 2) is used during the week by workers as an alternative to the traffic jams on the

Table 2 Analysis of the Environmental Characteristics of injury Crashes Among Vulnerable Road Users in Cotonou, Benin, from 2008 to 2017

Variables	Road Crash		p	cOR	95% CI
	Injury Crash (%) n=71	Material Crash (%) n=594			
Road type			0.103		
RNIE	31.0	21. 4		1	
Urban Road	66.2	77.3		1.7	1–2.9
Side street	2.8	2.3		0.7	0.1–3.5
Intersection			< 0.001		
Yes	22.5	48.5		3.2***	1.8–5.8
No	77.5	51.5		1	
Pavement condition			0.001		
Good	84.5	97.8		8.2***	3.5–19.1
Poor	15.5	2.2		1	
Type of day			0.234		
Weekend	35.2	25.8		0.6	0.4–1.1
Holiday/Market day	2.8	3.5		1.1	0.2–4.8
Ordinary day	62.0	70.7		1	
Road geometry			0.007		
Straight line	84.5	87.0		17.2**	2–192
Curve	12.7	12.8		16.9**	1.4–205
Narrowed pavement	2.8	0.2		1	
Brightness			0.855		
Daytime	76.1	75.7		1	
Night without street lighting	15.4	14.0		0.9	0.6–1.8
Night with street lighting	8.5	10.3		1.2	0.5–3
Marking on the road			0.423		
Yes	42.3	37.4		1	
No	57.7	62.6		1.2	0.7–2

Notes: ** p < 0.01; *** p < 0.001.
Abbreviations: CI, confidence interval; cOR, crude odds ratio; p, p-value.

roads through the city of Cotonou; it is also an obligatory crossing point for users going to Cotonou beach on weekends for recreation, which would explain the number of crashes at this point.

Factors Associated with Vulnerable Road User Injury

One of the factors, in the final regression model, associated with injury among vulnerable road user was intersections (aOR: 3.3, 95% CI: 1.8–6.1). This result from the multivariate analysis is close to that from the spatial analysis and confirms the initial hypothesis that hotspots are more frequent at intersections than on other sections of road. This

Table 3 Factors Associated with injury Crash Among Vulnerable Road Users in Cotonou, Benin, 2008–2017

Variables	aOR	95% CI
Intersection		
Yes	3.3***	1.8–6.1
No	1	
Pavement condition		
Good	7***	2.9–17.1
Poor	1	

Notes: *** p < 0.001; Goodness-of-fit test (p= 0.691); Linktest (p <0.001).
Abbreviations: CI, confidence interval; aOR, adjusted odds ratio.

observation is similar to a study conducted by Meuleners and his coauthors in 2019 in which most cyclist crashes occurred at intersections (aOR: 2.98, 95% CI: 1.2–7.6).[40] Similarly, in 2019, Kullgren and his coauthors found that crashes were common at intersections.[41] Other studies have found a high incidence of road crashes at intersections.[18,22]

Field observation shows that the main points of conflict between users are intersections. Most of the roads were separated by a median avoiding conflicts between users going in opposite directions. The meeting points between users were therefore limited to intersections, which were the most high-risk points in the road network for these road users. Most of these points did not have functional traffic lights, and where these were present and functional, they were not always respected. No hotspot had safe crosswalks and only one had traffic calming devices (hotspot 5).

In the present study, crashes were more frequent on pavements in good condition (aOR: 7, 95% CI: 2.9–17.1). A study conducted by Pawłowski and his coauthors in 2019 instead identified poor road surface conditions as factors associated with the occurrence of traffic crashes.[42] These authors mention as factors speeding and high traffic levels, especially on wide roadways with more than two lanes per direction.

In this study, good pavement condition without traffic calming devices favors the practice of speeding, especially among young road users who practice it for leisure purposes. Also the absence of safe passage for pedestrians, the absence of traffic calming devices and functional traffic lights could suggest that speeding and the non-respect of traffic regulations, particularly the rules of priority, are risk factors for crashes among VRUs in the city of Cotonou at these hotspots. All this is aggravated by the additional traffic generated by international travelers on the Abidjan-Lagos corridor, which has become the preferred route for the transport of people and goods between different countries in the West African economic area. The development of corridors in Africa and their impact on communities has been studied by some authors who see this phenomenon as a source of opportunity for the country and logistics companies, but without taking into account the impact on local populations.[43] Other studies see these corridors as vectors of road congestion with serious consequences.[44]

Strengths and Limitations

This study is an inventory and exploratory analysis of road crashes in Cotonou using GIS. Its main limitation is the low completeness of the geographic coordinates of the crashes due to the pilot phase of geographic data collection in Benin. Not all crashes are recorded in Cotonou because of the cost of this service, which is paid by the users involved. GPS coordinates were not systematically recorded for all crashes; their encoding was sometimes subject to errors. Studies have found that the limitation of geolocation of road crashes is common in developing countries. In 2018, Jooma and his coauthors observed this poor geocoding of the crash data mined in their study.[45]

However, the results of this study are still useful for an assessment of road safety in Cotonou. They could serve as a methodological guide for future analyses of more complete road crash data in Benin. Finally, they could serve as feedback and advocacy tools for those in charge of crash reports to improve the quality of the data collected. Improving the completeness of geographic road crash data by the police is useful to improve the contribution of GIS in road crash prevention in Benin. Finally, the implementation of targeted actions at these hotspots will have a strong impact on the prevention of the crashes among VRUs in Cotonou.

Conclusion

The GIS and mapping, combined with statistical analysis and field observations, have enormous potential for improving road safety by giving a more in-depth understanding of the characteristics of the highest risk road crashes sites, the implementation of corrective measures and the monitoring of these sites.

The results could serve as a starting point for evaluating the effectiveness of future road safety interventions. They could also be useful to police officers in charge of crash reports, road safety officials, and road network managers in terms of the methodology to be used for more comprehensive data analysis. This study could also serve as an advocacy tool to improve the quality of geographic data collected in this city. Finally, this will contribute to having quality data to identify priorities in road development to improve road safety in Cotonou.

Based on these results, we recommend to: (i) make traffic lights functional, (ii) install traffic calming devices before intersections,[34] mark crosswalks especially at hotspots, (iv) strengthen police traffic surveillance at these hotspots, and (v) continue to raise awareness of compliance with traffic laws.

Abbreviations

aOR, Adjusted Odds Ratio; BAAC, Police Recorded Crash Analysis Form; CNSR, National Road Safety Center; cOR, Crude Odds Ratio; GIS, Geographic Information System; GPS, Global Positioning System; RNIE1, National Inter-State Road 1; VRUs, Vulnerable Road Users.

Ethics Approval

This study is part of a doctoral thesis. Due to the absence of an ethics committee at the Regional Institute of Public Health (IRSP) in Ouidah, the protocol describing this thesis was approved by the Ethics Committee of the University of Parakou (Benin), one of the 3 ethics committees in Benin, under the reference 0182/CLERB-UP/P/SP/R/SA. In addition, database does not contain any personal data.

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Disclosure

The authors report no conflicts of interest in this study.

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