

Article

Effect of Built Environment Factors on Pedestrian Safety in Portuguese Urban Areas

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Abstract: This paper identifies and analyzes variables that influence pedestrian safety based on the definition of models of pedestrian crash frequency for urban areas in Portugal. It considers three groups of explanatory variables, namely: (i) built environment; (ii) pedestrian infrastructure, and (iii) road infrastructure, as well as exposure variables combining pedestrian and vehicular traffic volumes. Data on the 16 variables considered were gathered from locations in the counties of Braga and Guimarães. The inclusion of pedestrian infrastructure variables in studies of this type is an innovation that allows for measuring the impacts of the dimensions recommended for this type of infrastructure and assessing the implementation of policies to support the mobility of vulnerable users, especially pedestrians. Examples of such variables are unobstructed space for pedestrian mobility and the recommendable distance separating regulated crossings. Zero-Truncated Negative Binomial Regression Models (ZTNB) and Generalized Estimation Equations (GEE) are used to develop crash prediction models. Results show that in addition to the variables identified in similar studies such as carriageway width, other statistically significant variables like longitudinal slope and distance between crosswalks have a negative influence on pedestrian safety. On-street parking places, one-way streets, and the existence of raised medians have an opposite contribution to safety.



Citation: Barón, L.; Otila da Costa, J.; Soares, F.; Faria, S.; Prudêncio Jacques, M.A.; Fraga de Freitas, E. Effect of Built Environment Factors on Pedestrian Safety in Portuguese Urban Areas. *Appl. Syst. Innov.* **2021**, *4*, 28. <https://doi.org/10.3390/asi4020028>

Academic Editor: Claudio Zunino

Received: 17 February 2021

Accepted: 13 April 2021

Published: 16 April 2021

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Keywords: pedestrian safety; road infrastructure; built environment; urban areas; road safety

1. Introduction

The World Health Organization (WHO) has revealed that every year there are 1.35 million deaths in the world caused by road traffic. Globally, pedestrians and cyclists represent 26% of all deaths [1]. In Portugal, according to the Annual Fatalities Report for 2018 (*Relatório Anual de Sinistralidade*), among the categories of road users, pedestrians have the second highest death rate, accounting for around 21% of deaths, which corresponds to a rate of two deaths per 100 victims [2].

Regarding the areas and locations where crashes involving pedestrians are most prone to occur, the European Commission has found that pedestrians are at greatest risk on urban roads where 69% of pedestrian deaths occur [3]. That being so, there is an urgent need to investigate the factors that have the most influence on pedestrian crashes within urban areas, making it feasible to create policies designed to reduce the number of these crashes and to promote pedestrian transport modes [4,5].

Several studies in the field of road safety have already been conducted as part of the effort to find solutions for the problem of traffic crashes involving vulnerable road users such as pedestrians [6,7]. The studies show that the main factors directly related to exposure to risk and the frequency and severity of crashes are the pedestrian traffic volume, the vehicular traffic volume, and the speed of traffic operation [8–11]. However, there is still a lack of analyses with a broader outreach encompassing the influence of factors associated with the pedestrians' spaces used for their mobility [12,13]. Not all environments are equally safe, and various characteristics may prove to be related to different levels of the risk to pedestrians' safety [12,14].

The present paper aims to identify factors related to the built and road environments in addition to the characteristics of the traffic that influence pedestrian safety in Portuguese urban roads, using a transversal study (aggregated data) and a longitudinal study (disaggregated data). The environmental factors are classified into three groups: built environment, pedestrian infrastructure, and road infrastructure. Within each group, the factors were identified by developing crash prediction models using two modeling techniques: Zero-Truncated Negative Binomial (ZTNB) and Generalized Estimating Equations (GEE). These techniques were selected due to the limitations of the database (see Section 3.2). To develop the models, the Portuguese National Road Safety Authority (*Autoridade Nacional de Segurança Rodoviária*—ANSR) made available a database with information on all the road crashes registered for the period from 2009 to 2015. The complete database also contains a set of specific variables referring to the road network characteristics selected for this study, which are located in the Portuguese counties of Braga and Guimarães.

2. Factors Influencing Pedestrian Safety

The safety problems associated with pedestrian mobility can often be related to the imbalance between the design and use of public space [10,15]. Therefore, it is essential to carry out a rigorous interpretation of the impact of factors associated with the built environment, pedestrian, and road infrastructure (Figure 1).



Figure 1. Factors influencing pedestrian safety.

In this sense, Table 1 presents a summary of the existing studies on pedestrian safety and the variables used.

Table 1. Variables addressed in pedestrian safety works.

Group	Variable	Literature Review
Built Environment	Land use	Granié et al. [4], Miranda-Moreno et al. [9], Ukkusuri et al. [10], Ukkusuri et al. [16], Chen and Zhou [17], Pulugurtha and Sambhara [18], Wang and Kockelman [19], Wedagama et al. [20], Wier et al. [21], Mukherjee and Mitra [22], Thomas et al. [23]
	Bus stops	Miranda-Moreno et al. [9], Ukkusuri et al. [10], Ukkusuri et al. [16], Chen and Zhou [17], Wang and Kockelman [19], Thomas et al. [23]
	On-street parking	Granié et al. [4], Thomas et al. [23], Martin [24], Rankavat and Tiwari [25]
Road Infrastructure	Road classification	Miranda-Moreno et al. [9], Ukkusuri et al. [10], Ukkusuri et al. [16], Dumbaugh and Rae [26].
	Carriageway width	Granié et al. [4], Ukkusuri et al. [10], Ukkusuri et al. [16], Mukherjee and Mitra [22], Rankavat and Tiwari [25], Lee and Abdel-Aty [27], Noland and Oh [28], Sawalha and Sayed [29]
	Traffic directions	Ukkusuri et al. [10], Ukkusuri et al. [16], De Lavalette et al. [30], Dommes et al. [31], Holland and Hill [32], Lobjois and Cavallo [33]
	Central reservations	Thomas et al. [23], Rankavat and Tiwari [25], De Lavalette et al. [30], Damsere-Derry et al. [34], Zegeer et al. [35], Gårder [36]
Pedestrian Infrastructure	Sidewalk	Ding et al. [12], Ukkusuri et al. [16], Rankavat and Tiwari [25]
	Pedestrian network continuity	Rankavat and Tiwari [25], Pucher and Dijkstra [37]
	Crosswalk type and their localization	Millot [15]
Traffic Characteristics	Public lighting	Mukherjee and Mitra [22], Lee and Abdel-Aty [27], Assum et al. [38], Wanvik [39]
	Pedestrian traffic volume	Elvik [8], Miranda-Moreno et al. [9], Chen and Zhou [17], Pulugurtha and Sambhara [18], Thomas et al. [23], Dumbaugh and Rae [26], Zheng et al. [40]
	Vehicular traffic volume	Elvik [8], Miranda-Moreno et al. [9], Pulugurtha and Sambhara [18], Wedagama et al. [20], Wier et al. [21], Thomas et al. [23], Rankavat and Tiwari [25], Lee and Abdel-Aty [27], De Lavalette et al. [30], Clifton et al. [41], Diogenes and Lindau [42], Landis et al. [43], Yagil [44]

2.1. Factors Associated with the Built Environment

Several studies have analyzed the effect of land use on the frequency of pedestrian crashes. Residential land use was associated with a significantly lower probability of pedestrian crash [10], while on the other hand, a higher fraction of industrial, commercial, and open land use types was associated with a higher probability of crashes [9,10,16]. In other studies, mixed land use was associated with higher frequency and risk of pedestrian crashes [12,17,19].

Other factors in the group of built environments that some authors have identified as contributing to an increase in crash frequency involving pedestrians include the existence of bus stops and the presence of parking spaces along the street. One of the causes may be due to the constant presence of the buses or vehicles parked, which can block the view of pedestrians and drivers. Additionally, zones with transport services and on-street parking are expected to have more human activities, associated with more conflicts between pedestrians and vehicles [9,16,17]. However, some authors found that higher bus stop density appears to contribute to less-injurious crash rates [19].

2.2. Factors Associated with Road Infrastructure

Mahalel and Szternfeld [45] put forward the idea that improving urban road infrastructure could increase the risk of crash. The authors explain that better conditions would lead drivers to reduce their levels of attention and drive at higher speeds due to the feeling of comfort they experience. Fatal collisions in urban areas also seem to be mainly influenced by the effect the type of road has on vehicle speed [10,26].

In addition, there are studies suggesting that the width of the roadway and the number of traffic lanes are strongly related to greater exposure of pedestrians to the risk of a crash

due to the following factors: vehicles circulating simultaneously in several lanes can mask areas of driver visibility and prevent them from seeing pedestrians [10,15,29]; the increased time needed for pedestrians to get across the road [10]; and the heightened sense of safety and comfort drivers experience on such roads, leading them to drive at higher speeds [4].

2.3. Factors Associated with Pedestrian Infrastructure

The network for pedestrian circulation is typically undersized and the infrastructure itself is inadequate; there is no logic behind the layout of the walkways, nor continuity of sidewalks, especially in the vicinity of crossings. The existence of obstacles in the sidewalk such as traffic lights and other urban furnishings can force pedestrians to deviate from their course, making their trips riskier and less attractive and often forcing them to cross the road in dangerous spots or places with poor visibility [15].

It is also well-known that pedestrians almost always choose the route that is the shortest, quickest, and requires the least effort. In the context of road user safety, the location of pedestrian crossings should be carefully considered to ensure that they are installed in places where pedestrians will not ignore them [46].

2.4. Factors Associated with the Traffic Characteristics

Most of the research into pedestrian road safety has considered and included traffic volume as one of the explanatory variables when modeling crash statistics [9,20]. Diogenes and Lindau [42] observed that high traffic flows lead to a reduction in traffic speed and, therefore, to a reduction in the crash rates. However, other authors report that the frequency of traffic crashes involving pedestrians increases when there is an increase in the number of motorized vehicles [8,9]. Regarding the volume of pedestrian traffic, Chen and Zhou [17] found that an increase in pedestrian volumes increases the probability of pedestrians being run over due to the increased exposure to traffic.

3. Materials and Methods

The method adopted to identify the major characteristics (factors) of public places where pedestrians circulate and have been involved in crashes consisted of four steps (Figure 2).



Figure 2. Principal steps of the method.

3.1. Definition of the Variables

After carrying out a broad literature review in the field of pedestrian safety, the present study identified three groups of independent variables, in addition to those related to the characteristics of the traffic: built environment, pedestrian infrastructure, and road infrastructure.

Table 2 shows these variables along with the dependent variable: the number of annual pedestrian crashes for the GEE model and the corresponding aggregated number for the ZTNB model.

Table 2. Model dependent and explanatory variables.

Category	Variable	Description	Mean	Std. Dev.	Min	Max
Dependent	Y	Number of pedestrian crashes for GEE model and ZTNB model	1.125	1.283	0	6
Built environment	ROAD_L	Roadway length (m)	7.875	4.874	1	21
	LU	Land use (Mixture = 1, Residential = 0)	496.4	287.322	68	1317
	PARKS	On-street parking places (Yes = 1, No = 0)				
	BUS	Bus stops (Yes = 1, No = 0)				
Pedestrian infrastructure	NET_C	Pedestrian network continuity (Yes = 1, No = 0)				
	SIDEWALK	Sidewalk unobstructed width (m)	1.233	0.649	0	3
	DIST	Average distance between crosswalks (m)	167.223	150.976	30	918
	SLOPE	Longitudinal slope (m)	0.03	0.029	0	0.154
	LIGHTING	Number of lighting posts more than 7 m away from the middle of pedestrian crossing	1.15	1.231	0	4
Road infrastructure	OBST	Presence of an obstacle on the light pole (Yes = 1, No = 0)				
	C1	Functional Road Classification (Collector and Principal Distributor = 0, Local Distributor and Local Access = 1)				
	C2	(Collector and Local Distributor = 0, Principal Distributor and Local Access = 1)				
	LANES_TF	Number traffic lanes	2.8	1.381	1	6
	WIDTH_W	Carriageway width (m)	3.399	0.422	2.775	4.9
	DIRECTIONS	Traffic directions (One-way = 1, Two-way = 0)				
	R_MED	Raised Medians (Yes = 1, No = 0)				

Table 2. Cont.

Category	Variable	Description	Mean	Std. Dev.	Min	Max
Traffic characteristics	LnVped (Vped)	Natural logarithm of pedestrian traffic volume during the peak period (Ped/h). Offset variable	6.093 (575.277)	0.755 (423.438)	4.143 (62.968)	7.781 (2394.620)
	LnVveh (Vveh)	Natural logarithm of vehicle traffic volume during the peak period (Veh/h)	6.976 (1419.900)	0.797 (1080.182)	4.823 (124.305)	8.539 (5109.930)
	LnSPV (SPV)	Natural logarithm of the sum of pedestrian and vehicular traffic volume during the peak period (Total traffic/h)	7.395 (1995.177)	0.678 (1249.166)	5.451 (232.939)	8.758 (6363.904)
	LnPVQ (PVQ)	Natural logarithm of the product between the pedestrian volume and the squared vehicular volume (Ped \times Veh ² /h)	20.045 (2228879144.864)	1.993 (5148747239.305)	14.337 (1684557.621)	24.253 (34125977944.548)

The outstanding variables of those groups, in addition to those identified in the literature review, were associated with pedestrian infrastructure. They help to evaluate the impacts of the dimensions recommended for this type of infrastructure and to assess the implementation of policies to support the mobility of pedestrians. Examples of such variables are sidewalk continuity, unobstructed space for pedestrian mobility, and the recommendable distance separating regulated crossings. As no studies addressing the influence of those variables on pedestrian safety were found in the literature, it is accordingly interesting to verify their possible relation to the numbers of registered pedestrian crashes in a given urban road.

3.2. Organization of the Database

In this study, data for two Portuguese counties, Guimarães and Braga, were collected. The database contains three groups of information: records of crashes involving pedestrians in streets with crosswalks without traffic light control, characteristics of the roadway surroundings, and vehicular and pedestrian traffic volumes. The crash data were obtained from a broad data set supplied by the ANSR covering the period of January 2009 through December 2015.

To investigate the factors that effectively influence pedestrian safety in urban streets and roads, it is necessary to collect a great amount of detailed and reliable data on road characteristics, traffic flows, pedestrian flows (which involves proceeding to manual counts), etc. Gathering these data was not possible on the whole road networks of Guimarães and Braga. Thus, it was decided to limit the sample to urban roads or streets where at least one pedestrian was injured in the total period (seven years) of analysis. However, the data can show zero counts for one or more of those years.

Therefore, 20 roadways were identified and selected in each county, regardless of the type of road, with a total of 163 pedestrian crashes in the county of Guimarães and 152 in the county of Braga (Figures 3 and 4).

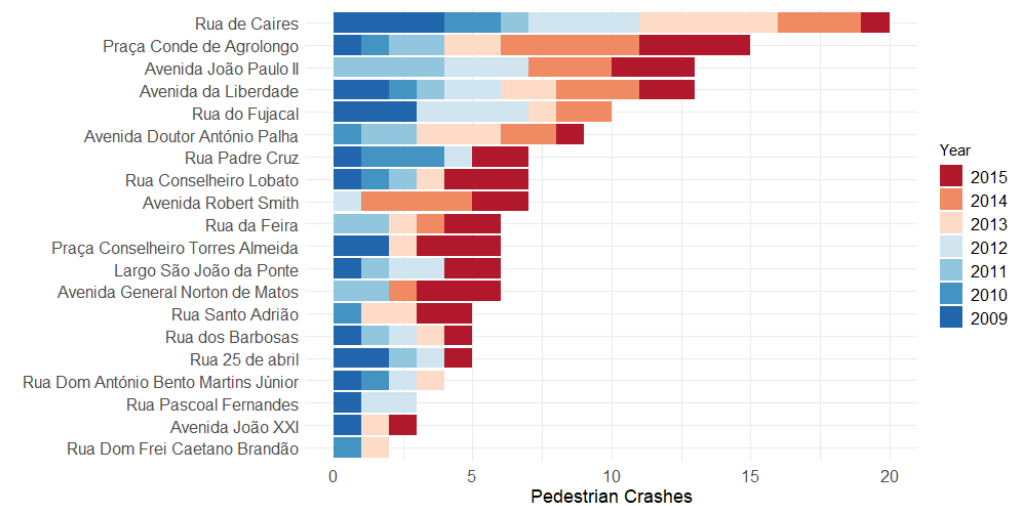


Figure 3. The number of pedestrian crashes per road and year in Braga.

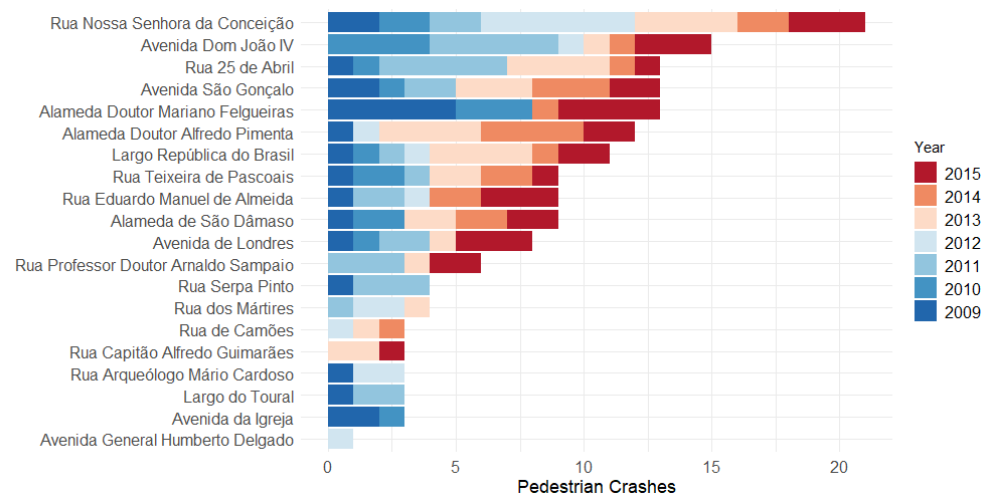


Figure 4. The number of pedestrian crashes per road and year in Guimarães.

Despite the apparently reduced number of roadways under study (40 in total), the data concerns the center of two medium-sized Portuguese cities with populations of approximately 52,000 (Guimarães) and 140,000 (Braga) inhabitants. Furthermore, the streets considered in this study were those without traffic lights and where the crash frequency was higher.

The data corresponding to each one of the 40 roads were organized into a database that encompassed all the previously selected factors that could influence the frequency of crashes with pedestrians, along with the annual number of these occurrences.

Except for the pedestrian crash statistics, all the data were obtained by observation and analysis of each road. Once the roads had been defined, manual traffic counts were made at peak hours for all of them in the period from 18 May 2017 to 22 June 2017. The peak hours were considered to be from 08 a.m. to 10 a.m., and 5 p.m. to 7 p.m., from Mondays to Fridays. Additional information was gathered regarding the explanatory variables of the built environment, pedestrian infrastructure, and road infrastructure.

Given the lack of traffic data for all the years analyzed in the road crashes database supplied by the ANSR (2009 to 2015), different growth rates were estimated for both road and pedestrian traffic, based on statistics supplied by the National Statistics Institute (*Instituto Nacional de Estatística*—INE). The data extracted to determine the growth rates of pedestrian volumes were statistics regarding the numbers of people who go on foot to undertake their daily activities. The growth rates of the vehicle volumes were based on the numbers of people who go to and from using automobiles (as a driver or a passenger), collective transport of companies or schools, motorcycles, and bicycles. These data were taken from Portugal's 2001 and 2011 censuses [47,48].

3.3. Model Development

This study used two statistical modeling techniques to determine the effect of factors that contribute to the occurrence of pedestrian crashes in urban roads. The Zero-Truncated Negative Binomial regression model (ZTNB) is applied in situations where the analyst aims to apply a NB model, but does not take into account observations with the value zero for the dependent variable due to the sampling scheme employed [49,50]. In the present research, the model fitted for aggregated data corresponded to this situation. The Generalized Estimating Equations (GEE) use the disaggregated (longitudinal) data and are appropriated for statistical analyses aiming to describe the average value of the dependent variable based on a set of independent variables by taking into account the correlation among their different values (in the present case, annual values). In addition, the main effects and interactions of independent, categorical, or continuous, variables are tested.

Several authors have described them in detail, including the different correlation structures that can be used with GEE [51–53]. The exchangeable correlation structure was used.

The particular sampling scheme used (removing streets where zero counts were observed for each of the seven years) involves some loss of information but does not require an adaptation of the GEE modeling technique, since this method is not based on distributional assumptions regarding the random effects.

The general form adopted in this paper for collision prediction models was the following, formulated here for the GEE case (Equation (1)):

$$y_{mt} = Vped_{mt}^{\alpha} \times V_{mt}^{\gamma} \times EXP\left(\beta_0 + \sum_{j=1}^J \beta_j X_{jmt}\right), m = 1, \dots, 40, t = 2009, \dots, 2015 \quad (1)$$

$\beta_j, \gamma \in \mathbb{R}, j = 0, 1, \dots, J$

$\alpha = 1$ ($Vped$ is an offset variable in the model)

where:

y_{mt} —Number of pedestrian crashes for street m within t time period;

$Vped_{mt}$ —Pedestrian traffic volume during the peak period in street m within t time period (this is treated as an offset in the model);

V_{mt} —Variables associated with the exposure to traffic of pedestrians in street m within t time period (see variables regarding to the traffic characteristics presented in Table 2);

EXP —Exponential function;

X_{jmt} —Explanatory variable j observed in street m within t time period (see variables regarding to the built environment, pedestrian, and road infrastructure presented in Table 2);

γ, β_j —Model parameters to be estimated; and

J —Number of explanatory variables X .

Transforming the Equation (1) to logarithmic function:

$$\ln y_{mt} = \alpha \times \ln Vped_{mt} + \gamma \times \ln V_{mt} + \beta_0 + \sum_{j=1}^J \beta_j X_{jmt}, m = 1, \dots, 40, t = 2009, \dots, 2015 \quad (2)$$

The pedestrian traffic volume during the peak period ($Vped$) was introduced in the models as an “offset variable” to represent exposure to risk. Furthermore, three variables associated with the exposure of traffic to pedestrians (V) were used: (i) $Vveh$, vehicle traffic volume during the peak period, (ii) SPV , the sum of pedestrian and vehicular traffic volume during the peak period, and (iii) PVQ , the product between the pedestrian volume and the squared vehicular volume, used as the criterion for the installation of a pedestrian crossing in the UK that has been universally adopted. Natural logarithm was applied to the variables of vehicular and pedestrian traffic volumes due to the calibration procedure. The descriptive statistics of the continuous variables considered in this study are presented in Table 2.

The variables were selected using the backward technique during the model calibration. The final model presents the explanatory variables that are statistically significant to a level of 10%. This significance level is acceptable given the model purpose, which is identifying factors affecting pedestrian crashes and not estimating the number of these crashes. Another critical aspect of the modeling process was the analysis of the signs of the model parameters, which should be compatible with what would be expected from the traffic engineering point of view. The study made use of SAS[®] Software (SAS Institute, Lisboa, Portugal), and RStudio (1.1.463) Software (PBC, Boston, MA, USA).

3.4. Model Evaluation

The assessment of the fitted model is an essential part of the regression analysis. The Akaike’s information criterion, AIC, was used to assess the goodness of fit in ZTNB models. The lower the AIC, the better the goodness of fit (see more details on Akaike [54]). As for

GEE, this criterion cannot be used directly and should be replaced by QIC (quasi-likelihood under the independence model criterion), proposed by Pan [55].

Residual analysis is a helpful tool for the validation of the fitted model [56]. The Pearson residuals were considered for performing residual analysis. Plots of Pearson residuals versus fitted values and versus observation number can be used to assess the adequacy of the fitted model. If the model is correctly specified, these plots should show no detectable pattern.

Additionally, the mean absolute deviation (MAD), Equation (3), and root mean square error (RMSE), Equation (4), were calculated to investigate further the variation of the estimates given by the model fitted relative to the data used [57]. Smaller values are preferable to larger ones.

$$MAD = \frac{1}{MT} \times \sum_{m=1}^M \sum_{t=1}^T |\hat{y}_{mt} - y_{mt}| \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{m=1}^M \sum_{t=1}^T (\hat{y}_{mt} - y_{mt})^2}{MT}} \tag{4}$$

where:

MAD—Mean absolute deviation;

RMSE—Root mean square error;

\hat{y}_{mt} —Predicted number of pedestrian crashes for street m within t period;

y_{mt} —Observed number of pedestrian crashes for street m within t period.

4. Results

The analysis was conducted on two levels: one based on aggregated data (using ZTNB) and another based on disaggregated data (using GEE). The estimated parameters (γ , β_j and β_0) and standard errors (S.E.) for the variables included in the final model, i.e., those for which the p-value was less than 0.10, are listed in Tables 3 and 4.

4.1. Modeling Temporal Aggregated Crash Data

The dependent variable for the modeling temporal aggregated crash data is the total number of pedestrian crashes over the whole period (2009–2015) in a given street. The model developed by using Zero-Truncated Negative Binomial Distribution (ZTNB) is presented in Table 3. The variables related to the risk exposure LnVveh, LnSPV, and LnPVQ were not significant. For this reason, the model is the same in all cases (Model 0).

Table 3. ZTNB model—aggregated crash data (Model 0).

Category	Variable	Parameter Estimate	S.E.	p-Value
Built environment	ROAD_L	0.0012	0.0002	<0.0001
	PARKS	−0.3418	0.151	0.0236
Pedestrian infrastructure	NET_C	0.5003	0.2313	0.0305
	DIST	0.0035	0.0005	<0.0001
	SLOPE	9.5943	2.3012	<0.0001
Road infrastructure	WIDTH_W	0.3525	0.1646	0.0323
	DIRECTIONS	−0.4972	0.2211	0.0245
	R_MED	−0.3313	0.1665	0.0466
Intercept (β_0)		−6.8345	0.7629	<0.0001
AIC			238.3586	
MAD			2.8962	
RMSE			3.8673	

Table 4. GEE models—disaggregated crash data (Models 1, 2 and 3).

Category	Variable	Model 1 and Model 2			Model 3			
		Parameter Estimate	S.E.	p-Value	Parameter Estimate		S.E.	p-Value
		β_j			β_j	γ		
Built environment	ROAD_L	0.0013	0.0003	<0.0001	0.0013		0.0003	0.0001
	PARKS	−0.2722	0.1423	0.0558				
Pedestrian infrastructure	NET_C				0.4311		0.2475	0.0815
	DIST	0.0025	0.0003	<0.0001	0.003		0.0004	<0.0001
	SLOPE	9.7511	2.3645	<0.0001	6.9419		2.5352	0.0062
Road infrastructure	WIDTH_W	0.5105	0.1817	0.0050	0.5329		0.1657	0.0013
	DIRECTIONS				−0.456		0.2528	0.0713
Exposure	LnVveh							
	LnSPV							
	LnPVQ					−0.0907	0.0524	0.0833
Intercept (β_0)		−9.0026	0.7090	<0.0001	−7.7187		1.1768	<0.0001
QIC			455.5955				461.7280	
MAD			0.97362				0.97769	
RMSE			1.25250				1.24312	

In the category of pedestrian infrastructure, the variables SLOPE and DIST indicate that they contribute to the increase in the frequency of pedestrian crashes. The steeper road incline may be related to higher speeds practiced by drivers. However, this variable may also be related to the distance between crosswalks because steeper streets, or far back crosswalks, can lead to a higher probability that pedestrians will not cross the street at crosswalks and will choose the fastest and easiest way to cross the street.

The result of the variable NET_C is opposite to what would be expected. The continuity of the pedestrian infrastructure should help to reduce the frequency of crashes due to minor conflicts between pedestrians and vehicular traffic. On the contrary, this result may indicate that lack of good walking conditions may lead to safer behaviors.

Lastly, within the group of road infrastructure, two variables had a positive effect on the safety of pedestrians: DIRECTIONS and R_MED. These variables could help to reduce the estimated number of pedestrian crashes, first, by the fact that in one-way streets the task of observing vehicles is much easier for pedestrians and there may be no vehicle masks that move in another direction. Second, medians serve as a refuge for pedestrians when they cross the streets as they can do it in two different stages.

Otherwise, the carriageway width indicates that it contributes to the increase of the frequency of crashes with pedestrians, which can be justified by the rise in the time necessary for pedestrians to cross the road and sense of comfort and safety felt by drivers, leading them to the practice higher speeds.

4.2. Modeling Temporal Disaggregated Crash Data

In this section, the disaggregated data were used to construct the models, and therefore, the modeling technique used was GEE. The dependent variable is the total number of pedestrian crashes per year in each street, and the models considered the following three exposure variables:

1. Model 1: LnVveh, in addition to the offset variable LnVped;
2. Model 2: LnSPV, in addition to the offset variable LnVped;
3. Model 3: LnPVQ, in addition to the offset variable LnVped;

As shown in Table 4, Model 1 and Model 2 have the same significant variable set and corresponding parameter estimates. The exposure variables LnVveh and LnSPV were not statistically significant and, therefore, these models will be referred to as Model 1/2.

The results obtained with models based on disaggregated data show many similarities with the previous model obtained with the aggregated data (Model 0). The variables

such as ROAD_L, DIST, SLOPE, and WIDTH_W show a negative impact on pedestrian safety. Similarly, the variables with a positive impact on pedestrian safety were PARKS and DIRECTIONS.

The LnPVQ exposure variable was significant in Model 3, with a negative parameter. This suggests that high volumes of vehicular and pedestrian traffic have a positive impact on pedestrian safety. The explanation might be that in urban areas with intense movements of both vehicles and pedestrians, all road users proceed with a much higher level of attention and the vehicles are often obliged to slow down. There is a need for complementary studies to confirm this, but it cannot be discarded a priori, especially given the fact that there is no consensus in the literature regarding the influence of vehicular traffic on crash rates. Indeed, some authors like Diogenes and Lindau [42] state that greater traffic volumes are associated with a reduction in crash rates, whereas others like Miranda-Moreno et al. [9] report just the opposite.

5. Analysis and Discussion of the Models

The summary of the significant variables and the respective signals identified in all valid models is presented in Table 5. It is important to point out that, though the effect of all the variables was consistent, the models did not identify the same variables. The best fitting statistics also cannot be compared between models generated with different databases.

Table 5. Summary of the impact of significant variables.

Category	Variable	ZTNB Model	GEE Models	
		Model 0	Model 1/2	Model 3
Built environment	ROAD_L	+	+	+
	PARKS	–	–	
	NET_C	–		+
Pedestrian infrastructure	DIST	+	+	+
	SLOPE	+	+	+
	WIDTH_W	+	+	+
Road infrastructure	DIRECTIONS	–		–
	R_MED	–		
Exposure	LnPVQ			–
	Intercept (β_0)	–6.8345 ***	–9.0026 ***	–7.7187 ***
	AIC	238.3586		
	QIC		455.5955	461.728
	MAD	2.8962	0.97362	0.97769
	RMSE	3.8673	1.2525	1.24312

*** *p*-Value < 0.0001.

A general analysis of the models developed reveals that broader exposure considerations (through variables that aggregate vehicular and pedestrian volumes) were significant only for the GEE models. A possible explanation could be the difference between the database sizes, formed by 40 sets of observations for the ZTNB model and by 280 for the GEE models. However, it is important to highlight that for all models, the LnVped_{mt} (the offset variable) is included, and it is also an exposure variable.

Model 0 is the one that identified the higher number of contributory factors for pedestrian crashes in the streets considered (Table 5). However, according to this model, the vehicular traffic volume has no impact on the number of pedestrian crashes.

Taking into account that the objective of this study is to identify factors that contribute to the occurrence of crashes involving pedestrians and not to obtain estimates of the predicted numbers of such occurrences, both models prove to be favorable for the study under the point of view of traffic engineering. However, it is essential to verify the quality of the models to sustain the previous analysis. For that purpose, the plot of the Pearson residuals for the two models are shown in Figure 5.

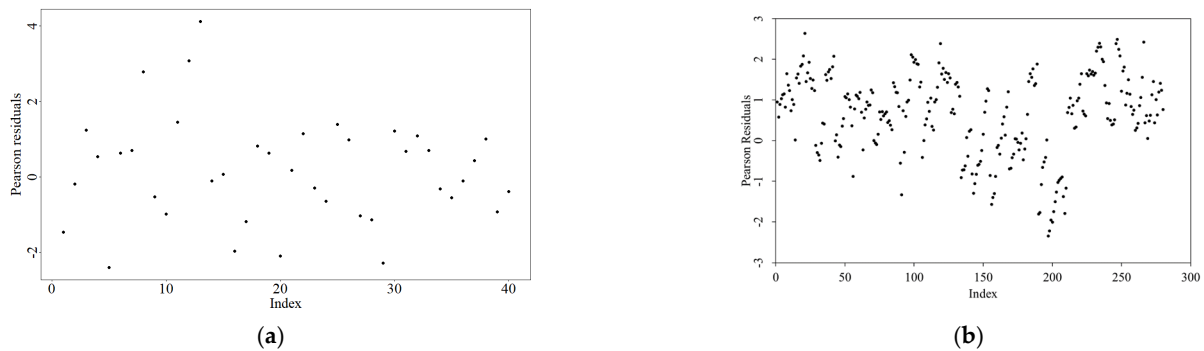


Figure 5. Pearson residuals: (a) for the Model 0; (b) for the Model 3.

These plots suggest that the residuals appear to be randomly scattered around zero, mainly between -2 and 2 , indicating good fit of these models.

When plotting the Pearson residuals versus the fitted values for two models (see Figure 6), it is noticeable that the residuals are equally distributed around zero.

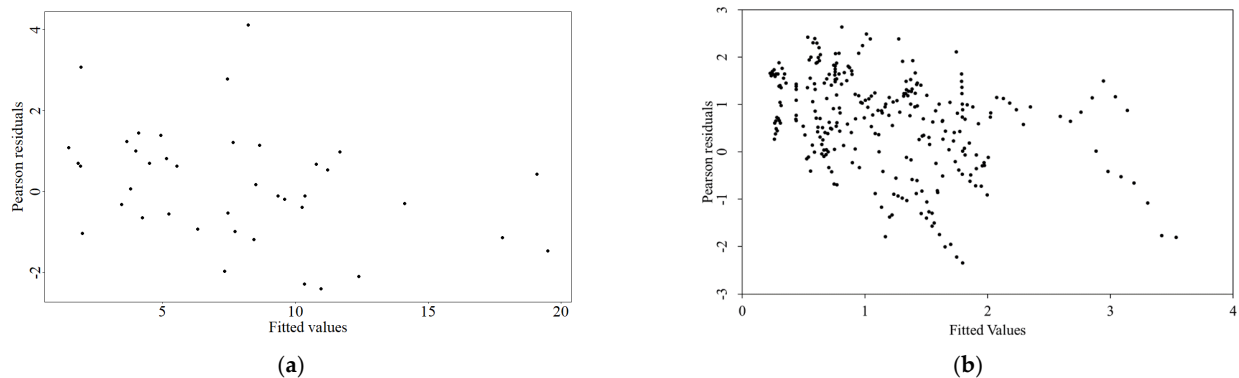


Figure 6. Pearson residuals vs. fitted values: (a) for Model 0; (b) for Model 3.

6. Conclusions

This study succeeds in showing the influence of new variables related to the built environment, pedestrian infrastructure, and road infrastructure on pedestrian safety.

In the group of variables associated with pedestrian infrastructure, one of the most important variables in this study is the distance between crosswalks, indicating that longer distances negatively affect pedestrian safety. It may be strongly associated with pedestrian comfort levels and perception of safety when they are walking and waiting for the appropriate moment to cross the road without running the risk of being run over. Streets with greater inclination or with distant subsequent crosswalks may lead to a greater likelihood of pedestrians not crossing the street at crosswalks.

One result that requires further investigation is the continuity of the pedestrian network in the pedestrian crash frequency. In this study, the variable continuity of the pedestrian network contributes to increasing pedestrian crash frequency, which could suggest that when good walking conditions do not exist, pedestrians are more cautious. However, confirmation of the impact of that particular variable would require specific studies.

Within the group of the variables of the built environment, there are differences between the conclusions of the studies that have investigated the effect of the existence of parking places in the street on pedestrians' safety. In this study, this variable showed to have a positive impact on pedestrians' safety, which indicates that potential problems of traffic flow in streets with parking lots can reduce the number of crashes, possibly due to the reduced speed of the vehicles. However, the literature suggests the contrary. That

result was underscored by the observations of the impact of the risk factor PVQ whose coefficient was negative in the disaggregated data Model 3 (less crash frequency).

In addition to the variables previously studied by other authors within the group of road infrastructure, such as the carriageway width, this study shows the existence of a relationship between other variables and the number of collisions with pedestrians. Specifically, the variables of one-way streets and the existence of raised medians were associated with the decreasing of the vehicle–pedestrian crash frequency. Along with the carriageway width, these three variables may be related to the need to reduce the number of conflicts between pedestrians and vehicular traffic, emphasizing the importance of additional measures for the protection of pedestrians at road crossings.

The main drawback to this study was the absence of data on the volumes of motorized and pedestrian traffic corresponding to the data regarding crashes involving collisions with pedestrians during the seven years analyzed. The lack of such data in official databases made it necessary to determine using short-duration traffic counts and applying expansion factors and prediction methods, thus undoubtedly introducing uncertainty to the precision of the adopted values. That limitation, however, is unlikely to be overcome in studies involving pedestrians in Portuguese roads and streets given that the traffic authorities keep no systematic records of pedestrian flows.

Bearing this limitation in mind, the relationship between pedestrians and vehicular traffic had a clear influence on the models. When pedestrian and vehicular traffic volumes are considered at the same time, this exposure variable shows a positive impact on pedestrian safety. This finding seems to reinforce the “safety in numbers” hypothesis and could help to make decisions, for example, to create shared public space projects. This work also reinforces the importance and the need to investigate new low-cost and time-saving methods to monitor this type of data to make the models more reliable.

It is important to emphasize that the objective of this study was to assess the relationship of variables within three groups (the built environment, pedestrian infrastructure and road infrastructure) with the number of pedestrian crashes. These results may be useful for future research to explore in greater depth the theoretical importance of the variables considered in this study, and therefore use them to develop models for the prediction of the frequency and severity of pedestrian crashes.

Author Contributions: L.B. was responsible for the methodology, the data collection, the data analysis, and the original draft preparation; J.O.d.C. was responsible for the data analysis and participated in the methodology; F.S. participated in the methodology and the data collection; S.F. participated in the data analysis; M.A.P.J. was responsible for the draft review and editing; and E.F.d.F. was responsible for the methodology, and for the draft review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FUNDAÇÃO PARA A CIÊNCIA E A TECNOLOGIA (FCT), in the scope of the projects AnPeB—Analysis of pedestrian behavior based on simulated urban environments and its incorporation in risk modelling (PTDC/ECM-TRA/3568/2014) and Studies to promote sustainable and safe urban mobility (Agreement FCT/CAPES), in the frame of the strategic project (UIDB/04029/2020) and doctoral scholarships (SFRH/BD/131638/2017) and (SFRH/BD/138728/2018).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data is composed of three parts. The first part, the pedestrian crashes recorded in the period from 2009 to 2015 for each road under study, was obtained from Autoridade Nacional da Segurança Rodoviária (ANSR) and are available with their permission. The second part, the statistics of road and pedestrian traffic, was obtained from Instituto Nacional de Estatística (INE) and are available at <https://www.ine.pt/>. The third part, pedestrian and vehicular traffic counts and the explanatory variables about built environment, pedestrian infrastructure, and road infrastructure, were obtained by observation and analysis of each road.

Acknowledgments: This is not applicable for this study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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