Effect of population density in aging societies and severity of motor vehicle crash injuries: the case of Spain

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Abstract

The concentration of population in cities and processes of rural depopulation coupled with the generational shift to older societies represent new challenges in road safety. Here, we examine the severity of injuries suffered by the occupants of motor vehicles involved in a crash based on the population density of the area in which the crash occurs, the driver's age and the density of their place of residence. We conduct the study in Spain, a country with one of the highest levels of elderly population concentrated in rural areas in Europe. Relational methods are used to match Eurostat's urbanization classifications with the accident database of Spain's Directorate General of Traffic so as to correlate each crash with the population density of the place where it occurred. A set of generalized linear models with random effects is fitted to analyze the relationship between population density and the bodily injury severity of the occupants of the vehicle(s) involved in a crash, measuring the effect of drivers' relocation and aging by geographical area. Independence of injury severity and the degree of urbanization was rejected at the 5% significance level. While 53.8% of the Spanish population is living in densely populated areas and only 13.5% in rural areas, the latter concentrates most crashes with fatalities: 2.3 times more than in urban areas (43.5 and 18.6%, respectively). Drivers living in rural areas are more likely to be associated with serious or fatal injuries when involved in a crash in urban and intermediate areas. Moreover, drivers aged over 75 are significantly more likely to be associated with serious and fatal injuries, especially when the crash occurred in urban areas. Recent research alerts on the implications for rural (often elderly) residents of concentrating public services, particularly healthcare, in densely populated areas. Our study shows that motor crashes in more densely populated areas are also a rural health concern. Policy decision-makers need to address this issue to reduce the number of victims and their bodily injury severity.

Keywords Rural areas, Aging societies, Mobility, Motor crashes, Injuries

1 Introduction

Many factors determine the risk of being injured in a road traffic crash and their interaction is complex. The generational shift towards older societies, the unequal spatial distribution of people and their different sociodemographic characteristics lead to new mobility needs of individuals. Responding to these mobility challenges is of concern to both governments and mobility stakeholders [29]. The ongoing concentration of population in cities in conjunction with rural depopulation hinders the achievement of economies of scale outside cities [9], which continue to concentrate more facilities over time, while the

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provision of local services in low-density areas continues to fall [12, 40, 54]. This trend is widespread throughout the EU, with some countries presenting a difference in rural and urban accessibility to services of more than 40 percentage points [27]. Existing inequalities to access basic services are likely to be exacerbated, even if it runs counter to the Sustainable Development Goals of the 2030 Agenda [70, 73].

As such, permanent rural residents have traditionally been forced to be more reliant on their private vehicles and to commute longer distances to urban centers where jobs, education and other services are concentrated [53]. The higher dependence on the private vehicle of rural residents has implications in terms of road safety. Some studies, as Clark and Cushing [22], provide evidence that increased distance between people and/or medical facilities is a determinant of mortality from vehicle collisions. In fact, many studies have shown that the risk of crash depends on the distance driven [10, 25] and the severity of traffic crashes is higher on low-density areas than in urban areas [6, 56, 75]. In Spain, over 52% of all road traffic fatalities in 2021 occurred on rural roads [26].

Here, we seek to determine how the severity of the injuries suffered by victims of a motor vehicle crash differs in relation to the population density of the area in which the crash occurs. Our goal is to contextualize traffic crashes in the geographical area in which they take place, based on whether it has a low, medium, or high population density. We control for the population density of the driver's residence, given that this may differ from the population density of the place in which the crash occurred. To do so, an exhaustive exercise has first to be conducted to determine the location of each crash and the place of residence of the driver(s) and to assign to those places their corresponding population densities. In addition, we analyze the influence of other variables related to the crash, mainly the driver's age, but also some other characteristics of the vehicle, the crash, the occupants, and severity of the injuries. Ultimately, we wish to examine possible links between higher concentrations of the elderly in rural areas (resulting from decentralization) and the severity of bodily injuries incurred; yet, also, we seek to determine whether drivers from rural areas are more likely to be associated with serious or fatal injuries when involved in crashes in urban and intermediate areas.

We focus here on the specific case of Spain, one of the countries in Europe with the highest level of population concentration in its cities [31], with the most aged population [59], and with the highest level of elderly population concentrated in rural areas [14, 59]. In so doing, we draw on the accident database of the Directorate General of Traffic (DGT), focusing on crashes that

occurred between 2016 and 2019, and combine this with the Eurostat classification of the degree of urbanization of Spanish municipalities, to attribute a population density to each geographical location at which a crash occurred. Although we also dispose of accident data for 2020 crashes, we opted to exclude them because they reflect the consequences of the SARS-CoV-2 epidemic on mobility. In the analysis, we include a wide range of regressors, among which we highlight the age of the drivers segmented as follows: under 65, between 65 and 75, and over 75.[1] From a methodological perspective, therefore, we evaluate the severity of injuries suffered by occupants of a vehicle involved in motor vehicle crashes in Spain according to the degree of urbanization, using univariate and multivariate analyses, and in this sense each vehicle is our unit of analysis. For each vehicle, we classify its global bodily injury (BI) severity level according to the maximum BI severity observed for its occupants and, in this sense, we establish four categories: (i) non-BI damages, when none of the occupants suffers BI damages; (ii) slight BI damages, when the greatest severity suffered by the occupants is slight; (iii) severe BI damages, when the maximum category is serious and, (iv) fatal, when at least one occupant is killed. We use generalized linear mixed models (GLMMs), which include random effects to accommodate dependency between observations in the data set and so can include the different vehicles involved in a crash [62].

The analysis of driver longevity is not new. Researchers have highlighted that in numerous high-income countries, older drivers are disproportionately represented among the victims of road accident statistics [15, 42, 65, 74]. Many argue that the increased physical frailty of the elderly explains why they suffer worse crash outcomes [38, 63, 66], especially in older adults aged 75 years and above [2]. Additionally, the consequences of a crash are more likely to be exacerbated by pre-existing health conditions [30, 72]. It has also been reported that the loss of visual and cognitive capacities among the elderly leads to impaired driving and increases their likelihood of being involved in a crash [23, 50, 61].

Other studies demonstrate that some older drivers are aware of their limitations [58] and self-regulate the number of kilometers they drive, either by reducing their exposure to challenging driving conditions, decreasing their overall mileage, changing how they drive or even ceasing to drive at all [3, 46, 47, 51, 60]. Yet, the capacity of older drivers to self-regulate may be limited by their desire to maintain their lifestyle, the unavailability

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[1] Note that this age segmentation has been statistically validated in a previous study of motor vehicle crashes in Spain [4].

of family and friends to provide transport when required, or an unwillingness to ask them for help with transportation, and the lack of availability of public transport [5, 7]. There is evidence that driving cessation has a detrimental effect on the social and physical health of older adults [13, 19, 20, 55]. These factors may be particularly significant in rural areas.

Keeping on mind that one of the main challenges to analyze the population density of the crash location is the definition of the geographical unit of analysis, the first relevant contribution of our research is to employ the European classification of the degree of urbanization of the local administrative units in conjunction with Spain's official traffic accident statistics in an attempt at correlating each crash with the population density where it occurred. Secondly, we model the relationship between population density and the severity of the crash, measuring the effect of relocation and aging by geographical area on the bodily injuries suffered by the victims.

The rest of this paper is structured as follows. Section 2 presents the Eurostat methodology for determining the degree of urbanization of a municipality and its specific application to Spanish geography, as we seek to assign the correct population density to each place where a crash was recorded. In Sect. 3 we detail the criteria used to structure the micro databases provided by Spain's DGT and identify the variables we opt to maintain. Additionally, we present the methodology used to model the severity of bodily injuries suffered. The main results of the analysis are presented in Sect. 4, both at a descriptive statistical level as well as for the binomial logistic regression with random effects modelling. We conclude the paper with a discussion of these findings and present our main conclusions.

2 Contextualization
2.1 Composition of population density in Spain and distribution of motor vehicle crashes by zone
We use Eurostat's urbanization classification procedure (DEGURBA) to classify the degree of urbanization of Spain's municipalities. This methodology classifies each Local Administrative Unit (LAU[2]) according to its population density and contiguity into three categories: "Cities" (densely populated areas), "Towns and suburbs" (intermediate density areas) and "Rural areas" (thinly populated areas). In the rest of this study we refer

to the categories as 'Urban', 'Intermediate' and 'Rural', respectively.

The classification follows a two-step procedure. First, the EU territory is divided into 1-km^2 raster cells, which are classified based on population density and contiguity. Urban centers are defined as contiguous cells with a density of at least 1500 inhabitants/km^2 and a minimum of 50,000 inhabitants. Urban clusters are defined as contiguous cells (including diagonals) with a density of at least 300 inhabitants/km^2 and a minimum of 5000 inhabitants. Cells that are not labeled as urban centers or urban clusters are assigned to the "rural grid cell" category.

In the second step, each LAU is classified based on the share of its population living in urban clusters and urban centers. LAUs with at least 50% of their population living in urban centers are classified as densely populated areas (*Urban*); those with less than 50% of their population living in urban centers and less than 50% of their population living in rural grid cells are classified as intermediate density areas (*Intermediate*); and, those with at least 50% of their population living in rural grid cells are classified as thinly populated areas (*Rural*).

We have mapped Spanish municipalities by their respective degree of urbanization, according to Eurostat's 2018 classification (Fig. 1, left), and the natural logarithm of the number of crashes between 2016 and 2019 (Fig. 1, right).

The Spanish population is not evenly distributed, being essentially concentrated in the Mediterranean coast and provincial capitals of the interior. Cities tend to be surrounded by areas of intermediate population in the southern half of the country and by rural areas in nearly all the northern half with the exception of Catalonia. Motor vehicle crashes seem to correlate to the degree of urbanization as denser the population is, the higher the number of crashes recorded in the municipality. However, this comparison for rural areas is not as direct given the differences in the number of crashes depending on their geographical location.

2.2 Composition of the driver census by population density in Spain
Table 1 shows the evolution in the percentage of drivers (that is, individuals holding a valid driving license) and their share over the population by degree of urbanization. To obtain these percentages, we have combined data from Eurostat's annual correspondence table, which contains the degree of urbanization of each municipality, with the DGT's driver census by municipality.

We collected Spanish driver census data in December 2016, 2017, 2018, and 2021, the latest years for which the disaggregation by municipality was available. First, the driver census and the degree of urbanization data

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[2] LAUs are the unit used by the EU to provide statistics at the local level. As defined by Eurostat, LAUs are low-level administrative divisions of a country below that of province, region or state. Not all countries classify their locally governed areas in the same way. LAUs may refer to municipalities, communes, parishes or wards, among others. In Spain, the local administrative unit is the municipality.
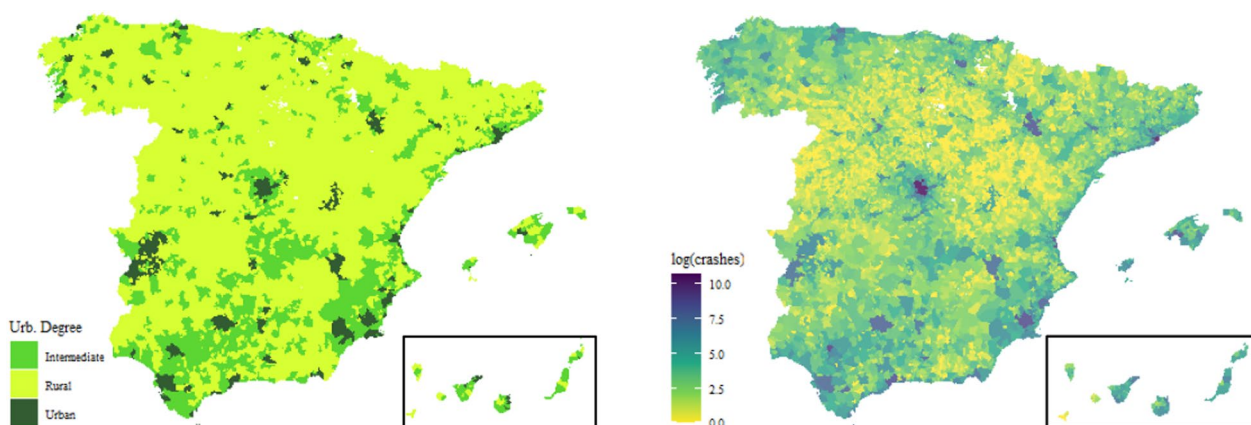
Fig. 1 Map of Spanish municipalities by degree of urbanization in 2018 (right) and natural logarithm of the number of motor vehicle crashes 2016–2019 (left)

Table 1 Drivers, population and drivers with respect to population by degree of urbanization, Spain 2016–2019 (%). *Source* Own elaboration based on DGT (2023) and Eurostat (2023)

Year	Drivers			Population			Drivers with respect to population		
	Urban (%)	Intermediate (%)	Rural (%)	Urban (%)	Intermediate (%)	Rural (%)	Urban (%)	Intermediate (%)	Rural (%)
2016	52.5	33.3	14.3	53.7	32.6	13.7	66.3	69.2	70.5
2017	52.4	33.4	14.2	53.7	32.6	13.7	66.4	69.6	70.3
2018	52.4	33.5	14.2	53.7	32.7	13.6	66.4	69.8	70.7
2019	52.2	33.6	14.1	53.8	32.7	13.5	65.9	69.9	70.9

by municipality were summarized. Each table contained the name of a municipality together with the number of drivers in each year and the corresponding urbanization categorization. Then, for each year, the number of drivers conditional on the degree of urbanization of the municipality (urban, intermediate or rural) was summed. Finally, the number of drivers in each area was divided by the total to obtain their share.

When grouping these data, we faced two obstacles: first, the driver census by municipality was not available for years 2019 and 2020; and, second, the criteria for defining the degree of urbanization change in 2018 thus limiting comparability prior to that year. We proceeded as follows. The driver census for 2019 was estimated by calculating the compound annual growth rate by degree of urbanization between 2018 and 2021, and the 1-year estimated growth rate was applied to the 2018 values. In the second issue, given that the degree of urbanization of municipalities is very stable and there are few year-on-year classification changes, the degree of urbanization of 2018 was attributed to the years 2016 and 2017.

In Table 1, the three columns corresponding to 'Drivers' show the distribution of Spanish drivers by the degree of urbanization in their municipality of residence. The three columns corresponding to 'Population' show the residential distribution of the general Spanish population aged 15 and above. Finally, the last three columns, labeled 'Drivers with respect to population' show the proportion of drivers relative to the total population, categorized by degree of urbanization.

Between 2016 and 2019, there was no noticeable change in the share of drivers by degree of urbanization. When comparing the distribution of drivers and population with respect to the degree of urbanization, the pattern that emerges is largely similar. However, the percentage of drivers in urban areas is smaller than their representation in the general population, while the opposite is the case for drivers in intermediate and rural areas. When evaluating the number of drivers with respect to the population by area, even though most of the population live in urban areas, people with valid driving licenses in these areas constitute the smallest percentage of the three areas considered. Conversely, rural areas
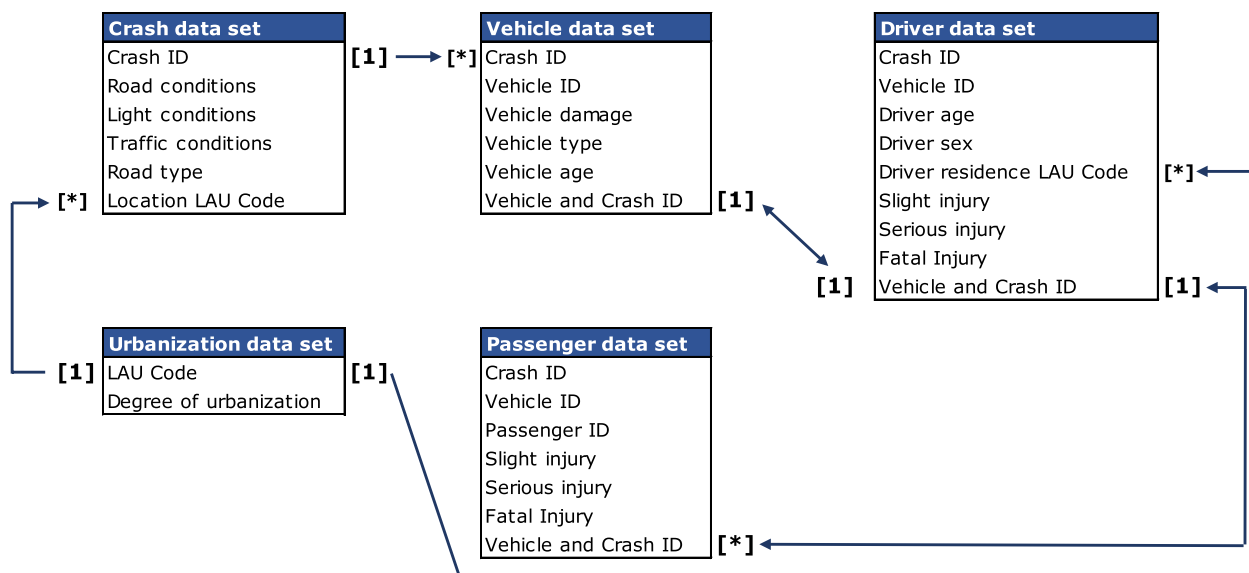
Fig. 2 Schema of database combination. One-to-one relationships are indicated by [1] ↔ [1], while one-to-multiple are shown by [1] → [*]. Source: Own elaboration

concentrate the smallest percentage of the population but present the highest proportion of drivers, exceeding that of urban areas by 5 percentage points, with intermediate areas falling between the two.

3 Research design
3.1 Data
To study the effect of both driver and motor vehicle crash attributes on the severity of a crash by geographical area, four DGT datasets were used. Detailed information of police reports for all motor vehicle crashes between 2016 and 2019 involving at least one injured victim is available. Police officers monitor the health progression made by these victims over a 30-day period and update their reports accordingly. Each data set comprises a set of micro databases centered on a specific aspect of the crash: namely, traffic crash (Crash dataset), vehicles involved (Vehicle dataset), drivers (Driver dataset) and passengers (Passenger dataset). The degree of urbanization was attributed by linking the postal code of the crash location and driver residence to the Eurostat data set (Urbanization dataset).

All the information from the different datasets is related by means of a relational model, as illustrated in Fig. 2, employing a series of chained one-to-many and one-to-one relationships. In the Urbanization dataset, each unique postal code is attributed a population density classification. The postal code links this dataset and the Crash dataset, which includes the location of the crash. The Crash dataset has a unique ID for each traffic crash that links it to the Vehicle dataset, which contains the crash ID for each vehicle. The Vehicle, Driver and Passenger datasets have two identifiers, one for the crash and another for the specific vehicle in the crash, which are concatenated to create a joint crash and vehicle ID. The joint crash and vehicle ID links each vehicle to its driver and each driver to his or her passengers.

The complete database contains information for 398,590 police-reported crashes involving 672,439 vehicles for the period from January 2016 to December 2019. Occupants suffered no injuries in 283,097 (42.1%) of these vehicles, while there was at least one injured occupant in the remaining 389,342. Only vehicles with complete records according to the requirements of our research, i.e., no missing values in the risk factors defined in Table 4, were selected. So, we ended up with a database of 177,192 crashes involving 286,437 vehicles. When more than one vehicle was involved in a crash, they were all included as long as complete information for all vehicles involved in the crash was available.

The study followed the classification of injury severity given by the Spanish Traffic Authority. According to this classification, minor injuries are those that did not require hospitalization; serious injuries are those that required hospitalization for more than 24 h, and fatal injuries are those in which the victim died within 30 days as a result of the crash. Our observational unit is the crashed vehicle. As a standard practice, the severity of the injuries in a vehicle was classified according to the worst injury sustained by its occupants. A vehicle with minor injuries (*slight*) was one in which the most seriously injured occupant(s) sustained minor injuries.

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Table 2 Distribution of BI severity of vehicles involved in a motor crash with victims by degree of urbanization of the crash location (Spain, 2016–2019)

Injury	Urban (%)	Inter. (%)	Rural (%)`	Total (%)
None	47.0	39.4	27.2	41.6
Slight	49.9	54.1	59.8	52.7
Serious	2.7	5.0	9.6	4.5
Fatal	0.4	1.5	3.4	1.2
Total	100	100	100	100

Table 3 Distribution of the degree of urbanization of the location where motor vehicle crashes with victims occurred by BI severity of vehicles involved (Spain, 2016–2019)

Area	None (%)	Slight (%)	Serious (%)	Fatal (%)	Total (%)
Urban	60.2	50.4	32	18.6	53.2
Inter	29.7	32.1	35	37.9	31.3
Rural	10.1	17.5	33	43.5	15.4
Total	100	100	100	100	100

A vehicle with serious injuries (*serious*) was one in which the most seriously injured occupant(s) required hospitalization. Finally, a vehicle with fatal injuries (*fatal*) was one in which the most seriously injured occupant(s) died. According to these criteria, 41.6% of the crashed vehicles had no injured occupants, 52.7% of the vehicles were classified as slightly injured, 4.5% of the vehicles were classified as seriously injured and 1.2% of the vehicles were classified as fatally injured.

The percentage of crashed vehicles by the degree of urbanization of the crash location and the injury severity of the vehicle(s) involved is disaggregated in Tables 2 and 3. Table 2 shows that 72.8% of vehicles involved in a crash in rural areas had at least one occupant who was injured, in contrast to 53% of vehicles in urban areas and 60.6% of vehicles in intermediate areas. The proportion of vehicles which had occupants that did not present any bodily injuries differs markedly between the areas. Thus, rural areas have the smallest share of occupants without injuries (none), 19.8 percentage points below that of urban areas, and concentrate more vehicle occupants in worse injury categories. Thus, the proportion of vehicles associated with serious bodily injuries in rural areas is 3.6 times greater than that in cities, while in the case of fatalities it is 8.5 times higher. The Pearson's Chi-square test of independence to determine whether there is an association between two categorical variables was computed. Independence between BI severity of crashed vehicles and degree of urbanization of the crash location was rejected at the 5% significance level (p-value < 2.2e−16).

When examining the distribution of the degree of urbanization of the places where the crashes occurred differentiated by the BI severity of the vehicles involved, urban areas present the highest share of vehicles with none or slight injuries (Table 3). Vehicles with serious injuries are more evenly split although most are reported in intermediate areas (35%), while rural areas concentrate most vehicles with fatalities (43.5%), that is, 2.3 times more than urban areas (18.6%).

3.2 Risk factors

We now analyze the factors that affect the severity of bodily injuries of the occupants of a vehicle involved in a crash based on the geographical area in which the crash took place. The variables included are shown in Table 4. Thus, for the driver, we consider age, sex, and place of residence; for the vehicle, we consider age, type, and number of occupants. In the case of the crash, we consider the degree of urbanization where the crash occurred as our segmentation variable, and a number of additional variables, including road pavement conditions, light and visibility, traffic flow, number of drivers involved in the crash, damage to the vehicle, and road type.

Driver ages are divided into three categories: 18–64, 65–75, and 76 and older. Initially, we considered just two groups: younger drivers (aged 18–64) and older drivers (65 and older), as we sought to stress the potential differences attributable to aging. Then, we split the older drivers into young-older (65–75) and old-older (76 or older), to account for the different outcomes on bodily injuries reported by Ayuso et al. [4] when using the DGT's 2016 datasets. The maximum values observed for vehicle age, number of occupants and number of drivers were very high but feasible in case of, for example, a crash involving a historic vehicle, a coach or a multiple-vehicle accident, respectively. So, we decided to keep the observations with these values in the analysis.

3.3 Generalized linear model with random effects

Our analysis focuses on the relationship between a set of risk factors and the injury severity of the occupants of a vehicle involved in a crash, where the unit of observation is the vehicle involved in a crash. We include three dependent binary variables: a vehicle with light injures (*l*), a vehicle with serious injuries (*s*) and a vehicle with fatalities (*f*). Generalized linear models (GLMs) for binary variables assume that observations are independent. This assumption could be very restrictive in our context. When multiple vehicles are involved in a collision, the injury severity of occupants of different vehicles could presumably be correlated. When data present correlated clusters, generalized linear mixed models (GLMMs) are a more appropriate specification

Table 4 Description of variables

Name	Categories	Description	Mean*	Min	Max
Driver and vehicle					
Driver age	18–64	Driver is aged below 65 years old (Reference category)	91.3%	0	1
	65–75	Driver is aged between 65 and 75 years old	6.0%	0	1
	>75	Driver is older than 75 years old	2.7%	0	1
Driver sex	Man	Driver is a man (Reference category)	71.4%	0	1
	Woman	Driver is a woman	28.6%	0	1
Driver residence	Urban	Densely populated areas (Reference category)	54.1%	0	1
	Intermediate	Intermediate populated areas	33.2%	0	1
	Rural	Thinly populated areas	12.7%	0	1
Vehicle age		Age of the vehicle involved in the crash	10.7	0	74
Vehicle type	Car	Passenger cars (Reference category)	70.4%	0	1
	Heavy vehicles	Trucks, tractors, and other heavy vehicles	5.5%	0	1
	Motorcycles	Motorcycles and quads	16.5%	0	1
	Van	Vans and minibuses	7.6%	0	1
Occupants		Number of occupants in the vehicle (including the driver)	1.4	1	61
Crash					
Road conditions	Optimal	Optimal driving conditions of the road surface (Reference category)	86.0%	0	1
	Non-optimal	Non-optimal driving conditions of the road surface (wet, frozen, muddy)	14.0%	0	1
Light conditions	Optimal	Driving with good visibility (Reference category)	71.2%	0	1
	Moderate	Driving with moderate visibility	6.5%	0	1
	Not optimal	Driving without appropriate visibility	22.3%	0	1
Traffic conditions	White	Traffic is fluid and normal (Reference category)	68.4%	0	1
	Green	The traffic is so intense that it does not allow the maximum speed allowed on the road to be reached	19.3%	0	1
	Other	Intermittent or interrupted traffic	12.3%	0	1
Vehicle damage	No damage	Vehicle has no damage (Reference category)	7.7%	0	1
	Frontal	Vehicle has the most damage in the frontal area	49.4%	0	1
	Rear	Vehicle has the most damage in the rear area	18.8%	0	1
	Side	Vehicle has the most damage on one of its sides	24.1%	0	1
Road type	Local	City streets and township roads (Reference category)	45.7%	0	1
	Conventional	Minor arterials	31.1%	0	1
	High speed	Highways, freeways, and other principal arterials	19.8%	0	1
	Other	Subsidiary roads, unpaved roads, cycling lanes, and others	3.4%	0	1
Number of drivers	Number of drivers involved in the crash	2.0	1	27
Crash location urbanization	Urban	Densely populated areas (Reference category)	53.2%	0	1
	Intermediate	Intermediate populated areas	31.3%	0	1
	Rural	Thinly populated areas	15.4%	0	1
Vehicle injury severity					
Slight injuries		Vehicle in which a slight injury is the most severe injury	52.7%	0	1
Serious injuries		Vehicle in which a serious injury is the most severe injury	4.5%	0	1
Fatal injuries		Vehicle in which a fatal injury is the most severe injury	1.2%	0	1

* Relative frequency in % for categorical variables

[41, 71]. GLMMs are an extension of GLMs that incorporate random effects for the analysis of multilevel data. Under the GLMM framework, a motor collision is considered a cluster with as many observations as vehicles involved.

The GLM relates the conditional mean of the distribution μ^j for the vehicle injury severity j, $j \in \{l, s, f\}$, and the linear regression through the link function g as follows: $g\left(\mu_i^j\right) = \eta_i = x_i^{\mathrm{T}} \beta^j$ for the i-th vehicle, $i = 1, \dots,$ I,

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where η_i is the linear predictor, β^j is the vector of the regression coefficients and x_i is the vector of regressors. We focus on a binomial distribution with a canonical function, $g\left(\mu_i^j\right) = \frac{\pi_i^j}{1-\pi_i^j}$, where π_i^j is the probability that vehicle i presents an injury severity j. In this case, the binomial specification is equivalent to the logit regression model [45].

The GLM for discrete variables assumes that observations are independent. Now we introduce a Q-dimension vector of cluster-specific parameters $\theta_n^j = \left(\theta_{n1}^j, \ldots, \theta_{nQ}^j\right)$ and a vector z_{ni} of predictors corresponding to the random effects, for $n=1,\ldots,N$. In our case n indicates the crash and only one cluster-specific parameter is considered, so θ_n^j and z_{ni} are scalars where z_{ni} is an indicator variable that takes 1 if the i-th vehicle was involved in the crash n and 0 otherwise. In the GLMM with a cluster-specific variable, the conditional mean π_{ni}^j is regressed on the predictors as follows: $\pi_{ni}^j/\left(1 - \pi_{ni}^j\right) = x_{ni}^{\mathrm{T}}\beta^j + z_{ni}\theta_n^j$. The constant term of the linear predictor is no longer the same for all observations but now varies for each group of vehicles involved in the same crash. Thus, unobserved individual-specific heterogeneity associated with the crash in which the vehicle was involved is introduced into the regression modeling. The size of the standard deviation of the random effects, $sd\left(\theta^j\right)$, will be an indicator of how relevant the presence of cluster-specific heterogeneity in the motor data set is.

4 Results

4.1 Descriptive statistics
The characteristics of the parties involved in a crash differ with the degree of urbanization, as illustrated by the variables presented in Table 5. The differences in proportions tend to be greater when comparing the injury severity levels by different degrees of urbanization, i.e., comparing serious injuries in the three areas, rather than when making a comparison of the proportion of different BI categories within the same area, i.e., comparing the proportions of the three injury severities in urban, intermediate and rural areas. Pearson's chi-square tests for each of these categorical variables reject the fact that the distribution by the degree of urbanization of the crash location are the same for all variables and BI categories.

It is worth highlighting that less densely populated areas (primarily rural) are associated with a higher share of older drivers involved in motor vehicle crashes with injuries, and with a higher proportion of vehicles involved in crashes that occur when traffic conditions are fluid. Male drivers are involved in a markedly higher proportion of motor vehicle crashes with injured occupants

than women drivers; moreover, in less densely populated areas, a greater share of men are recorded as drivers of vehicles associated with slight injuries. As regards driver residence, drivers in each of the three categories (i.e., urban, intermediate and rural) suffer the most crashes in their own area of residence, regardless of the BI classification. For all BI levels, the proportion of motorcycles involved in a crash is significantly higher in urban areas compared to the rest; in contrast, the proportion of passenger cars and heavy vehicles is higher in less densely populated areas.

Vehicles with injured occupants in rural and intermediate areas were involved in more crashes while driving in non-optimal road conditions. Frontal damage to vehicles tends to be more prevalent in intermediate and rural areas, while urban areas presented a greater prevalence of rear and side damage. Finally, road types present the greatest proportional differences. Thus, local roads in urban areas present the highest proportion of crashes for all BI injuries, significantly more than on these roads in intermediate and, especially, rural areas. The opposite is the case for conventional roads, with rural areas presenting the highest proportions, with intermediate areas at some distance albeit this gap closes as the severity of the BI injury increases. As for high-speed roads, the difference is most noticeable in the case of fatal injuries, where the proportion of vehicles recording fatalities in urban areas doubles that in the other two areas.

4.2 Model selection
The logit regression model with random effects described in Sect. 3.3 is fitted to explain the injury severity based on the risk factors included in Table 4. Nine regression models combining the three degrees of urbanization and the three injury levels are considered. To dispose of a benchmark, the same number of regression models without random effects were fitted. We present the Akaike information criteria (AIC) and the Bayesian information criteria (BIC) for the regressions in Table 6. The inclusion of random effects led to the lowest AIC and BIC in six of the models, i.e., all the models except those for which we evaluated vehicles associated with slight injuries. Although the differences are not large, the consistent improvement in the information criteria across most of the regressions is a sign of the presence of heterogeneity in the data and the way in which GLMMs can help to partially capture it. In other words, we found evidence that observations from the same cluster were not independent of each other when the vehicles involved in the crash sustained serious or fatal injuries. The moderate improvements in terms of AIC and BIC reduction could be due to the fact that most clusters contain only one or, at most, two observations.

Table 5 Descriptive statistics of risk factors by bodily injury severity of vehicle(s) involved and degree of urbanization of crash location

Crash location urbanization	Slight				Serious				Fatal			
	Urban	Inter	Rural		Urban	Inter	Rural		Urban	Inter	Rural	
Sample size for vehicles with injured occupants	76,001	48,487	26,446		4,131	4,525	4,260		639	1,302	1,493	
Categorical variables (relative frequency in **%**)												
Driver age												
Under 65 years old	95.1	91.4	87.8		93.6	89.9	85.5		88.0	83.3	81.9	
65–75 years old	3.7	5.9	7.7		4.7	6.7	9.6		7.8	9.4	10.8	
Over 75 years old	1.2	2.8	4.4	a	1.7	3.4	4.9	a	4.2	7.4	7.4	a
Driver sex												
Man	67.5	67.1	72.0		85.8	83.2	84.3		89.7	87.3	89.2	
Woman	32.5	32.9	27.9	a	14.2	16.8	15.7	a	10.3	12.8	10.8	
Driver residence												
Urban	81.0	23.1	30.1		81.6	22.0	30.2		72.9	22.2	28.9	
Intermediate	14.9	67.0	24.7		14.1	66.9	24.4		18.8	63.9	24.7	
Rural	4.1	9.9	45.1	a	4.3	11.1	45.4	a	8.3	13.9	46.4	a
Vehicle type												
Car	59.1	71.9	72.9		26.8	48.8	56.5		42.7	55.0	61.1	
Heavy vehicles	2.5	3.2	5.1		2.7	4.2	5.9		5.0	6.7	9.9	
Motorcycles	34.4	17.9	13.8		67.9	41.2	31.9		48.2	30.6	21.8	
Van	4.0	7.0	8.1	a	2.6	5.8	5.7	a	4.1	7.8	7.2	a
Road conditions												
Optimal	85.7	84.7	77.6		88.3	87.5	82.2		90.1	87.7	82.3	
Non-optimal	14.3	15.3	22.3	a	11.7	12.5	17.8	a	9.9	12.3	17.8	a
Light conditions												
Optimal	69.5	70.7	71.6		62.5	63.9	72.4		56.7	61.3	65.9	
Moderate	6.6	6.5	5.4		6.4	6.5	4.7		6.4	6.2	5.3	
Non optimal	23.8	22.8	22.9	a	31.1	29.6	22.9	a	36.9	32.5	28.8	a
Traffic conditions												
White	63.2	73.0	87.5		68.1	80.3	91.1		82.5	88.3	90.7	
Green	21.5	17.6	9.3		22.1	15.7	7.7		13.6	9.5	7.7	
Other	15.4	9.4	3.1	a	9.8	4.0	1.3	a	3.9	2.2	1.6	a
Vehicle damage												
No damage	2.4	1.0	0.7		1.6	0.8	0.7		0.8	0.4	0.5	
Frontal	41.7	53.5	61.9		53.0	63.4	61.9		58.4	62.4	62.6	
Rear	25.7	21.1	11.2		5.7	5.1	4.3		7.7	5.7	4.6	
Side	30.2	24.5	26.1	a	39.7	30.7	33.1	a	33.2	31.6	32.2	
Road type												
Local	63.4	24.8	4.4		58.6	16.5	3.5		31.3	6.6	2.5	
Conventional	11.9	49.5	73.0		19.4	62.1	76.8		33.5	67.4	76.8	
High-speed	22.2	21.0	18.2		18.2	15.5	14.2		30.7	19.7	14.1	
Other	2.6	4.7	4.3	a	3.8	5.9	5.5	a	4.5	6.2	6.6	a
Numerical variables (mean and standard deviation -in parentheses)												
Vehicle age	9.9	11.4	12.1	a	10.3	11.6	12.3	a	11.1	12.7	13.1	a
	(6.4)	(6.6)	(6.7)		(6.8)	(6.8)	(7.2)		(7.1)	(7.0)	(7.5)	
Occupants	1.5	1.6	1.6	a	1.3	1.5	1.6	a	1.5	1.6	1.6	a
	(0.9)	(1.0)	(1.1)		(0.7)	(1.1)	(1.6)		(1.3)	(2.3)	(1.4)	
Number of drivers	2.1	1.9	1.6	c	1.8	1.7	1.5	a	1.7	1.7	1.6	b
	(0.8)	(0.9)	(1.0)		(0.8)	(0.8)	(0.8)		(1.0)	(1.0)	(0.7)	

Statistical independence between the risk factors and the degree of urbanization of the crash location was evaluated. Pearson's chi-square test for independence in categorical variables and the one-way ANOVA for differences in the means in numerical variables were computed. a. *P*-value < 0.01, b. *P*-value < 0.05, c. *P*-value < 0.1

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Table 6 Comparison of logit regressions with and without random effects

Injury	Degree Urb		Without random effects	With random effects
Slight	Urban	AIC	165,383	–
		BIC	165,611	–
Slight	Intermediate	AIC	108,003	108,005
		BIC	108,219	108,230
Slight	Rural	AIC	53,641	53,643
		BIC	53,841	53,851
Serious	Urban	AIC	31,552	31,510
		BIC	31,780	31,748
Serious	Intermediate	AIC	31,336	31,242
		BIC	31,552	31,468
Serious	Rural	AIC	25,948	25,905
		BIC	26,148	26,113
Fatalities	Urban	AIC	6997	6984
		BIC	7225	7223
Fatalities	Intermediate	AIC	12,119	12,103
		BIC	12,335	12,329
Fatalities	Rural	AIC	12,475	12,464
		BIC	12,675	12,673

4.3 Model estimation results

Coefficient estimates of risk factors by injury type and degree of urbanization were qualitatively equal in terms of significance and sign of coefficient estimates for the GLMs and the GLMMs (not shown). Table 7 shows the estimated coefficients for the selected logistic regression models by injury type and the degree of urbanization of the crash location. As explained before, logit regression models were preferred without random effects for vehicles in crashes classified as slight injury severity and with random effects for those classified as serious or fatal. A negative (positive) coefficient indicates a decrease (increase) in the expected probability of the maximum injury severity in the vehicle being slight, serious and fatal, respectively. Note that the three severity levels are mutually exclusive. So, the sign and significance of the coefficients associated with a risk factor should be interpreted jointly in the three severity regression models to better understand their effect on injury severity.

The effect of driver's age is significant in most cases. The sign of the coefficients associated to the driver's age depends on the vehicle injury severity considered. The probability of the crashed vehicle sustaining minor injuries in the different urbanization areas decreases with the age of the driver, while the probability of the crashed vehicle sustaining fatal injuries increases with the age of the driver. The increase in the likelihood of

fatal crashed vehicles is higher for drivers aged over 75 (old-older) than those aged 65–75 (young-older), and for urban roads than intermediate and rural roads. However, in the case of serious injuries, we find that drivers aged over 75 are significantly more likely to cause injuries in a crashed vehicle that occurs in urban areas than they are in intermediate and rural areas where there is no significant difference in this likelihood with drivers below the age of 65. When evaluating the sex of the driver, women are more likely in all three areas to cause slight injuries to their vehicles' occupants and less likely to cause them serious or fatal injuries.

Drivers resident in rural areas are significantly less likely to be involved in crashes resulting in slight injuries in the vehicle when driving in urban areas, but more likely to be involved in crashes with serious or fatal injuries in the vehicle in urban and intermediate areas. This effect is greater in urban areas, especially in crashes involving fatal injuries. These same drivers (rural residents) are as likely to suffer serious and fatal injuries in rural areas as urban drivers. No significant differences are observed between drivers living in intermediate areas and in urban areas for serious and fatal injuries.

All three levels of BI are positively associated with the number of vehicle occupants. The more occupants there are in a car, the greater is the likelihood of one of them suffering an injury. The size of this effect is greater in urban areas. Conversely, the greater the number of drivers involved in a collision (multiple collision), the lower the probability of injury of any kind to each of the vehicles involved. Collisions involving multiple vehicles are often rear-end collisions, which are associated with less severe BI outcomes [1]. The effect of road conditions is similar for all areas. Non-optimal road conditions increase the likelihood of slight injuries to the crashed vehicle, while they reduce the likelihood serious and fatal injuries. This counterintuitive result may be associated with a risk-compensation behavior of drivers driving more carefully on non-optimal pavements [18, 48].

Moderate light conditions do not affect the likelihood of injury in rural areas, while they reduce the likelihood of slight injuries in urban and intermediate areas and increase it for serious and fatal injuries in intermediate areas. Non-optimal light conditions increase the likelihood of all injuries except for slight injuries in urban and intermediate areas. An evaluation of traffic conditions shows that less fluid traffic flows seem to be associated with a reduction in slight and fatal injuries when the crash takes place in urban and intermediate areas, as well as in serious injuries in rural areas.

As for the actual vehicles involved in the crash, heavy vehicles are associated with a greater reduction in the likelihood of occupants' suffering slight injuries in less

Table 7 Coefficient estimates of the logistic regression without and with random effects according to the vehicle injury severity and the degree of urbanization of the crash location

		Slight			Serious			Fatal		
		Urban	Inter	Rural	Urban	Inter	Rural	Urban	Inter	Rural
	Intercept	− 3.30a	− 2.78a	− 1.86a	− 6.07a	− 5.47a	− 4.49a	− 8.17a	− 8.04a	− 6.08a
Driver age	Under 65 years old (Ref.)	–	–	–	–	–	–	–	–	–
	Between 65–75 years old	− 0.30a	− 0.20a	− 0.15a	0.27a	0.10	0.27a	0.67a	0.47a	0.36a
	Above 75 years old	− 0.27a	− 0.12a	− 0.09c	0.39a	0.12	0.12	1.10a	0.87a	0.47a
Driver sex	Man (Ref.)	–	–	–	–	–	–	–	–	–
	Woman	0.58a	0.54a	0.59a	− 0.37a	− 0.30a	− 0.30a	− 0.82a	− 0.62a	− 0.76a
Driver residence	Urban (Ref)	–	–	–	–	–	–	–	–	–
	Intermediate	− 0.10a	0.04b	0.03	0.06	0.06	0.00	0.10	0.11	0.01
	Rural	− 0.15a	0.02	− 0.08a	0.25a	0.22a	0.05	0.60a	0.36a	0.00
Occupants		0.80a	0.38a	0.15a	0.14a	0.09a	0.10a	0.15a	0.08a	0.04b
Drivers		− 0.21a	− 0.37a	− 0.55a	− 0.32a	− 0.33a	− 0.28a	− 0.52a	− 0.30a	− 0.22a
Vehicle age		0.02a	0.01a	0.01a	0.03a	0.02a	0.02a	0.02a	0.03a	0.02a
Road conditions	Optimal (Ref.)	–	–	–	–	–	–	–	–	–
	Non-optimal	0.31a	0.34a	0.31a	− 0.28a	− 0.17a	− 0.13a	− 0.59a	− 0.25a	− 0.20a
Light conditions	Optimal (Ref.)	–	–	–	–	–	–	–	–	–
	Moderate	− 0.04c	− 0.06b	0.05	0.10	0.16b	0.03	0.23	0.22c	0.19
	Non-optimal	− 0.01	0.00	0.04c	0.40a	0.40a	0.17a	0.57a	0.47a	0.46a
Traffic conditions	White (Ref.)	–	–	–	–	–	–	–	–	–
	Green	− 0.13a	− 0.10a	0.02	0.07	− 0.02	− 0.12c	− 0.45a	− 0.52a	− 0.07
	Other	− 0.20a	− 0.18a	0.01	− 0.19a	− 0.54a	− 0.59a	− 1.54a	− 1.22a	− 0.28
Vehicle damage	No damage (Ref.)	–	–	–	–	–	–	–	–	–
	Frontal	1.81a	2.46a	2.41a	1.62a	1.90a	1.73a	2.25a	2.31a	1.88a
	Rear	2.58a	3.02a	2.52a	0.62a	0.81a	0.88a	1.45a	1.36a	1.09a
	Side	1.85a	2.47a	2.32a	1.26a	1.61a	1.66a	1.85a	2.23a	1.92a
Vehicle type	Car (Ref.)	–	–	–	–	–	–	–	–	–
	Heavy vehicles	− 0.23a	− 0.85a	− 0.98a	0.34a	− 0.06	− 0.16b	0.27	0.21c	0.24b
	Motorcycle	2.61a	1.39a	0.27a	2.31a	1.74a	1.33a	1.52a	1.17a	0.62a
	Van	− 0.28a	− 0.23a	− 0.15a	0.02	− 0.02	− 0.23a	− 0.04	0.12	− 0.09
Road type	Local (Ref.)	–	–	–	–	–	–	–	–	–
	Conventional	0.34a	0.36a	0.49a	1.00a	0.93a	0.55a	1.88a	1.71a	0.85a
	High-speed	0.48a	0.61a	0.69a	0.75a	0.84a	0.62a	1.79a	1.80a	0.75a
	Other	0.19a	0.22a	0.36a	0.67a	0.76a	0.56a	1.33a	1.53a	1.09a
	SD(Random effect)	–	–	–	0.73	0.80	0.65	1.01	0.82	0.69

densely populated areas, while in the case of serious injuries, heavy vehicles increase this likelihood of BI in urban areas but reduce it in rural areas. Crashes involving motorcycles increase the likelihood of all injuries in all areas; however, the less densely populated an area is, the smaller the increase in the likelihood of injury is. Finally, all other road types are significantly more dangerous than local roads for all three degrees of urbanization, the effects being greatest in the case of slight injuries and lowest in those of serious and fatal injuries in rural areas.

5 Discussion

While many studies have investigated the characteristics of the locations where traffic crashes occurred, there have been far fewer studies that analyzed residence characteristics of the drivers [21, 36, 37]. In our study we have analyzed the effect of the population density of both the crash location and the driver's residence on the injury outcome. We found that more crashes with injured victims occur in more densely populated areas, however, the ratio of serious injuries and fatalities to total injury

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crashes rises as the population density of the area falls, a finding that is consistent with previous studies [8, 39, 75]. The literature review of Keeves et al. [35] concluded that of the studies reporting injury-related mortality, there were a greater risk of fatality following an injury in rural areas.

One of the main results of our study was that drivers from rural areas present a significantly higher likelihood of suffering worse injuries and fatalities when driving outside areas similar to those of their place of residence, such as intermediate and urban areas. This finding is supported for Shrira and Noguchi [64] who also found that rural residents presented higher fatality rates than urban residents on urban roads. When the focus is on crashes on rural roads, we found that the risk of serious injury and fatality was not different for drivers living in urban or intermediate areas compared to rural drivers. In this respect, our findings run contrary to those obtained by Donaldson et al. [24], who reported that it was drivers from urban counties that presented the highest risk of fatalities when involved in rural crashes, and, in part, Shrira and Noguchi [64], who found that urban residents presented a substantially higher fatality risk than rural residents when driving in rural areas. However, in line with our results, Chen et al. [17] observed no difference in the risk of injurious crashes by place of residence in their study among young drivers. Therefore, we did not find evidence of a riskier behavior of rural drivers compared to urban drivers in rural roads [57].

The greatest injury and fatality risk for rural drivers on crashes on highways in densely populated areas and the lack of significance of the driver's residence on the injury and fatality likelihood on crashes on rural roads seem contrary to what we might expect from the 'familiarity' argument. It has been well documented in the literature that most drivers crash at locations close to their homes [11, 16, 67], it being argued that familiarity increases proneness to crashes as a result of driving processes becoming more automated and drivers seeking to minimize their travel time at the expense of an increased risk of crash [32, 33, 44, 49]. When the argument regarding a driver's 'familiarity' with his or her road environment is made, it is employed primarily to frame differences in the crash rate, although Burdett et al. [11] provide validation that the familiarity effect also applies to all levels of injury severity. In our study, a higher risk of serious and fatal crashes due to the familiarity effect of drivers was not detected.

When analyzing the interaction between the driver age and the population density of the crash location, some relevant associations were observed. The effect of driver age on the likelihood of serious and fatal injuries appears to be more pronounced in crashes in urban areas than in

crashes in intermediate and rural areas. Thompson et al. [68, 69] indicated that the age range of particular interest when looking at serious or fatal injury crashes was 75 years and above, and they found that rural drivers over 75 were the most likely to be involved in serious or fatal crashes. While we also recommended segmenting the age range of older drivers into two age groups: 65–75 years and 75 years and above, in our study we found evidence that the relative increase in the probability of serious and fatal crashes associated with the two age groups of older drivers was greater on urban roads than on intermediate or rural roads. Some of the challenges elderly face when driving in urban environments have been identified by Payyanadan et al. [52]: namely, driving in dense traffic conditions, problems taking alternative routes when a main route cannot be taken, poor understanding of certain driving rules, and problems associated with knowledge of different speed limits on certain roads. These risk factors associated to older drivers would have a lower incidence in rural areas. In short, serious and fatal crashes are more likely in rural areas, but older drivers increase proportionally more the risk of serious and fatal crashes in urban areas.

This study is not without its limitations. The inclusion of random parameters in the data modelling process to capture the dependence between vehicles involved in the same crash appears to be an improvement on the use of conventional logistic regression, showing itself to be, in line with other studies [28, 71], a better fit. However, we have assumed that the factors impacting injury severity are stable overtime, Mannering [43] and Islam and Mannering [34] suggest that some caution could be required in this respect. Additionally, efforts to compare our results with those in the extant literature have been hampered by the absence of a standardized approach to the categorization of rural, intermediate and urban areas. However, arguably one of the main contributions of this paper has been to demonstrate the practical utility of Eurostat's degree of urbanization framework when categorizing such areas. Significantly, employing this categorization enables more robust comparisons to be made, not only with other EU member states, but also with other geographical regions where the methodology is applied.

6 Conclusions

The study reported here has sought to offer a comprehensive understanding of how the degree of urbanization impacts occupant injuries in motor vehicle crashes, assessing the influence of both the location of the crash and the driver's origin on injury outcomes and their interaction with aging drivers. Drivers from rural areas are more likely to sustain serious or fatal injuries to

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themselves or their passengers when involved in crashes within urban or intermediate areas. Although advanced driving age appears consistent as a risk factor for fatal crashes in all areas, its effect is particularly relevant on urban roads.

The growing population of older drivers in rural areas might have a proportionally greater impact in terms of more severe crash outcomes on urban roads. The ongoing concentration of public services in densely populated areas obliges the rural drivers (often elderly) to drive long distances to unfamiliar environments to acquire them, particularly healthcare. It is apparent that to reduce the number of victims from rural areas, analyses must extend beyond the obvious rural factors and focus their attention also on the journeys that rural residents make to cities, in an awareness that both serious and fatal injuries from motor vehicle crashes in more densely populated areas are also a rural health concern. Addressing this issue effectively requires a joint institutional response from different government bodies, not just the traffic authorities but also those responsible for services provision.

Availability of data and materials
Data will not be shared (*Dirección General de Tráfico* data).

Declarations

Competing interests
The authors declare that they have no competing interests.

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