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Considering built environment and spatial correlation in modelling pedestrian injury severity

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ABSTRACT

Objective. This study looks at mitigating and aggravating factors that are associated with the injury severity of pedestrians when they have crashes with another road user and overcomes existing limitations in the literature by posing attention on the built environment and considering spatial correlation across crashes.

Method. Reports for 6539 pedestrian crashes occurred in Denmark between 2006 and 2015 were merged with geographic information system resources containing detailed information about built environment and exposure at the crash locations. A linearised spatial logit model estimated the probability of pedestrians to sustain a severe or fatal injury conditional on the occurrence of a crash with another road user.

Results. This study confirms previous findings about older pedestrians and intoxicated pedestrians being the most vulnerable road users, and crashes with heavy vehicles and in roads with higher speed limits being related to the most severe outcomes. This study provides also novel perspectives by showing positive spatial correlation of crashes with the same severity outcome and emphasising the role of the built environment in the proximity of the crash.

Conclusions. This study emphasises the need for thinking about traffic calming measures, illumination solutions, road maintenance programs and speed limit reductions. Moreover, this study emphasises the role of the built environment, as shopping areas, residential areas, and walking traffic density are positively related to a reduction in pedestrian injury severity. Often, these areas have in common a larger pedestrian mass that is more likely to make other road users more aware and attentive, while the same does not seem to apply to areas with lower pedestrian density.

Keywords

Pedestrian Crashes; Injury Severity Models; Built Environment; Spatial Correlation.

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INTRODUCTION

Active travel contributes to the sustainability of cities and regions and the health of their inhabitants. Unfortunately, active travellers are the most vulnerable road users when considering that the risk of injury for pedestrians and cyclists is respectively 4.0 and 7.5 times higher than for car occupants (Elvik, 2009).

Having previously looked at the factors associated with cyclist injury severity (Kaplan et al., 2014), this study poses the same research question while turning the attention towards pedestrians. The motivation is fourfold: (i) the development of effective safety policies requires the understanding of not only crash occurrence but also factors affecting injury severity once a crash occurs (Savolainen et al., 2011); (ii) focusing on Denmark allows the use of a crash database integrated with geographic information system (GIS) resources to provide a broad picture of the factors affecting pedestrian injury severity; (iii) focusing on Denmark as an active travel nation serves as an outer marker for highlighting issues and proposing countermeasures (Pucher and Buehler, 2008); (iv) pedestrian safety in Denmark is a top priority when considering that pedestrians account for 15% of road fatalities and 11% of serious injuries, but only 2% of the traffic-km.

Existing literature on pedestrian injury severity investigates generally five types of factors. From the pedestrian perspective, higher injury severity is clearly related to the frailty of older age (Eluru et al., 2008; Clifton et al., 2009; O'Hern et al., 2015; Sasidharan and Menendez, 2015) and the level of intoxication (Eluru et al., 2008; Clifton et al., 2009), while contradicting evidence exists about its relation to gender (Lee and Abdel-Aty, 2005; Abay, 2013; Verzosa and Miles, 2016). From the driver and vehicle perspective, higher injury severity is associated with

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intoxicated drivers (Eluru et al., 2008; Abay, 2013), heavy vehicles (Roudsari et al., 2005; Abay, 2013; Mohamed et at., 2013; Sasidharan and Menendez, 2015), and vehicles with low New Car Assessment Program (NCAP) values (Strandroth et al., 2011). From the behaviour perspective, higher injury severity is linked to pedestrians crossing far from crosswalks (Rothman et al., 2012; Abay, 2013; Sasidharan and Menendez, 2015) or walking along curve road sections (Kim et al., 2008), and drivers going straight and the impact being frontal (Eluru et al., 2008; Abay, 2013; Mohamed et al., 2013). From the roadway perspective, lower injury severity is associated with the presence of medians, sidewalks, crossing buffers, and lower speed limits (Eluru et al., 2008; Abay, 2013; Mohamed et al., 2013; Sasidharan and Menendez, 2015). From an environment perspective, higher injury severity is related to both inclement (Mohamed et al., 2013; Sasidharan and Menendez, 2015) and good weather (Lee and Abdel-Aty, 2005; Eluru et al., 2008), and to both peak (Kim et al., 2008) and night hours (Mohamed et al., 2013; Verzosa and Miles, 2016).

Limitations are identifiable in the existing literature: (i) lack of an overarching analysis considering an extended set of mitigating and aggravating factors; (ii) limited to no attention to the built environment and traffic exposure, with contradicting conclusions concerning both lower (Clifton et al., 2009) and higher (Zahabi et al., 2011) injury severity being associated with transit access, and more severe consequences being related to both urban environments with commercial and parking spaces (Miranda-Moreno et al., 2011; Mohamed et al., 2013) and mixed land uses and proximity to rural areas (Zahabi et al., 2011; Abay, 2013); (iii) ignorance of spatial correlation between crashes although the issue is recognised as essential for modelling injury severity (Castro et al., 2013; Mannering and Bhat, 2014).

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This study addresses these limitations by presenting an extended analysis of mitigating and aggravating factors of pedestrian injury severity for 6539 pedestrian crashes occurred in Denmark between 2006 and 2015. The crashes from the nationwide database were geocoded and matched to GIS resources containing information about built environment and exposure at their locations, and a linearized spatial logit model estimated the probability of the pedestrians sustaining a severe or fatal injury conditional on the crash occurrence while accounting for spatial correlation.

DATA

Crash Data

Crash data were extracted from the national database compiled by the Danish Road Directorate on the basis of police reports. Three files compose the database: (i) the crash file lists information about geographical coordinates, collision types, road user maneuvers, involved road users, infrastructure characteristics, and environmental conditions; (ii) the person file lists information about demographics, alcohol or drug consumption, restraint use, license validity, and injury severity; (iii) the vehicle file lists information about make, model, registration, maneuver, collision point, and reported damage.

This study analyses crashes involving a pedestrian and a vehicle that occurred on Danish roads during the ten-year period between 2006 and 2015. Selecting pedestrian-vehicle crashes limits the noise associated with multiple vehicle crashes and their dynamics (Mohamed et al., 2013; Sasidharan and Menendez, 2015). Selecting a ten-year period guarantees a large sample size where the GIS resources correct for road and traffic variations by matching the versions of each crash year.

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The crash database contained 6539 complete records whose severity outcomes were (i) damage only including bruises and material damages of at least 5000 DKK (about 700 USD), (ii) light injuries needing proper medical treatment, (iii) severe injuries involving incapacitation (e.g., lesions, fractures, concussions), and (iv) fatalities occurring within 30 days of the crash. Table I presents an extract of the variables according to the categories that the modelling process has found the most suited for obtaining the best model specification (the complete list of the variables is presented in table AI in the Appendix). The crash database contained also geographical coordinates for GIS resource matching as described in the following sub-section.

GIS Data

Each crash geographical location was matched with the Danish register of buildings, the Danish register of businesses, the Danish population in 1ha grid cells, the land cover dataset of the European Environment Agency, and the network and traffic data of the Danish National Transport Model (NTM) for private and public transport. Table II summarises the data extracted from these resources (the complete data are presented in table AII in the Appendix).

Road characteristics from the NTM road network corrected for incomplete records and provided up-to-date characteristics at the time of the crash by using the information for the crash year. The characteristics included category, directions, lanes, section type, intersection type and speed limits. Traffic exposure from the NTM provided road and walking traffic densities in the zone where the crash occurred.

Built environment characteristics were extracted at the street buffer level (within 500m of the crash location), and the traffic zone level (within the NTM traffic zone). At the street buffer level, the characteristics grasped the effect of the immediate walking surroundings and included land use, road density, road being low speed, road being low volume, intersections, schools, leisure locations, and public transport stops or stations. At the traffic zone level, the characteristics grasped the effect of a larger area characterised by homogenous traffic and population conditions and included measures of population composition, income distribution, car ownership, job density, unemployment rate, rurality level based on a weighted average of 14 indices (for details, see Danish Ministry of Food Agriculture and Fisheries 2011), and land use diversity (Song et al., 2013).

MODEL

Spatial models have been applied sparingly in the injury severity literature (Castro et al., 2013; Mannering and Bhat, 2014) and their major drawback is the heavy computational requirement of inverting large matrices expressing the spatial correlation. With the aim of avoiding matrix inversion, this study formulates a linearised spatial logit model where the utility U_{in} of a crash i leading to a pedestrian injury of severity n is written as (Klier and McMillen, 2008):

$$\boldsymbol{U_i} = \boldsymbol{\beta X_i} + \boldsymbol{\rho W U_j} + \boldsymbol{\varepsilon_i} \quad (1)$$

$$\boldsymbol{U_{in}} = \sum_{k=1}^{K} \boldsymbol{\beta_k X_{ik}} + \boldsymbol{\rho} \sum_{j=1}^{J} \boldsymbol{w_{ij} U_{jn}} + \boldsymbol{\varepsilon_{in}} \quad (2)$$

where X_{ik} are values for the variables k expressing the characteristics of crash i, U_{jn} are the utilities of each crash j leading to a pedestrian injury of severity n, w_{ij} are elements of the weight matrix $\boldsymbol{W}$ expressing the spatial correlation between crashes i and j, β_k are parameters to be estimated, ρ is the spatial correlation parameter to be estimated, and ε_{in} are error terms.

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A positive value of the parameter ρ implies clustering and a negative value implies dispersion across severity outcomes of the crashes. The elements w_{ij} are a function of the distance d_{ij} between crashes i and j according to an exponent s:

$$\boldsymbol{w_{ij}} = \begin{cases} \left(\frac{1}{\boldsymbol{d_{ij}^{s}}}\right) / \sum_{j=1, j \neq i}^{J} \left(\frac{1}{\boldsymbol{d_{ij}^{s}}}\right) & \boldsymbol{for\ i \neq j} \\ 0 & \boldsymbol{for\ i = j} \end{cases} \quad (3)$$

As the estimation of spatial logit or probit models is extremely complex because of the need for inverting ($J \times J$) matrices, the spatial logit is reformulated with a linearised generalised method of moments (Klier and McMillen, 2008):

$$\boldsymbol{U_i} = \left(\boldsymbol{I} - \boldsymbol{\rho W}\right)^{-1} \boldsymbol{X_i \beta} + \left(\boldsymbol{I} - \boldsymbol{\rho W}\right)^{-1} \boldsymbol{\varepsilon} \ (4)$$

where the vector $\boldsymbol{P_i}$ of probabilities of pedestrian injury severity n for crash i is expressed as:

$$\boldsymbol{P_i} = \frac{\boldsymbol{exp}\left(\boldsymbol{X_i^{**} \beta}\right)}{1 + \boldsymbol{exp}\left(\boldsymbol{X_i^{**} \beta}\right)} \text{ where } \boldsymbol{X_i^{**}} = \left(\boldsymbol{I} - \boldsymbol{\rho W}\right)^{-1} \boldsymbol{X_i^{*}} \text{ and } \boldsymbol{X_i^{*}} = \boldsymbol{X_i} / \boldsymbol{\sigma_i} \ (5)$$

where $\boldsymbol{X_i}$ are vectors of characteristics of crash i and σ_i are the diagonal elements of the covariance matrices. A two-stage estimation procedure (Klier and McMillen, 2008) was implemented in the R package McSpatial: (i) estimation of a standard logit with $\rho = 0$ to obtain estimates $\boldsymbol{\beta}_0$ and calculation of the utilities and gradient terms $G_{\beta i} = \hat{\boldsymbol{P}}_i \left(1 - \hat{\boldsymbol{P}}_i\right) X_{\boldsymbol{i}}$ and $G_{\rho i} = \hat{\boldsymbol{P}}_i \left(1 - \hat{\boldsymbol{P}}_i\right) \boldsymbol{W} X_{\boldsymbol{i}} \hat{\boldsymbol{\beta}}$ at estimates; (ii) regression of the vectors $\boldsymbol{G_\beta}$ and $\boldsymbol{G_\rho}$ on the instruments Z corresponding to the geographical coordinates of the crashes, calculation of the predicted values $\hat{\boldsymbol{G}}_{\boldsymbol{\beta}}$ and $\hat{\boldsymbol{G}}_{\boldsymbol{\rho}}$, regression of $\boldsymbol{U}^0 + \hat{\boldsymbol{G}}_{\boldsymbol{\beta}} \hat{\boldsymbol{\beta}}_0$ on $\hat{\boldsymbol{G}}_{\boldsymbol{\beta}}$ and $\hat{\boldsymbol{G}}_{\boldsymbol{\rho}}$, and retrieval of the parameters β_k and ρ.

MODEL RESULTS

The initial estimation of aspatial models revealed that the binary model considering two different injury severity levels, namely damage only / light injury versus severe injury / fatality, was performing better than the multinomial model considering the four different levels: in the latter model, the estimates for the two lower severity levels and the ones for the two higher severity levels were not statistically different. Figure I presents the spatial distribution of the pedestrian injury severity levels for the analysed crashes alongside a classification of the areas and the highlight of the five major cities in Denmark.

The linearised spatial logit model was estimated with the aim of searching the best model specification for the two aforementioned injury severity levels. The iterative process progressively considered additional variables in the model and the best specification retained continuous and categorical variables that were significant at least at the 0.10 level (for a discussion about retaining variables on the basis of their significance levels, see Kockelman, 2002) and showed a low variance inflation factor. The best model specification was obtained for s equal to 3 (similar to Klier & McMillen, 2008). A likelihood ratio test showed that the linearised spatial logit is a significant improvement over a binary logit with ρ equal to 0 (LRT = 16.74, p = 0.000), and the Hansen's (1982) test (J-test = 0.142, p =0.001) proved the validity of the estimator and the instruments. Tables III and IV present and extract of the estimates and the marginal effects for the binary logit and the spatial logit models with the best model specification: (i) the model estimates represent the estimated parameters β_k and ρ where each β_k represents the logarithm of the odds-ratio for the considered level of the factor as compared to the reference level of the factor; (ii) the marginal effects represent the relative increase (or

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reduction) of the probability of the pedestrian experiencing severe or fatal injury for the considered level of the factor, as compared to the reference level of this factor.. The most notable difference between the two models is that the marginal effects of the logit model are biased towards an under-estimation of the effects of the factors on the injury severity levels. The comments on the results pertain the spatial logit model as the best model. Please refer to estimates and marginal effects for all the variables in tables AIII and AIV in the Appendix

Characteristics of Pedestrians, Vehicles and Crashes

From the pedestrian perspective, with the exclusion of children and young adolescents, younger and older pedestrians are associated respectively with a lower and higher probability of sustaining severe or fatal injuries, in line with existing findings of higher severity with increasing age (Eluru et al., 2008; Clifton et al., 2009; O'Hern et al., 2015; Sasidharan and Menendez, 2015). Pedestrian intoxication is also positively related to a higher probability of suffering severe or fatal injuries, in line with previous studies (Kim et al., 2008; Clifton et al., 2009). This model adds the perspective that foreigners are associated with less severe outcomes when involved in pedestrian crashes.

From the other road user perspective, this model confirms previous findings about heavy vehicles being related to higher injury severity (Abay, 2013; Mohamed et at., 2013; Sasidharan and Menendez, 2015; Verzosa and Miles, 2016), but adds the original perspectives of vans and pickup trucks not having an effect different from cars, and two-wheelers causing less severe consequences than cars. Also, the model adds some perspective: male drivers are related to higher severity for the pedestrians, while older drivers are associated with lower severity for the

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pedestrians. Notably, unlike previous studies (Kim et al., 2008; Eluru et al., 2008; Abay, 2013), the level of intoxication of drivers is not related to pedestrian injury severity.

From the pedestrian behaviour perspective, walking along or at the side of the road is associated with lower severity with respect to crossing, in disagreement with existing studies (Kim et al., 2008; Rothman et al., 2012; Abay, 2013; Sasidharan and Menendez, 2015) that, however, did not correct for spatial correlation and omitted built environment variables. From the driver behaviour perspective, the model confirms existing findings about the relation between turning manouvers and lower severity (Eluru et al., 2008; Abay, 2013; Mohamed et al., 2013), but also adds the perspective of reversing maneuvers being related to lower severity.

From the environment perspective, lower severity is associated with autumn and winter seasons and poor visibility, while higher severity is related to wet or slippery surface conditions as well as afternoon peak, evening and night conditions, in agreement with existing research (Mohamed et al., 2013; Verzosa and Miles, 2016). This model adds that artificial illumination mitigates the negative effect of darkness and afternoon peak (and not peak hours in general) is associated with more severe crash outcomes for pedestrians.

Characteristics of the Built Environment

The model confirms that the higher the speed limits, the higher the pedestrian injury severity (Eluru et al., 2008; Abay, 2013), and adds that curve road sections are related to higher severity when compared to straight road sections or intersections.

At the street buffer level, the land use in proximity of the crash is significantly associated with the injury severity. When compared to open areas, residential areas are related to lower injury severity (in particular low-rise buildings) and so are industrial and shopping areas. These findings contradict the few studies that analysed the influence of the built environment (Miranda-Moreno et al., 2011; Mohamed et al., 2013) albeit without accounting for spatial correlation across crashes. This model adds the perspective of a higher share of low speed roads in the crash surroundings being also related to lower probability of severe and fatal injuries.

At the traffic zone level, differences across regions are observed as Mid- and South-Jutland are related to higher injury severity, even after controlling for spatial correlation and built environment. Areas classified as intermediate are related to lower injury severity with respect to urban areas, even after controlling for the land use in proximity of the crash. This model provides additional perspectives by finding an association of higher injury severity with the distance between hospitals and crash locations, confirming what observed in Denmark for low volume rural roads (Prato et al., 2014), as well as a relation between lower injury severity and walking traffic density, suggesting that the "safety in numbers" paradigm (Jacobsen, 2003) applies also to pedestrians and not only to cyclists (Kaplan and Prato, 2015).

CONCLUSIONS

This study presents a linearised spatial logit model of the injury severity suffered by pedestrians in crashes with another road user in Denmark. The contribution of this study lies in the extensive coverage of the aggravating and mitigating factors of pedestrian injury severity, including the often omitted characteristics of the built environment and traffic exposure, as well as the consideration of spatial correlation.

Limitations apply to this study, in particular as police reports are often incomplete and crashes are often under-reported. Enriching the police data with GIS resources mitigates the

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former, while considering crashes between pedestrians and another road user limits the latter (see, e.g., Mohamed et al., 2013; Sasidharan and Menendez, 2015; Janstrup et al. 2016). Also, a binary model was estimated and the effects of the linearization of the spatial logit in a multinomial setting was not explored fully. Albeit limitations exist, the findings from this study provide food for thought when thinking about mitigating pedestrian injury severity.

Firstly, the findings confirm that older pedestrians and intoxicated pedestrians are the most vulnerable road users. Albeit investments are made substantially in campaigns about the risks of drinking and driving, it seems that they should be extended to vulnerable road users as similar findings were found also for cyclists (Kaplan et al., 2014). Further research should investigate whether walking or cycling under the influence is socially accepted and should promote shared responsibility as a concept that makes roads safer.

Secondly, the findings suggest the need for thinking about traffic calming and other measures for mitigating the outcomes of crashes for pedestrians. Traffic calming needs to make simpler for pedestrians to cross, as it is the event associated with higher injury severity, and for other road users to approach, as going straight is related to higher injury severity. It appears that attention should be posed towards illumination, especially in the darkest hours, road surface maintenance, especially when there are precipitations, and speed limits, especially in rural areas. The findings point to these elements being relevant to higher injury severity, and thus further research should test solutions via before-after studies.

Thirdly, the findings emphasise the role of the built environment in the proximity of the crash. Results indicate that shopping areas, residential areas, low speed roads, and walking traffic density are positively related to a reduction in pedestrian injury severity. Often, these areas have

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in common a larger pedestrian mass that is more likely to make other road users more aware and attentive, and the same does not seem to apply to intermediate and rural areas. Further research should investigate what triggers awareness and attention in particular in drivers, and how hazards could be recognised more easily in areas with lower pedestrian density.

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APPENDIX

<AQ>Please Provide Content for Appendix table I to IV.</AQ>

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Table I Crash characteristics

Variable	Category	%	Category	%
		Characteristics of the pedestrian		
Injury severity	No injury	45.4	Severe injury	32.1
	Light injury	17.4	Fatality	5.1
Gender	Male	46.5	Female	53.5
Age	<= 9 years old	7.5	40-49 years old	11.1
	10-14 years old	7.9	50-59 years old	10.3
	15-19 years old	10.8	60-69 years old	9.5
	20-29 years old	15.2	>= 70 years old	17.4
	30-39 years old	10.4		
Intoxicated	No	89.1	Yes	10.9
Behaviour	Crossing from the right	36.5	Walking on the pavement	5.1
	Crossing from the left	27.4	Standing on the road	10.6
	Hidden	8.8	Hit by reversing vehicle	6.0
	Walking along the road	5.6		
Nationality	Danish	86.9	Foreigner	13.1

Table II GIS data characteristics

Variable	Category	Value	Category	Value
Built environment at the street buffer level (within 500m of the crash location)				
Roadside land use	Shopping street (%)	17.4	Low residential area (%)	19.2
	Industrial area (%)	6.4	Buildings with no access (%)	6.3
	High residential area (%)	35.6	Spare buildings (%)	15.1
Built environment at the traffic zone level (within the NTM zone)				
Unemployment rate	mean (%)	7.2	st. dev. (%)	3.0
Region	Copenhagen (%)	37.6	North Jutland (%)	8.0
	Zealand (%)	12.1	Mid-Jutland (%)	20.1
	Fyn (%)	9.4	South Jutland (%)	12.8
Rural index of the municipality	Urban (%)	56.5	Rural (%)	22.4
	Intermediate (%)	14.9	Peripheral (%)	6.2
Distance to hospital	mean (km)	5.6	st. dev. (km)	6.9
Exposure measures (per NTM zone)				
Road traffic density	mean (1000 veh/day/km^2)	26.3	st. dev. (1000 veh/day/km^2)	29.4

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Walking traffic density	mean (1000 walk-km/day/km²)	5.5	st. dev. (1000 walk-km/day/km²)	12.8

Table III Model estimates

Variable	Category	est.	Sig	est.	Sig
Built environment at the traffic zone level (within the NTM zone)					
Unemployment rate	log (%)	0.175	**	0.181	**
Region	Copenhagen	-		-	
	Zealand	-0.208	**	-0.220	**
	Fyn / South Jutland	-0.155	*	-0.158	*
	Mid-Jutland	0.083		0.102	*
	North Jutland	0.168	*	0.204	*
Rural index of the municipality	Urban	-		-	
	Intermediate	-0.226	**	-0.241	**
	Rural / Peripheral	-0.037	*	-0.038	*
Distance to hospital	km	0.007	*	0.007	*
Exposure measures (within the NTM zone)					
Walking traffic density	log (100 walk-km/day/km²)	-0.044	*	-0.045	*
Spatial parameter	ρ	-		0.296	**
Number of estimated parameters		48		49	
Initial log-likelihood		-4532.49		-4532.49	
Final log-likelihood		-3887.87		-3879.50	
Adjusted rho-square		0.132		0.133	

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Table IV Marginal effects

Variable	Category	logit	spatial logit
Built environment at the traffic zone level (within the NTM zone)			
Unemployment rate	log (%)	10.2%	11.2%
Region	Copenhagen	-	-
	Zealand	-10.4%	-12.4%
	Fyn / South Jutland	-5.9%	-7.7%
	Mid-Jutland	9.6%	13.1%
	north Jutland	17.1%	22.0%
Rural index of the municipality	Urban	-	-
	Intermediate	-14.6%	-17.6%
	Rural / Peripheral	-2.1%	-2.4%
Distance to hospital	km	2.5%	2.6%
Exposure measures (within the NTM zone)			
Walking traffic density	log (100 walk-km/day/km²)	-2.7%	-2.9%

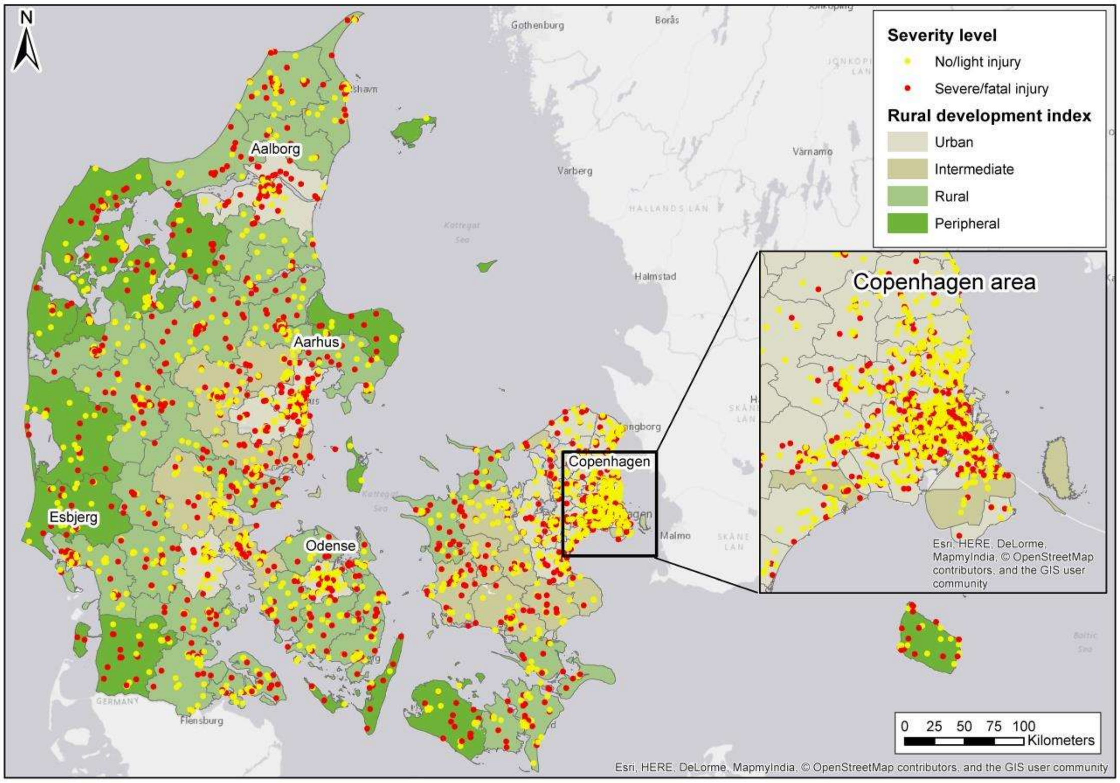

Figure I Spatial distribution of pedestrian crashes in Denmark