Title: Frequency and severity of crashes involving vulnerable road users – An integrated spatial and temporal analysis

TRB Paper number: 18-00382

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Keywords: road crashes, injury severity, multinomial logistic regression analysis, cyclists, pedestrians, vulnerable road users, KDE, spatial, temporal analysis.

Aknowledgements: Special thanks to ANSR for road crashes data, Laura Laranjo and Bárbara Romeira in georeferencing data and: Centre for Mechanical Technology and Automation Strategical Project UID/EMS/00481/2013-FCT and CENTRO-01-0145-FEDER-022083; @CRUiSE PTDC/EMS-TRA/0383/2014 funded within Project 9471–RIDTI–Reforçar a Investigação, o Desenvolvimento Tecnológico e a Inovação and supported by European Community Fund FEDER; MobiWise P2020 SAICTPAC/0011/2015 co-funded by COMPETE2020, Portugal2020 - Operational Program for Competitiveness and Internationalization (POCI), European Union's ERDF (European Regional Development Fund), and FCT – Portuguese Science and Technology Foundation. E. Macedo and P. Tafidis also thank CISMOB – PGI01611 funded by Interreg Europe Programme.

INTRODUCTION

Worldwide, 1.2 million people lose their lives every year in road crashes, resulting in huge impacts in societies and national economies, costing governments approximately 3% of their GDP (*1*). Active transportation modes have being promoted for mitigating transportation externalities. However, vulnerable road users (VRUs), in particular pedestrians and cyclists, are more exposed to vehicle-crash injuries and with more severity level. In 2015, the percentages of pedestrians' and cyclists' fatalities were, respectively, 14% and 2% for USA, and 23% and 5% for Portugal (*1*).

Several studies have investigated spatial and temporal patterns of traffic crashes (*2,3*), and some involving pedestrians or cyclists. The recognition of risky areas – blackspots – is important for traffic safety analysis. Risk areas for crashes involving motor-vehicles may present different characteristics than areas of greatest risk for pedestrians and cyclists (4*)*. Spatial analysis of road crashes can be based either on density or a severity index (2). Prato et al. (3) concluded that older or intoxicated pedestrian are most vulnerable within this already extremely vulnerable road users category and roads with higher speed limits are related to the most severe outcomes; shopping and residential areas, low-speed roads, and walking traffic density are related to a reduction in pedestrian injury severity. Pour et al. (*5*) showed most vehicle-pedestrian crashes occurring between 7:00 PM and 6:00 AM are more severe specially, around hotels, clubs and bars. Kitali et al. (*6*) proposed a predictive model for pedestrians-crash severity using complementary log-log models typically used for predicting rare events, and showed it performed quite well for predicting fatal and severe crashes. Studies regarding vehicle-cyclists crashes revealed presence of retail or service establishments increase risk of collision (*4*). Kaygisiz and Hauger (*7*) described a point pattern analysis methodology to show risky zones for cyclists vary in time and condition. Osama and Sayed (*8*) developed macro-level (zonal) collision prediction models incorporating bike networks indicators as explanatory variables, using generalized linear regression and Bayesian techniques. They showed spatial effects were statistically significant. There are also few studies involving both pedestrians and cyclists. Cai et al. (*9*) suggested a Bayesian joint approach to show dependency between crashes involving pedestrians and cyclists and total crashes. There are also studies revealing that models with spatial correlation are better than those that did not take into account spatial correlations (*10, 11*). Lee et al. (*12*) developed prediction model based on series of intersection crash models for total, severe, pedestrians and bicycle crashes with macro-level data from various geographic units, and showed macro-variables are significant.

The contribution of this paper is to perform an integrated spatial and temporal analysis of crashes involving VRUs, considering severity of injuries, in order to establish some pattern between cities with different specifications. This study evaluates pedestrians and cyclists crashes, comparing cities from Portugal with different population densities.

METHODOLOGY

The studied areas, crashes data and the methods used in identification of blackspots and in the development of the predictive model are presented.

Crash data involving VRUs from three distinct Portuguese cities - Aveiro, Porto and Lisbon – with different socio-demographic characteristics (Table 1) were analyzed.

TABLE 1 Socio-demographic characteristics from the case studies cities.

	Population (inhabitants)	Area (km^2)	Percentage of trips (%)	
			Walking	Cycling
Aveiro	78 450	197.6	21	2.7
Porto	237 591	41.42	21.6	0.22
Lisbon	547 733	100.05	19.4	0.2

Sources: INE, 2012; CIRA,2014

Since Aveiro has the highest percentage of both walking and cycling trips, it is a key study to compare with Porto and Lisbon.

VRUs-involving crash registrations from 2012 to 2015 were provided by ANSR (Portuguese National Road Safety Authority), and resulted in a total of 4439 observations with 4615 injured VRUs, 87% related to motor vehicle-pedestrians and 13% to -cyclists crashes. Many crashes' location had to be georeferenced using Google Maps. Analysis was mainly focused on the level of injury severity, which was subdivided into light injuries, serious injuries, and fatalities.

High-risk areas regarding VRU safety were identified using special tools implemented in ArcGIS 9.3 (*15*). Widely used Kernel Density Estimation (KDE) (e.g., *5*) was applied to obtain circular-cell-shape neighborhood patterns based on the level of severity of VRUs injuries. Different radius values were empirically tested and considering the study areas, 174 meters was considered a suitable value to obtain the density distribution. A specific weight on each VRU injured observation was considered based on the severity index suggested in (*16*) and taking into account the specificities of the study areas, as follows:

$$SI = l + 3s + 5f, \tag{3}$$

where SI stands for severity index, l and s are the number of VRUs with light and serious injuries, respectively, and f is the number of fatalities. KDE returned nine levels of risk, being Level 1 a high-risk area and Level 9 a low-risk area.

Temporal distribution of the crashes and injured people at different time periods was assessed. In particular, peak hours and days were highlighted for each city and related to specific VRUs characteristics.

Besides, a Multinomial Logistic Regression (MLR) predictive model that allows to infer which type of VRU is more likely to be involved in a crash, being the response variable categorical (pedestrian or cyclist) was developed using the statistical software SPSS (*17*). The set of predictor variables includes VRUs' gender and age, level of severity of the injury, temporal (weekday and time period) and weather conditions.

FINDINGS

Crashes involving VRUs occurrences were georeferenced and an injury attribute was used to generate spatial maps. Figure 1 illustrates the geographic distribution of crashes resulting on VRUs injuries by level of severity, highlighting blackspots on each city.

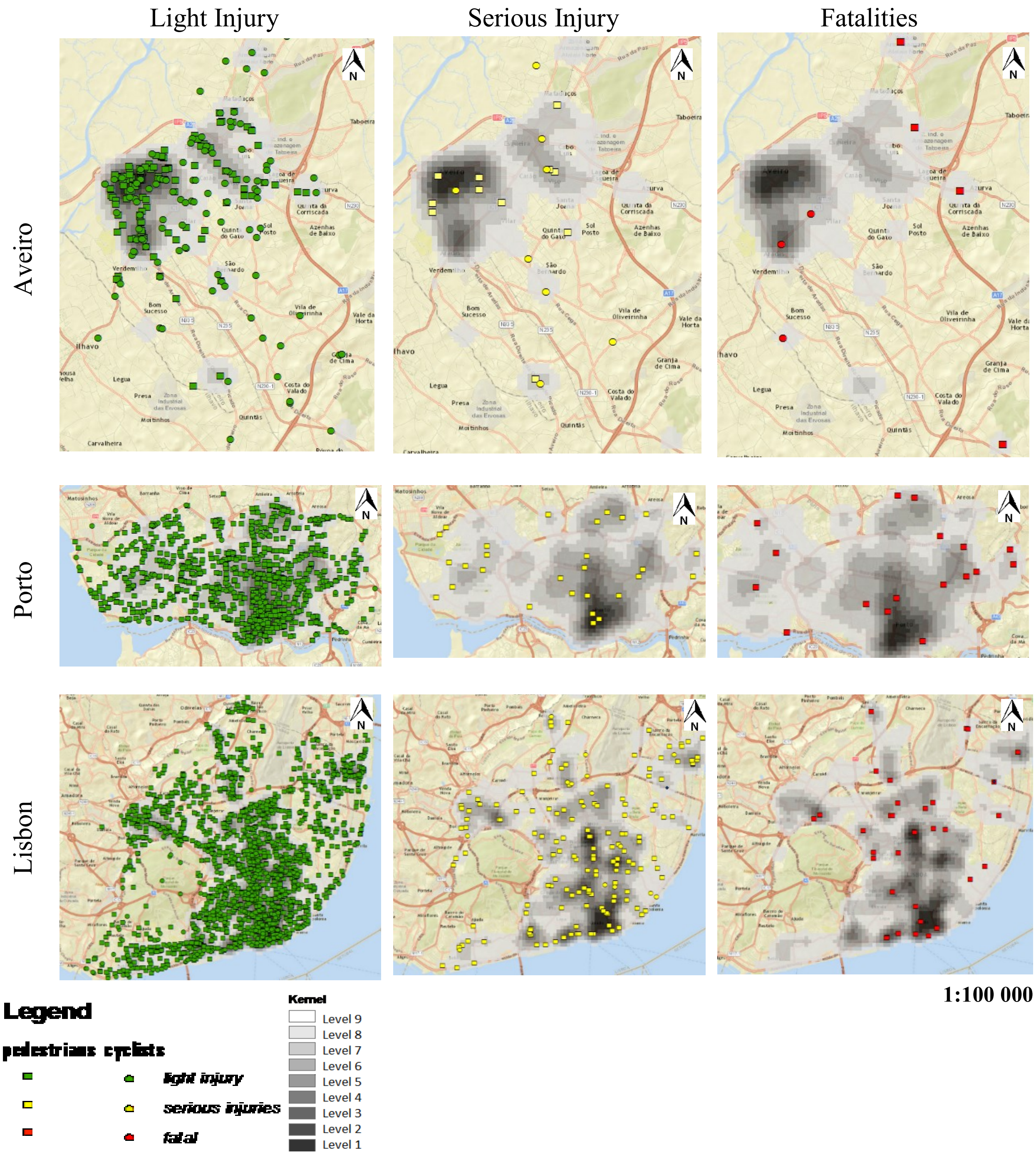

FIGURE 1 Spatial distribution of crashes involving VRUs based on level of severity injury for Aveiro, Porto and Lisbon.

Results revealed that for all cities most injuries occur close to high-attraction places, such as train stations, shopping areas and touristic points, in which the vehicles speed-limits are under 50km/h. Table 2 indicates a normalization of number of injuries taking into account population and area of each particular city.

TABLE 2 Number of injuries per ten thousand inhabitants and square kilometer for each city.

		Injuries/10000 inhabitants	Injuries/km^2
Aveiro	**Pedestrians**	21	1
	Cyclists	20	1
	Total	41	2
Porto	**Pedestrians**	51	30
	Cyclists	6	4
	Total	57	34
Lisbon	**Pedestrians**	49	27
	Cyclists	6	3
	Total	55	30

Considering number of VRUs injuries per ten thousand inhabitants, Aveiro presented 27%, while Porto and Lisbon presented 37% and 36%, respectively. Considering the number of VRUs injuries per square kilometer, Aveiro presented the lowest number (3%), while Porto and Lisbon presented significantly more, 52% and 45%, respectively. In terms of injured cyclists, the proportion of this class per ten thousand inhabitants is quite higher in Aveiro (62%) when compared to Porto and Lisbon than represent 19% each.

Regarding annual evolution, Aveiro presented a decrease of 34% and Porto 12% for pedestrians injuries from 2014 to 2015, while Lisbon presented an increase of 14%. A closer look regarding pedestrians shows Lisbon with an increase in general injuries, and Aveiro in relation to serious injuries. It can be emphasized a reduction in the number of cyclists injuries in 2015 for all cities, which can be explained by the implementation of specific legislation for this VRU class.

May is a critical month in Aveiro and Lisbon in terms of serious injuries and deaths, while February is worse for Porto. As expected, August, which is typically a vacation month, presented lower number of injuries, particularly for Porto and Lisbon.

Weekdays presented more occurrences than the weekend, being in general, Thursdays and Fridays critical days with 35% of the total injuries for all cities, and Sundays the least dangerous days.

Figure 2 illustrates the number of injuries per ten thousand inhabitants for each city distributed by hours of the day.

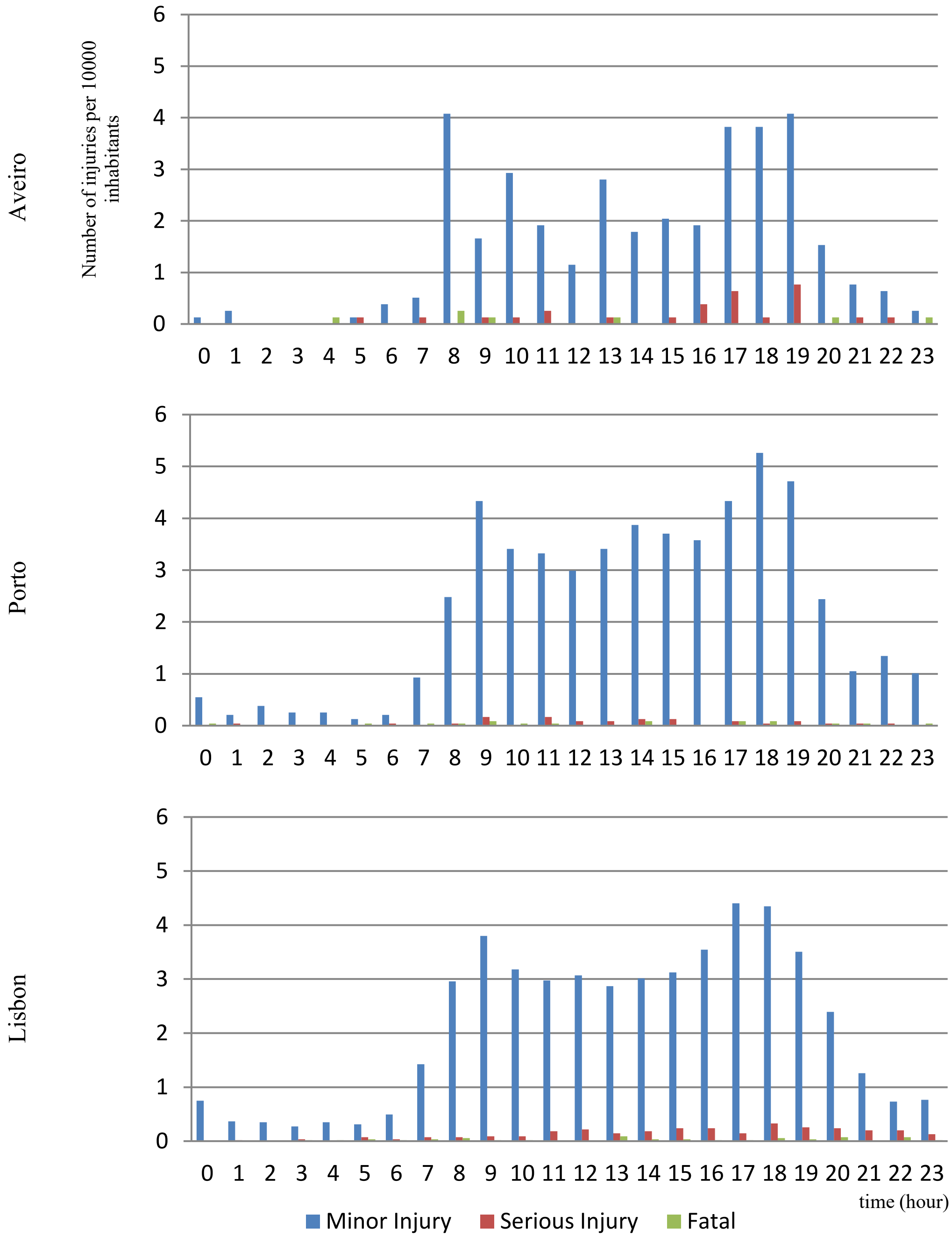

FIGURE 2 Temporal distribution of crashes involving VRUs based on level of severity injury for Aveiro, Porto and Lisbon.

Regarding temporal distribution of crashes involving VRUs taking into account level of injury severity showed Porto with the worst general scenario, followed by Lisbon and then Aveiro. In particular, in terms of light injuries per ten thousand inhabitants, Aveiro presented more than 4 injured VRUs at the peak-hour 8a.m., while Porto presented the highest number of injured VRUs during the whole period of working-hours (9a.m. to 8p.m.). Considering serious injuries and fatalities, Aveiro presented worst numbers around 5-7p.m. and around 8a.m., respectively.

Results showed that different VRU age groups have different peak hour moving patterns; however, there are higher occurrences involving cyclists with 25-49 years for all cities, which may be due to the potential majority of cyclists in this age interval, but it cannot be confirmed due to the lack of data. Concerning pedestrians, most occurrences involve the extended-age group 18-49 years in Aveiro, while in Lisbon and Porto 65+ years group clearly dominates.

The developed MLR model for each city with pedestrian or cyclist as the response variable revealed that VRU gender and age, as well as weather conditions, are statistically significant variables for all models, meaning that a predictive model should take into consideration these variables.

CONCLUSIONS

This study shows the importance of spatial and temporal analysis for crashes involving vulnerable road users. Comparing three cities with different geodemographic characteristics, we can found some patterns from spatial analysis. Results showed that most injuries occur surrounding high attraction places, with speed limits under 50km/h. For the temporal analysis, the patterns are not so common, since these can take into account other factors like meteorological conditions, special events in specific cities, exposure levels of pedestrians and cyclists, and population characteristics. However, results showed that most of crashes involving injured VRUs per ten thousand inhabitants occur during afternoon peak-hour period between 4-7p.m. for all cities, however Aveiro from the total severe injuries occur in this period Aveiro represent 53%. Porto presented worst scenarios in terms of number of VRUs injuries per ten thousand inhabitants or kilometers squared,. In particular, only Aveiro presented fatalities among cyclists, while in Porto there were just light injured cyclists.

The developed multinomial logistics regression models for each city showed VRUs gender and age, and weather conditions, are statistically significant predictor variables.

The limitations of this work are related with the size of the sample of crash records, lack of detailed information and clarity in georeferencing of the original registrations data. The findings from this study emphasize the need for considering temporal and spatial characteristics of VRUs-involving crashes, assessing injury severity, to improve safety strategies having in mind patterns related to peak hours of different age groups as well as specificities at a local level.

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