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Factors influencing the occurrence of traffic accidents in urban roads: A combined GIS-Empirical Bayesian approach

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Abstract
The problem of urban road accidents in Colombia is remarkable and has a significant magnitude. For this reason, a technical study of this important public health scourge is important. The quantitative techniques employed are usually highly aggregated and will not correctly identify the determinant variables of the problem. This paper examines the relationship between urban road accidents and variables related to road infrastructure, environment, traffic volumes and traffic control. Some accident-prone sections in the city of Cartagena (Colombia) are specifically identified by the empirical Bayesian method based on GIS. A total of 69 accident-prone sections were identified in the city. It was evident that the marginal effect on the accident rate for motorcycles is well above that for cars and buses. Empirical evidence also showed that the sections located in commercial areas tend to have higher frequency of accidents due to the high presence of pedestrians.

Keywords: urban road accident; accident-prone sections; empirical Bayesian approach; Geographic Information System.

Factores que influyen en la ocurrencia de accidentes de tránsito en vías urbanas: Un enfoque combinado GIS-Bayesiano empírico

Resumen
La magnitud del problema de la accidental vial urbana en Colombia es notable y por tal razón interesa estudiar técnicamente este importante flagelo de salud pública. Normalmente las técnicas cuantitativas empleadas son muy agregadas y no permiten identificar correctamente las variables determinantes del problema. El presente artículo estudia la relación existente entre la accidentalidad vial urbana y variables de la vía, el entorno, el tránsito y el control. Específicamente son identificados sectores críticos de accidentalidad en la ciudad de Cartagena (Colombia) mediante el método bayesiano empírico basado en SIG. Se encontró un total de 69 tramos críticos de accidentalidad en la ciudad y se evidenció que el efecto marginal sobre la accidentalidad de las motocicletas es muy superior al de autos y buses. También se encontró evidencia empírica que los tramos ubicados en zonas comerciales tienden a presentar mayor frecuencia de accidentes debido a la alta presencia de peatones.

Palabras clave: accidentalidad vial urbana; tramos críticos de accidentalidad; enfoque bayesiano empírico; Sistema de Información Geográfico.

1. Rationale

Knowing the exact number of people who are affected by traffic accidents is virtually impossible because minor injuries usually do not count as part of the official statistics. The same applies to the case of deaths caused by traffic accidents, as some countries are not governed by the international convention of counting those deaths that occurred up to 30 days after the event [1].

However, some estimates from the World Health Organization indicate that approximately 1.2 million deaths and between 20 and 50 million injuries result from traffic accidents on a global scale [2]. In examining the relationship of deaths and injuries per cause, traffic accidents rank first, causing seven times more deaths than wars and two times more than other forms of violence [2].

In Colombia the problem of road accidents is also of a great magnitude. Records indicate that during the period 2002-2012 accidents in the country resulted in approximately 62,000 deaths and over 443,000 injuries. Traffic accidents in the country have become the second leading cause of violent death and the leading cause of death among young Colombians less than 30 years of age [3].

According to official data from the sector, during 2012 there were a total of 45,592 road traffic injuries (13.5% fatal) in Colombia. Historically it can be observed that the number of deaths from traffic accidents has peaked over the last decade and has exceeded the 9.39% average for the previous nine years, which was 5,625 [4].

The impact of road accidents highlights the need to technically study this scourge of global public health problems that negatively impact the national panorama [5]. Sometimes analyses of traffic accidents are performed using quantitative statistical techniques, which place great importance on the evolution of accidents [6]. When the problem is approached in this way, the commonly used indicators such as morbidity or mortality appear to be highly aggregated and for that reason conceal the problem's determinant variables.

Worldwide, several studies have been developed that seek to explain the occurrence of traffic accidents from different perspectives. The analyses have addressed legal and judiciary perspectives, technical attributes of vehicles and infrastructure as well as the psychological, behavioral and socio-economic components of the road system users [7]. Recently, some analysis techniques based on the use of Geographic Information Systems (GIS) have been used, which allow the generation of maps, models and risk estimates from a spatial perspective.

Theoretically it is possible to reduce the number of accidents through specific actions at the highest accident sites; however, it is possible that the complexity of the problem requires a more elaborate analysis that considers the relationship between the variables involved [8].

Studies such as those in references [9-11] have shown that conventional linear regression models are sometimes inadequate to model the frequency of traffic accidents, as they may provide erroneous inferences. As such, recent research on the road accidents has based their methodologies on the use of Poisson and Negative Binomial regression models [12].

Currently, some researchers have conducted spatial analyses of accidents in order to establish relationships between the occurrence of accidents and the factors that contribute to their generation, using Poisson regression models [13,14]. Studies undertaken in the field have developed prediction models for high accident rates or potentially risky areas by using analysis techniques that can be grouped into four general categories: multivariate analysis, fuzzy logic, neural networks and empirical Bayes [15], which is an approach widely used in transport engineering [16].

The positive benefit of using GIS systems in safety analysis is evident. For example, a spatial data validation system based on GIS has been used to check the accuracy of the crash records [17]. This approach has also been used to explore different spatial and temporal visualization technologies to reveal patterns and significant factors relating to vehicle crashes, [18] or as a management system for accident analysis and the determination of hot spots [19]. Along similar lines to the present work, [20] shows that accidents can be related to infrastructure characteristics, while [21] relates accidents to socioeconomic properties such as income level, presence of children and crime rates.

In this context, using modeling techniques, this paper aims to establish the relationship between urban road accidents and the road, environment, traffic and control variables. Specifically, the model is applied to the city of Cartagena, identifying accident-prone locations using the empirical Bayesian method supported by GIS.

2. Theoretical framework

2.1. Statistical analysis procedure

The method of statistical accident analysis can be performed in four stages: building the model, calculation of the posterior distribution, the posterior distribution analysis, and inference and obtaining of final conclusions on the problem being considered.

In Poisson regression models the likelihood that n accidents occur in the i road section during j period is given by the following expression:

$$P\left(n_{ij}\right) = \frac{exp^{-\lambda_{ij}}\lambda_{ij}^{n_{ij}}}{n_{ij}!} \tag{1}$$

In turn, λ_{ij} is the expected value of n_{ij}, which can be expressed in terms of a vector of relevant variables describing the geometry of the road, the environment and other characteristics that affect the frequency of accidents in the sections studied. An exposure variable V_i is added to this set of variables, which relates to the traffic volume of the particular road section or to the vehicle-kilometers travelled. The expected value of the number of accidents can be estimated as follows:

$$E(n_{ij}) = \lambda_{ij} = \exp(\beta X_{ij} + LnV_{ij}^{\gamma} + \delta) \tag{2}$$

One of the main problems that models based on the Poisson regression can have is the over-dispersion of residuals, i.e., the model underestimates the degree of dispersion of the result because the Poisson distribution assumes that the counts variability of a covariant group is equal to the average. Failure to observe this relationship might result in the estimated coefficients being biased and inefficient, so a Negative Binomial distribution based on a Gamma distributed error term should be used. In this case, the expected value for the number of accidents is rewritten:

$$E(n_{ij}) = \lambda_{ij} = \exp(\beta X_{ij} + LnV_{ij}^{\gamma} + \delta + \varepsilon_{ij}) \tag{3}$$

Where $\exp(\varepsilon_{ij})$ is an error term that distributes Gamma and allows the variance of the mean to be differentiated as follows:

$$Var\left[n_{ij}\right] = E\left[n_{ij}\right] + \alpha E\left[n_{ij}^{2}\right] \tag{4}$$

In this case, α is known as an over-dispersion parameter, noting that when $\alpha = 0$ the Poisson distribution is obtained, for which the Negative Binomial probability is represented by the following mathematical expression:

$$P(n_i) = \frac{\Gamma(n_{ij}+\alpha^{-1})}{\Gamma(\alpha^{-1})n_{ij}!}\left[\frac{\alpha^{-1}}{\alpha^{-1}+\lambda_{ij}}\right]^{\alpha^{-1}}\left[\frac{\lambda_{ij}}{\alpha^{-1}+\lambda_{ij}}\right]^{n_{ij}} \quad (5)$$

Where $\lambda_{ij} > 0$ and $\alpha \geq 0$. This widely used model can be estimated by maximum likelihood [22-25].

2.2. *Identification of critical areas using the empirical Bayes method*

The empirical Bayesian approach for the analysis of road safety has gradually developed over the last thirty years and today it is a widely recommended method for the estimation of traffic accidents [26,27].

The empirical Bayesian method was originally developed to control the effect called "regression to the mean" in road safety studies "before and after". It is now also used to identify accident-prone locations in road safety analysis [28-32]. This method assumes that λ varies among different analysed sections and that the exact value for any of these is an unknown variable with a Gamma probability function density, expressed as follows:

$$f(\lambda) = \frac{\alpha^{\beta}\lambda^{\beta-1}e^{-\alpha\lambda}}{\Gamma(\beta)} \quad (6)$$

In these equations α is the shape parameter and β is the scale parameter of the Gamma function, with mean and variance given by eq. (7) and (8):

$$E(\lambda) = \frac{\alpha}{\beta} \quad (7)$$

$$Var(\lambda) = \frac{\alpha}{\beta^2} \quad (8)$$

The function parameters are determined from the data available about accidents in the reference group, and are expressed as follows:

$$\hat{\alpha} = \frac{\bar{n}}{\sigma^2 - \bar{n}} \quad (9)$$

$$\hat{\beta} = \frac{\bar{n}^2}{\sigma^2 - \bar{n}} \quad (10)$$

Where n is the number of accidents in a given section. The parameters of the posterior distribution, which is also of Gamma type, will be given by:

$$\alpha' = 1 + \hat{\alpha} \quad (11)$$

$$\beta' = n + \hat{\beta} \quad (12)$$

Where the expected value and the variance will be given by:

$$E(\lambda\backslash n) = \frac{\beta'}{\alpha'} \quad (13)$$

$$Var(\lambda\backslash n) = \frac{E(\lambda\backslash n)^2}{\beta'} \quad (14)$$

To identify the potentially critical sites, the probability that $E(\lambda|n)$ exceeds $E(\lambda)$ is:

$$P(\lambda|n > \lambda) = 1 - \int_0^{E(\lambda)} \frac{\alpha^{\beta}\,(\lambda\,|n)^{\beta-1}e^{-\alpha(\lambda\,|n)}}{\Gamma(\beta)}\,d(\lambda\,|n) \quad (15)$$

Where:

$E(\lambda)$: Expected number of accidents for the reference group during the study period.

$E(\lambda|n)$: Expected number of accidents adjusted by the empirical Bayesian method for a section of the reference group in the same study period.

Then, if the previously calculated probability exceeds threshold δ, which defines the confidence level chosen, the section is considered critical.

The determination of the parameters was done through maximum likelihood and, the statistical analysis was done using tests such as the t-student test.

3. Settings

The study was conducted in Cartagena, Colombia, which has a population of 923,219 inhabitants in an area of 616 km^2. The city has an urban road network of 656 km and its main economic activities are: tourism, petrochemicals and port industries.

The data used in this study corresponds to the information on accidents that was gathered in Cartagena during 2007 by the Administrative Department of Traffic and Transportation. The accidents classified as "only property damage" were not included in the study, so the analysis was focused on accidents involving deaths and injuries. Although we had more up-to-date information, we preferred to work with the data from 2007 considering that the other available data was affected by the construction of Cartagena's BRT system.

Local statistics from recent years show a significant increase in the number of fatalities and injuries and, a close relationship with the volumes of motorcycles circulating in the city, as shown in Fig. 1, 2.

It is possible that the phenomenon known as "mototaxismo" has a correlation with the number of road accidents in Cartagena. In this regard, the report on the status of road safety in the Americas region established that over the last ten years motorcycle-related deaths have dramatically increased [33].

One of the details that intrigued this study was the fact that Colombia is ranked as the country with the highest mortality rate for motorcyclists in Latin America, with 3.6 deaths per 100,000, followed by Brazil with 2.9, Paraguay 2.5 and Suriname 2.2 [33]. Fig. 1, 2 confirm that the percentage of accidents is high with some degree of severity in Cartagena when there is at least one motorcycle involved.

Fig. 3 shows that about 43% of those killed in traffic accidents correspond to motorcyclists, followed by pedestrians with 29%. This is consistent with what is shown in Fig. 4, which indicates that the type of accident with the most severe consequences is when a motorcycle collides with another vehicle.

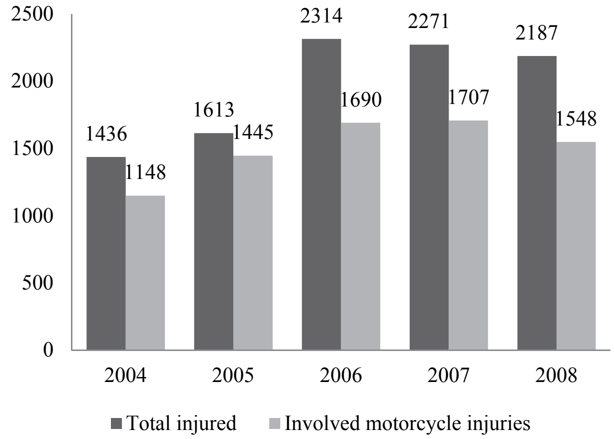

Figure 1. Motorcycle injuries and total injuries
Source: The authors.

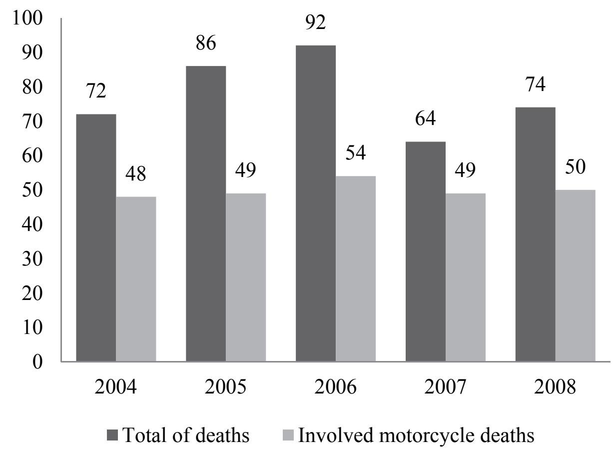

Figure 2. Motorcycle deaths and total deaths
Source: The authors.

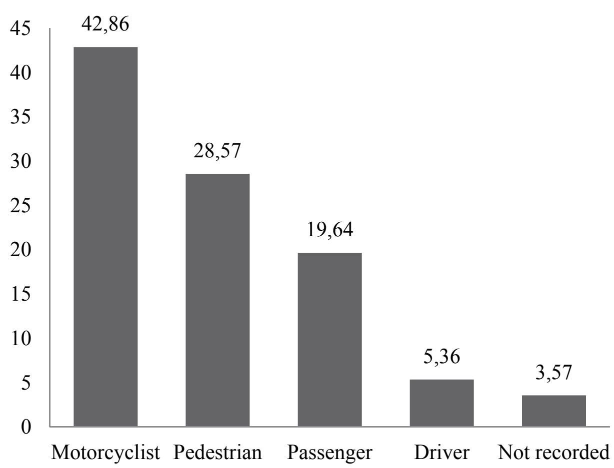

Figure 3. Percentage of deaths in traffic accidents for each condition
Source: The authors.

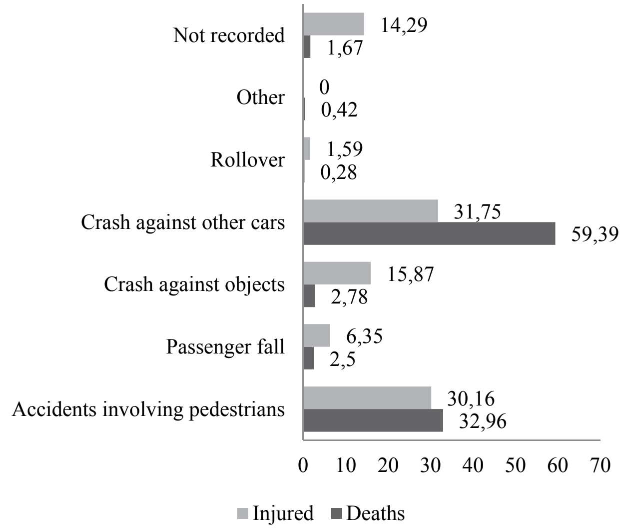

Figure 4. Percentage of injured and killed in traffic accidents by type of accident
Source: The authors.

Taking into consideration these behavioral patterns, we decided to include vehicular composition as one of the variables to be studied, in order to compare not only the effect of the motorcycle accident frequency, but also that of buses and cars. This is in response to referents that specifically demonstrate the impact of buses on accidents, both directly and indirectly [34-39]

4. Methodology

Exploratory and quantitative research was conducted, involving the processing of statistical data related to road accidents in the city of Cartagena in 2007.

The accident analysis considered the two usual classifications: accidents by severity and type. In terms of severity, accidents with injuries and deaths were considered, and only accidents with damage were excluded from the analysis. The second classification took into account if the accident happened as a result of a crash, if it was an accident involving pedestrians, a rollover, if an occupant fell, or any other type.

Each accident was classified by severity and type, and other aspects were analyzed such as its location on the road network of the city as well as the type and model of the vehicles involved. With respect to the individual attributes, age and gender were also considered, and the victim's status was specified as a: driver, passenger, driver's passenger or pedestrian. Additionally, some road geometric characteristics, road conditions and traffic flows were observed.

The methods used in the investigation primarily considered the Transport Research Laboratory's methodology (TRL), used in Great Britain, Sweden and other members of the European Road Assessment Programme (EuroRAP) and, secondarily, the Institute of Highways and Transportation's methodology (IHT) [40].

The TRL methodology does not take into account the possible causes of accidents, and the random component thereof; the statistical analysis simply determines the level of risk through the assessment of accidents and their severity. A risk index is calculated, which is defined as the number of fatal and serious accidents for 1,000 million vehicles per kilometer. Conversely, the IHT methodology proposes a clear and detailed procedure for the identification, diagnosis and selection of the sites to be studied. In this paper, combining both methods, the steps described below were developed.

4.1. Collection and processing of relevant information

Initially, we used the information contained in the accident reports of the Administrative Department of Traffic and Transport of Cartagena in 2007. The information was organized and digitized so that site of the event, date and time, age of people involved, type of vehicles involved and other important attributes could be identified.

In Colombia, as in other countries, the use of accident data from police reports has certain disadvantages [41, 42], also not all traffic accidents with victims are reported by the police [43]. For this reason, we compared the available information provided by the Road Prevention Fund (FPV) for the same period. The results from this verification were consolidated into a database of 1,367 traffic accidents with injuries or deaths.

Complementary, topographic surveys were conducted to define the geometric characteristic of each case study, such as road widths and turning radii. Additionally, vehicle volumes and vehicle composition studies were also applied, and were supplemented with information from previous studies conducted by the city agents. We also had cartographic information from various sources, which was used to quantitatively identify possible factors involved in the occurrence of accidents.

4.2. Spatial analysis

From the spatial distribution of accidents, a database to classify the road network in areas with similar characteristics in terms of traffic, land use, occupation of public space, and geometry was built. This classification allowed 241 sections of the road network to be identified and, for each of them, the number of accidents was recorded.

The spatial analysis also accessed maps by using kernel density tools and calculated magnitudes per area unit based on the entities of interest, in this case the location of accidents. This type of analysis has been used to analyze accidents in various urban settings, located in different countries such as Canada [44], India [45] and Turkey [19].

4.3. Generation of statistical models

The identification of explanatory variables was performed by Principal Component Analysis (PCA), which is widely used in the analysis of data that are not dimensionally homogeneous or when the order of magnitude of the random variables measured is not the same as with the data studied.

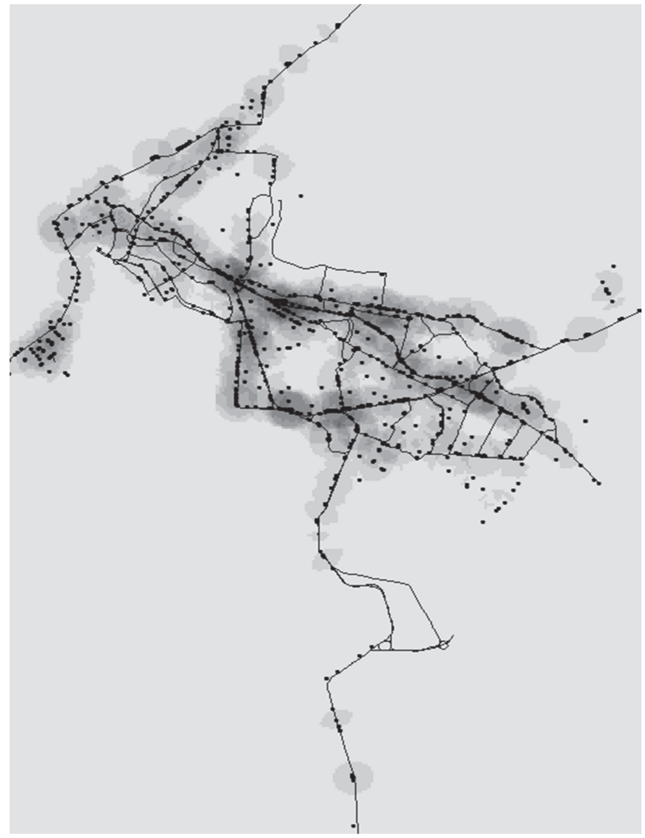

Figure 5. Spatial analysis of the concentration of accidents involving injuries using kernel type tools
Source: The authors.

The PCA identified the following variables that explain the frequency of accident occurrence: land use (1: Commercial, 0: otherwise), number of intersections, road width, section length, traffic directions (1: Two-way circulation, 0: otherwise) and average daily traffic.

Poisson and Negative Binomial regression models were estimated to describe the variation of the observed frequency of accidents on the section i during period j. Then, using an empirical Bayesian analysis, the identification of accident-prone locations was undertaken.

5. Results

Accident spatial analysis based on GIS allowed, besides the identification of homogeneous sections, the existing relationship between infrastructure, land use and accidents to be established, in order to consolidate the database that was to be used in the model generation phase. Fig. 5, which contains the spatial analysis of the concentration of accidents resulting in injuries using kernel type tools, clearly illustrates the relationship between road infrastructure and accidents. Other GIS data layers, such as layer urban land use for the city of Cartagena, was used for the spatial analysis prior to model calibration.

The statistical summary of the considered explanatory variables is shown in Table 1, where $AADT_B$, $AADT_M$ and $AADT_A$, represent the average daily transit for buses, motorcycles and cars, respectively.

Table 1.
Statistical summary of independent variables.

Variable	Notation	Mean	Mode	Deviation
Length of section (m)	L	533.39	500	370.40
No. of intersections		5	1	4.54
$Ln\ (AADT \cdot L)$	X_1	7.64	9.24	1.98
Road width	X_2	7.82	7.30	2.00
$AADT_B \cdot L/1000$	X_3	1.04	2.69	1,65
$AADT_M \cdot L/1000$	X_4	2.53	3.31	4,15
$AADT_A \cdot L/1000$	X_5	3.62	4.35	5.09
No. of intersections/L	X_6	0.01	0.01	0.0068

Source: The authors.

Although the model calibration was undertaken with and without constant, a better fit in those cases where the constant was specified was always found. This behavior was introduced in the Poisson model as well as in the negative binomial type models.

The results are presented in Table 2. This contains estimates and the statistical t-student that are in parentheses, which allows significance to be measured. It may be noted that the over-dispersion parameter is small and statistically insignificant, so the estimates of the obtained parameters for the two proposed models do not differ substantially.

All parameters have the expected signs and the important effect of the AADTM and AADTB is highlighted. This is much smaller than the effect of cars. It can be seen that the marginal effect of a motorcycle on the frequency of accidents with deaths and injuries is 2.5 times greater than the effect of an additional bus and 6 times larger than that of an automobile.

Moreover, *ceteris paribus* roads with two-way traffic have higher accident frequency. The same analysis is true for the sections located in areas with commercial land use, characterized by the strong presence of pedestrians. Intersection density, i.e. the number of intersections divided by the length of the section, is also a factor that tends to increase the occurrence of accidents, but the statistical significance of this variable is not high.

Table 2.
Estimated models.

Parameter	Notation	Poisson model	Negative Binomial
Constant		-0.1481 (-0.66)	-0.1481 (-0.69)
$Ln\ (TPDA \cdot L)$	X_1	0.1813 (7.74)	0.1813 (8.08)
Road wide	X_2	-0.0240 (-1.30)	-0.0240 (-1.42)
$AADT_B \cdot L/1000$	X_3	0.0817 (3.37)	0.0817 (3.83)
$AADT_M \cdot L/1000$	X_4	0.0317 (3.87)	0.0317 (4.74)
$AADT_A \cdot L/1000$	X_5	0.0117 (1.36)	0.0117 (1.66)
No. of intersections/L	X_6	6.8561 (1.45)	6.856 (1.55)
Two-way	X_7	0.1376 (1.96)	0.1375 (2.11)
Commercial use	X_8	0.1046 (1.38)	0.1046 (1.50)
Over-dispersion	α		0.0250 (1.61)
R^2		69.8	81.9

Source: The authors.

Table 3.
Classification of critical sections identified.

Type of road	Total of sections	Identified critical sections	Percentage (%)
Arterial	71	48	67.6
Collector	52	19	36.5
Local	118	2	1.7
Total	241	69	28.6

Source: The authors.

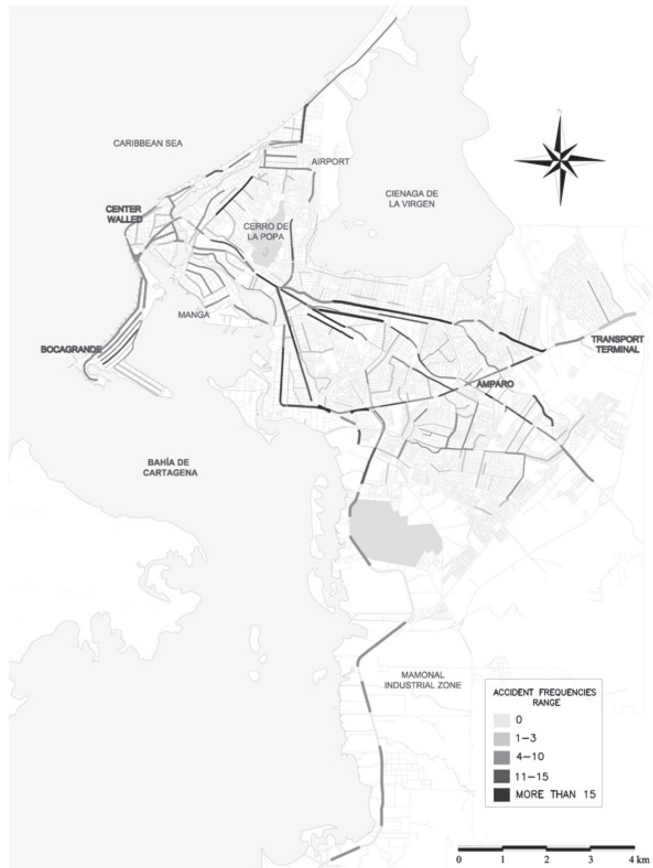

Figure 6. Density of accidents in Cartagena
Source: The authors.

Following the methodology proposed to implement the empirical Bayesian approach, the following parameters were calculated for the analyzed group of sections: S^2=31.23, $\hat{\alpha}$=0.441 and $\hat{\beta}$=2.424. As shown in Table 3 there were a total of69 critical sections, corresponding to 28.6% of sections analyzed, identified.

It is important to note that the largest number of accident-prone locations was located on arterials, on which 67.6% of the sections were considered critical. We also found the same to be true on the collector roads to a lesser degree. Local roads with just 1.7% of accident-prone locations were also identified. Fig. 6 illustrates this by showing the density of accidents resulting in injuries or deaths for the city of Cartagena, which identifies the accident-prone locations studied.

6. Conclusions

In an urban context, such as in the city of Cartagena, we have found empirical evidence demonstrating the relationship between the frequency of accidents and variables as well as traffic density, road width, density of intersections per segment, flow direction and land use environment.

The results found are representative of cities located in less developed countries, with low amount of traffic, which have a high occupancy of public space and important use of public transport and motorcycles in the cities. The latter are even sometimes used as an informal mode of public transport. This analysis enabled us to, from a systemic approach; identify the most potentially accident-prone areas with the help of the empirical Bayesian method.

The study was able to successfully involve spatial analysis of accidents through the use of a GIS to identify homogeneous sections in Cartagena, that were then established by modeling the impact of vehicular volumes of motorcycles, buses and cars on the expected number of traffic accidents for each sector. This showed that the marginal effect on the accident rate for motorcycles is significantly higher than for that of buses and, it is much higher than for that of cars.

Regarding road infrastructure variables, we found that there are more accidents in the sections with two-way traffic than in the single ones. The level of risk also decreases with the width of the road. This is a very important discovery to be taken into consideration when embarking on plans for the operational management of the road network in the city, as well as well as when the urban road sections for planning are defined. Likewise, the sections located in commercial areas, which normally have high presence of pedestrians, tend to have a higher frequency of the occurrence of accidents with serious consequences. It is in these places where authorities should maintain a greater presence to mitigate problems resulting from accidents.

By using the empirical Bayesian approach it was possible to statistically identify critical areas for accidents, which will allow local authorities to focus the efforts of mitigating the problems caused by the accidents. The method employed showed the importance of the spatial location of the accident and the formation of reference groups for data analysis, which were initially assessed on the basis of their similar characteristics, regardless of the frequency or severity of the accidents.

Among a total of 241 sections established, it was found that nearly 30% are identified as high-risk accident sections. This percentage is consistent with the findings of [15] who found that most accidents occurred on curves, which represent 29.7% of the total length of the studied motorway. These findings can also be found in [7] who reported that in the case of regional roads, 26% of basic spatial units (hectometer of road) have at least 1 accident.

The estimation of predictive Poisson type and negative binomial models for the frequency of accidents resulting in either injuries or deaths allows causal relationships to be established between the frequency of accidents and the explanatory variables. In this sense, this research provides some initial insights into directions for actions that the Administrative Department of Traffic and Transportation could take in order to reduce the likelihood of high impact accidents in urban environments.

First, measures should be focused on arterials as they are the areas with the highest number of critical sections, especially those located in areas with commercial land use that are characterized by a heavy pedestrian presence.

Future research can use similar methods to those presented in this paper for “before and after” studies that continue the application of the empirical Bayesian approach in response to the arrival of Cartagena’s BRT system.

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