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How do road infrastructure investments affect Powered Two-Wheelers crash risk?

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ABSTRACT

The drivers of Powered Two-Wheelers (PTWs) pertain to the collective of so-called vulnerable road users. Crashes have scarcely decreased for these roadway users in recent years, whereas among other users, e.g. cars users, they have declined considerably. Meanwhile, the use of PTWs has risen sharply worldwide. This situation adds a further concern to transportation policies and makes evident the need to explore factors involved in PTW crashes. Yet there is a lack of studies specifically about road safety for PTWs. The present study therefore aspires to advance in the knowledge of the factors affecting PTW crashes on interurban roadways, by means of analyzing the effects of some variables not considered previously in this type of studies —mainly economic resources invested in roads—while also accounting specifically for the exposure to risk of PTWs (veh-km), along with relevant variables related to road traffic, the roadway infrastructure, and socioeconomic, meteorological and legislative factors. To this end, and bearing in mind the latest advancements of incorporating unobserved heterogeneity in count data models, different configurations of *random parameters negative binomial models* for data panels are presented. The realm of study is the network of national roads in Spain, distributed over 43 provinces, and the time period between 2007 and 2015. The results show significant associations for 11 of the variables considered: annual and accumulated investment in construction, expense on maintenance, proportion of motorways, light and heavy vehicle traffic, per capita GDP, age, unemployment rate, price of gasoline, and modification of the demerit point system (DPS). With respect to transport policy implications, the findings provided in this study may serve to monitor the effects of economic resources allocated to road construction and maintenance —along with other measures, such as gasoline prices and DPS—on PTWs safety.

1. Introduction

The number of motorcycle drivers killed worldwide was over 225,000 in the year 2017, a reduction of just 0.6% with regard to the figure from 2007. This decline in fatalities is much smaller than the one corresponding to all other motor vehicles (2.5%) (GBD 2017 Causes of Death Collaborators, 2018). The global objective of reducing mortality involving Powered Two-Wheelers (PTWs) proposed by the United Nations for 2020 was not attained (Yasin et al., 2022). In the meantime, the popularity of PTWs as a reasonably priced mode of transportation has grown worldwide. The greatest increase in the fleet of PTWs has taken place in China —from 20 million in 1995 to 100 million in 2006. At the international level, the ten countries with highest proportions of PTWs (between 100 and 250 per 1000 inhabitants) are a blend having very diverse income levels: Malaysia, Greece, Thailand, Cambodia, Italy, Japan, Mauritius, Switzerland, Uruguay and Latvia (Haworth, 2012).

Thus, increased mobility by means of the transport mode showing the highest accident rate (Elvik, 2010; Kweon and Kockelman, 2003) stands as an additional challenge for current road safety policies and strategies. For example, the Vision Zero target adopted by the EU member countries sets the long-term goal for 2050 that nobody should die or suffer serious injury as the consequence of a traffic accident (Council of the European Union, 2017). In Spain, like in other European countries, the number of PTWs has increased by 9.4% in the period 2013–2019, and these users represent 25% of the total fatalities in 2019 (Fundación MAPFRE, 2021). The situation of these particularly vulnerable users has led to the development of specific plans to heighten the safety of PTWs (DGT, 2019; 2007), in view of Vision Zero and the strategic framework known as Safe System. This focus holds that *all elements of the system must be strengthened to multiply the effect and ensure*

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that even if one element fails, the other elements will provide sufficient protection (ITF, 2016). Hence, Safe System and Vision Zero both underline the importance of road and infrastructure design, together with various forms of enforcement and vehicle technology as means of improving road safety (Kristianssen et al., 2018).

Furthermore, according to the European Parliament: DG for Internal Policies (2014), PTW riders *are more susceptible [than other users] to difficulties and hazards created by the design, construction, maintenance and surface condition of roads*.

In fact, from the perspective of PTW riders, the roadway itself is a safety concern (Delhaye and Marot, 2015), and a number of in-depth PTW crash investigations report evidence of how roadway conditions have a great influence on the accidents involving PTWs (Abdul Manan et al., 2013; ACEM, 2009; Allen et al., 2017; Brown et al., 2021; Haque et al., 2012; Harnen et al., 2003; Manan et al., 2018; Wu et al., 2018).

One indirect way to approach such conditioning factors in the roadway context is through the economic resources invested in them (specifically, investment in construction and maintenance expenditure). Previous studies relate certain variables of economic resources invested in roadways with road safety, but for all types of vehicles (Albalate et al.,

Table 1
Summary of PTW studies that consider measures of exposure to risk specifically for PTW traffic.

Article	Measure of exposure (PTWs)	Analysis methodology	Risk ratio compared according to	Dependent variable	Other control variables	Period	Group or Sample	Source of exposure data or traffic data
Mannering and Grodsky (1995)	Miles ridden in past 12 months	Multinomial discrete choice modeling	Age, gender, experience, driving behavior	Feeling of likelihood of being involved in accident	State of residence	1993	1373	Survey
Harnen et al. (2003)	Year	Fixed parameters Poisson/ Negative binomial models	–	Crashes per year	Motorcycles ADT, non-motorcycles ADT, pedestrian flow, speed, lane width, number of lanes, intersecting legs, shoulder width, land use category	1997–2000	53 urban road intersections of Selangor, Malaysia	Highway Planning Unit, Ministry of Works
Harrison and Christie (2005)	Veh-km	Risk ratio comparison	Gender, age, residence, engine size, type of PTW	-	–	2002–2003	794 PTW riders from South Wales, Australia	Odometer
Beck et al. (2007)	Person-trips	Risk ratio comparison	Severity, gender, age, road user	-	–	1999–2003	United States	US National Household Travel Survey
Stipdonk and Berends (2008)	Veh-km	Risk ratio comparison	Road user	-	–	1950–2000	Netherlands	Statistics Netherlands and Ministry of Transport
Licaj et al. (2011)	Person-km, thousand young inhabitants, thousand users of each mode	Risk ratio comparison	Gender, age, road user, location	-	–	2005–2006	Rhône county (France)	Lyon Household Travel Survey
Haque et al. (2012)	Not-at-fault cases (quasi induced-exposure)	Risk ratio comparison with log-linear models	Location	Multi-vehicle crashes	Wet road surface, time of day, lane position, speed limit, intersection type, traffic configuration	2004–2008 (total sum of crashes)	Singapore	Singapore Traffic Police Department
Keall and Newstead (2012)	Veh-km	Risk ratio comparison	Gender, age, location	-	–	2005–2006	New Zealand	NZ Transport Agency
Abdul Manan et al. (2013)	Length per section	Fixed parameters negative binomial models	–	Fatalities per kilometer	ADT of motorcycles, ADT, No. of access, no. of curves, lane configuration, median, paved shoulder	2007–2009	124 road sections from three states of Malaysia	Highway Planning Unit
Blaizot et al. (2013)	Person-km, person-trips, person-hours	Risk ratio comparison	Gender, age, road user, location	-	–	1996–1997 2005–2006	Rhône county (France)	Regional Household Travel Survey
Rolison et al. (2013)	Person-trips	Fixed parameters negative binomial models	–	Fatalities per trip, nonfatal casualties per trip	Age, engine capacity	2002–2009	Britain (United Kingdom)	Department of Transport
Bouaoun et al. (2015)	Person-km, person-trips, person-hours	Risk ratio comparison	Gender, age, road user	-	–	2007–2008	France	National Household Travel Survey
De Rome et al. (2016)	Veh-km, hours-ridden, years riding, frequency to different environments	Risk ratio comparison	Age	-	Traffic violations, demerit points incurred, alcohol related offences, speed related offences	2012 (4 weeks)	506 PTW riders from New South Wales, Australia	Survey
Wu et al. (2018)	Not-at-fault cases (quasi induced-exposure)	Risk ratio comparison with logistic models	–	Loss-of-control crashes	Road alignment, road adhesion, alcohol, type of PTW, weekend vs. weekday, speed	2011	France	Safety project VOIESUR

2013; Navarro-Moreno et al., 2022a,b; Fridstrøm and Ingebrigtsen, 1991; Houston et al., 1995; Nguyen-Hoang and Yeung, 2014; Sánchez González et al., 2018, 2020; Sun et al., 2019). However, though the conditioning factors of the road affect PTW users relatively more than the users of any other vehicle type (Li et al., 2009; Van Elslande and Elvik, 2012), no studies to date analyze the effects of economic resources invested in highways on the road safety of PTWs. The absence of specific studies about PTWs may be due to a scarcity of exposure data concerning this type of vehicle, meaning a more limited research corpus about diverse risk factors (Yannis et al., 2010). Therefore, and since there are many factors that may influence the road safety of PTW users (related to the road, traffic, vehicle, drivers, traffic regulations, environment and weather), a selection of papers that take into account at least the road conditions and risk exposure of PTW users are described below.

Table 1 sums up previous studies that do include some risk exposure measure, but do not consider the influence of economic resources invested in roadways. As can be seen in the column of *analysis methodology*, most of these are *risk ratio comparison studies* that attempt to draw comparisons of the figures for accidents among different groups of roadway users.

Diverse data sources may be used to estimate exposure to risk involving PTWs: odometer measurements (Harrison and Christie, 2005), estimation based on national household travel surveys (Beck et al., 2007; Blaizot et al., 2013; Bouaoun et al., 2015; Licaj et al., 2011; Stipdonk and Berends, 2008), surveys of PTW riders (de Rome et al., 2016; Harrison and Christie, 2005; Mannering and Grodsky, 1995), quasi-induced exposure technique (Haque et al., 2012; Wu et al., 2018), publications put out by transportation departments (Stipdonk and Berends, 2008), or data extracted from PTW Technical Inspections (Keall and Newstead, 2012). The rates of risk in these studies vary considerably, depending on the level of exposure and the crash indicator selected. Nonetheless, in all the consulted studies, the risk rate for motorcycles is much higher than for cars (and other vehicles). Thus, the figures range from a crash risk that is 3.3 times higher (Keall and Newstead, 2012) up to a mortality rate that is 32 times higher (Bouaoun et al., 2015).

Within this corpus of comparative risk studies, just two take into account some roadway conditioning factor (i.e. road surface, signals at intersections, or road alignment) as explicative factors —Haque et al. (2012) and Wu et al. (2018). Still, these studies are not based on exposure data specifically regarding PTWs; rather, they calculate odds ratios by means of the quasi induced-exposure technique (Stamatiadis and Deacon, 1997) to establish a relative risk in their categorical analyses. Haque et al. (2012) arrived at an increased crash risk that was 11.9 times higher for intersections without signals as opposed to those with, and authors Wu et al. (2018) identified a risk of losing control of a motorcycle 20 times higher when deteriorated road adhesion was encountered unexpectedly.

Of all the studies reviewed containing variables relative to motorcycle traffic, just three entailed statistical models that considered annual variations in crashes and traffic: Abdul Manan et al. (2013); Harnen et al. (2003) and Rolison et al. (2013). These studies share a statistical focus as well as the formulation of fixed parameters negative binomial models to relate the traffic crash figures with possible explaining factors. Harnen et al. (2003) moreover apply a Poisson model. Despite the fact that all include some traffic variable, measurement of the exposure to risk varies in terms of the realm of study. Harnen et al. (2003) use time as a variable of exposure to risk in that their study involves a concrete location, namely, urban intersections in Selengor (Malaysia)— whereas the volume of traffic (both motorcycle and non-motorcycle flow) is incorporated as an independent variable. The results show a direct relationship for the variables *traffic flow* and *speed*, while those relative to the roadway features (lane width, shoulder width and number of lanes) reflected a reducing effect on crashes. Similarly, to analyze the crashes occurring on a selection of road segments in Malaysia, Abdul Manan et al. (2013) used the length of the road segment as a measurement of the exposure to risk, whereas the volume of PTW traffic and other factors tied to roadway conditions were considered as explicative variables. The results of this study showed a significant influence of a positive sign only for the variables average daily number (ADT) of motorcycles and the number of accesses per kilometer. In turn, Rolison et al. (2013) adopted the amount of person-trips as the measure of exposure to evaluate the figures for crashes involving motor vehicle drivers and motorbikers. These authors found a risk of mortality for each trip that was 76 times higher among the motocycle riders, although the mortality rate decreased with age.

Bearing in mind that the UN goal of reducing motorcycle mortalities has not been met, the growing use of motorcycles all over the world, and the adoption of safety policies such as Vision Zero by EU countries for 2050, it is clear that there is a need to continue gathering sound knowledge about motorcycle crashes. Moreover, it must be taken into consideration that the European Parliament: DG for Internal Policies (2014) reports that PTW riders run a greater risk of crashing due to roadway conditions, and that the EU (European Commission, 2020) affirms that new investments and proper maintenance of existing infrastructure throughout its life cycle are key recommendations for transportation policies and traffic safety strategies during the present decade. Accordingly, expenditure on highways can be used as a gauge of their general characteristics, and serves to study the influence of such investment upon the occurrence of crashes involving PTWs. This looms as a research topic of great necessity from a public health standpoint, as well as to justify spending public funds. Yet despite the potential practical implications for policies behind investment in infrastructure and road safety, there are no studies focusing on the role of PTWs in this relationship.

As seen before, the bibliographic references consulted did not include studies relating motorcycle traffic and road safety in conjunction with the influence of economic resources spent on highways. Therefore, the present study considers variables that may influence, at a macro level, the occurrence of PTW crashes, through the novel approach of considering economic resources invested in highways. Moreover, to explain this relationship more robustly and provide new evidence of the exposure specifically of PTWs, a risk factor is considered, along with other variables related to traffic, roadway network characteristics, and socioeconomic, meteorological, and legislative elements.

From a methodological point of view, random parameters negative binomial models are used. These kinds of models, in addition to giving a better statistical fit than other methods, have not been previously used in similar studies considering some measure of exposure to risk for PTW traffic. The realm of this study is the interurban network of national roads in Spain.

The results of this study may give rise to significant practical and political actions with implications for public health and public expenditure. The novelty of its contribution lies in the fact that it takes into account key variables not taken into account previously in PTWs road safety studies—investment in construction, expense in maintenance, traffic disaggregated by type of vehicle— along with the risk exposure of PTW users, and a longer period of study.

2. Methodology

2.1. Description of the models

The Poisson and negative binomial models are commonly used in the literature on road safety to analyze count data (Anastasopoulos and Mannering, 2009). In fact, the only three references shown in Table 1 that formulate a model of crash frequency over several years rely on fixed parameters negative binomial models (Abdul Manan et al., 2013; Harnen et al., 2003; Rolison et al., 2013).

Nonetheless, many recent studies have made progress in the area of incorporating unobserved heterogeneity in road safety models (Lord and Mannering, 2010; Mannering et al., 2016). Random-parameters negative binomial (RPNB) models have shown a better goodness-of-fit and predictive precision than fixed-parameter negative binomial (FPNB) models in analyses involving all vehicle types (Anastasopoulos and Mannering, 2009; Caliendo et al., 2019; Chen and Tarko, 2014; Coruh et al., 2015; Hou et al., 2018, 2021; Saeed et al., 2019). They have likewise been used to analyze PTW safety (Xin et al., 2017b), but no study reports on the goodness of fit or predictive precision for different specifications of the RPNB models. The approach applied here, to study PTW crashes with panel data, first adopts a FPNB model to check for the statistical fit of the RPNB models formulated a posteriori. The application of the latter models is also novel. As seen in Table 1, no previous study considers the exposure to risk of PTW users in conjunction with this type of models.

- Fixed parameters negative binomial model (FPNB)

Binomial negative distribution relaxes the assumption of equal measure and variance of the Poisson distribution. Thus, the expected number of crashes for observation *i*, λ_i, and the variance are specified as:

$$E(y_i) = \lambda_i \tag{1}$$

$$Var(y_i) = E(y_i)[1 + \alpha E(y_i)] \tag{2}$$

where α is called “overdispersion parameter” and represents the proportional relation between the variance and the mean. It should be pointed out that when α is equal to zero, the negative binomial model is reduced to a Poisson model. This definition above is the most usual for the negative binomial model, also called the NB2 model, with 2 indicating the degree of the exponential term, and wherein the probability of a crash for observation *i* is given by (Hilbe, 2011):

$$P(y_i) = \frac{\Gamma(y_i + 1/\alpha)}{\Gamma(1/\alpha)\Gamma(y_i + 1)} \left(\frac{1/\alpha}{1/\alpha + \lambda_i}\right)^{1/\alpha} \left(\frac{\lambda_i}{1/\alpha + \lambda_i}\right)^{y_i} \tag{3}$$

The NB1 model, or linear negative binomial model, was also verified. However, application of the Vuong test following Greene (2008) favors the choice of NB2. The FPNB model adopted for this study was therefore NB2. Furthermore, a time-series cross-sectional panel was used for i provinces and t years after Coruh et al. (2015), but adding a variable of exposure that accounts for the amount of vehicles-kilometer (PTWs) per province and year. In this way, regional and temporal variations of accidents can be appraised (Papadimitriou et al., 2013). The measure of exposure to risk is incorporated as an offset, as done previously in fixed-parameter models for PTWs (Abdul Manan et al., 2013; Flask et al., 2014; Harnen et al., 2003; Rolison et al., 2013) or other vehicle types (Albalate and Bel-Piñana, 2019; Blaizot et al., 2013), but not in random-parameter models. Thus, the expected number of PTW crashes in the fixed parameters negative binomial (FPNB) model is

$$\lambda_i = \exp\left(\beta X_i + \ln(Z_i) + \varepsilon_i\right) \tag{4}$$

where $X_i = X_{pt}$ are a series of independent variables for province p and year *t*, $Z_i = Z_{pt}$ are the values of exposure specifically for PTW, β is the vector of coefficients to be estimated, ε_i is the term of stochastic error to account for the heterogeneity in λ_i, and $\exp(\varepsilon_i)$ is apparently Gamma distributed with mean 1 and variance α.

- Random parameters negative binomial models

RPNB models are an extension of the FPNB that allow for the incorporation of unobserved heterogeneity in a number of ways. The general model, in which some parameters are random and others are not, has the following structure (Greene, 2016):

$$\beta_i = \left[\beta_1^t, \beta_{2i}^t\right]^t \tag{5}$$

$$x_i = \left[x_{1i}^t, x_{2i}^t\right]^t \tag{6}$$

where β_1 are the coefficients of the non-random K_1 parameters, which multiply the variables x_{1i}, whereas the coefficients of the random K_2 parameter, multiplying the variables x_{2i}, are defined as

$$\beta_{2i} = \beta_2 + \Gamma v_i \tag{7}$$

Here β_2 are the fixed means of the distributions for the K_2 random parameters, v_i are the unobservable $K_2 \times 1$ latent random terms in the *i*th observation in β_{2i} following a certain distribution, and Γ is either a lower triangular or a diagonal matrix that produces the covariance matrix of the random parameters, $\Omega = \Gamma\Gamma^t$. Recent studies have shown a better statistical fit of their models by incorporating heterogeneity in means and variances (Waseem et al., 2019; Hou et al., 2021). Therefore, this study will test such a possibility. As for the term v_i, the normal distribution appears to be the one producing a better statistical fit (Anastasopoulos and Mannering, 2009; Chen and Tarko, 2014; Hou et al., 2018), although it cannot be discarded that some of the random parameters follow another distribution; so other distributions (i.e., uniform, triangular or lognormal) will be checked during the estimation of the models. Finally, the expected number of PTW crashes and the log likelihood function can be expressed as:

$$\lambda | v_i = \exp\left(\beta_i^t X_i + \ln(Z_i) + \varepsilon_i\right) \tag{8}$$

$$LL = \sum\nolimits_i^n log \int_{v_i} g(v_i) P(y_i | x_i, v_i) dv_i \tag{9}$$

where $g(v_i)$ is the probability density function of the v_i. Notwithstanding, the maximum likelihood estimation of this model presents substantial computational complexity. For this reason, Greene (2016) developed a simulated maximum likelihood estimation procedure based on random draws, which is the estimation technique used here. Because Halton draws are far more effective than random draws for simulation (Bhat, 2003; Train, 2009), different numbers of Halton draws were used, and it was determined that with 600, stable and reliable parameter estimates were obtained, in line with Hou et al. (2021).

Table 2 indicates the models described above and the specification of the parameters. The software used to estimate the models was LIMDEP version 11.

Given the nature of the data, it is assumed that province-specific unobserved variations exist. Hence, 43 province-specific panels are created in model FPNB. However, in this fixed parameters model where the effects of the variables are restricted to be the same across all observations, unobserved heterogeneity is ignored, which in turn could lead to erroneous inferences and predictions from the estimated parameters (Mannering et al., 2016). To mitigate such adverse impacts, the intercept is allowed to vary across observations according to a certain distribution (i.e., normal) in the RPNB-1 model, while the RPNB-2 also allows for variation of other parameters. In the case of the RPNB-2, all off-diagonal elements of the covariance matrix, Ω, are pre-defined as zero. On the other hand, for the model RPNB-3, an unrestricted form of the Ω matrix is defined to account for correlations between the random parameters. Thus, the unobserved heterogeneity interactions are captured. Given the derivation of the variance-covariance matrix Ω, it is

Table 2
Models and specific random-parameters specification used.

No.	Model name	Acronym	Random-Parameters specification
1	Fixed parameters negative binomial	FPNB	$K_2 = 0$
2	Random intercept negative binomial	RPNB-1	$K_2 = 1$ (*intercept*) ; Γ: {1}
3	Uncorrelated random parameters negative binomial	RPNB-2	$K_2 = 4$; Γ: diagonal matrix
4	Correlated random parameters negative binomial	RPNB-3	$K_2 = 4$; Γ: lower triangular matrix

inferred that the computation of the standard deviations of the correlated grouped random parameters is based on the diagonal and off-diagonal elements of the Γ matrix (Fountas et al., 2018a; Saeed et al., 2019). The standard deviation of each correlated random parameter is estimated as:

$$\sigma_y = \sqrt{\sigma_{y,y}^2 + \sigma_{y,y-1}^2 + \cdots + \sigma_{y,1}^2} \tag{10}$$

where σ_y is the standard deviation of the random parameter, y; $\sigma_{y,y}$ is the corresponding diagonal element of the Γ matrix; and $\sigma^2_{y,y-1}+ \cdots + \sigma^2_{y,1}$ relate to the off-diagonal elements of the lower triangular matrix corresponding to a particular random parameter, y. The standard error and z-statistic for each correlated grouped random parameter are estimated on the basis of the software-generated crash-specific coefficients of the standard deviations of the random parameters, following Fountas et al. (2018a, 2018b):

$$SE_{\sigma_y} = \frac{S_{\sigma_{yi}}}{\sqrt{N}} \tag{11}$$

$$z_{\sigma_y} = \frac{\sigma_y}{SE_{\sigma_y}} \tag{12}$$

Here SE_{σ_y} is the standard error of the standard deviations; $S_{\sigma_{yi}}$ corresponds to the standard deviation of the crash-specific σ_{yi}; N denotes the number of observations; and z_{σ_y} is the z-statistic corresponding to the standard deviation (σ_y) of the random parameter y.

- Model evaluation and comparison

A number of goodness-of-fit statistics were employed to evaluate the behavior of the models and establish comparisons. As measurements of fit, Akaike's Information Criterion (AIC), the Bayesian Information Criterion (BIC) and the adjusted McFadden ρ^2 were calculated (Akaike, 1974; Long, 1997; Schwarz, 1978; Washington et al., 2020):

$$AIC = -2LL(\beta) + 2K \tag{13}$$

$$BIC = -2LL(\beta) + K(\ln(n)) \tag{14}$$

$$Adjusted\ McFadden\ \rho^2 = 1 - \frac{LL(\beta) - K}{LL(0)} \tag{15}$$

where $LL(\beta)$ is the log-likelihood at convergence, K is the number of parameters, and $LL(0)$ is the log-likelihood with only the constant term. Meanwhile, to evaluate *two competing models*, the likelihood ratio test was used:

$$\chi^2 = -2[LL(\beta_a) - LL(\beta_b)] \tag{16}$$

Here $LL(\beta_a)$ is the log-likelihood of model *a,* $L(\beta_b)$ is the log-likelihood of model *b,* and χ^2 is distributed with degrees of freedom equal to the difference in the number of parameters estimated in each model. Finally, serving as measures of prediction accuracy are the mean absolute deviation (MAD) and the root mean squared error (RMSE):

$$MAD = \frac{\sum_{i=1}^{n} \left| N_{obs,i} - N_{pred,i} \right|}{n} \tag{17}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(N_{obs,i} - N_{pred,i} \right)^2}{n}} \tag{18}$$

where n is the total number of observations used for prediction, $N_{obs,i}$ is the observed number of PTW crashes, and $N_{pred,i}$ represents the predicted ones.

2.2. Selection of variables and description of data

The variables of this study were selected in view of similar studies in the bibliography consulted, to include new ones that the authors hold to be relevant and provide further insights into road safety, but also depending on the availability of data to be implemented in the models. Below their inclusion is briefly justified.

The dependent variable is the number of PTW crashes that occurred on Spain's major road network in every province and year. To reflect spatial and temporal variations in crash trends, we included the veh-km covered by PTWs as an offset variable, so as to scale the number of accidents in each province together with the exposure to risk. The exposure measure chosen (veh-km) is the one that best captures traffic variations in the analysis of crashes (Papadimitriou et al., 2013) and allows for comparisons of risk among the different regions of a given country (Hakkert and Braimaister, 2002).

As main independent variables (target variables), three measurements of economic resources allotted to highways were incorporated: investment in construction accumulated over the past 10 years, annual investment in construction, and current expenditure on road maintenance. The reason for including cumulative investment in construction is to derive the marginal effects produced by new investment (Nguyen-Hoang and Yeung, 2014). These investment variables were homogenized by dividing them among the kilometers of each province's roadways, to make them comparable.

Then, a series of independent variables were taken, related to traffic, the composition of the national network, and socioeconomic, meteorological and legislative factors proven to have an influence on crash occurrence according to the road safety literature.

When joining a mixed flux of traffic, the riders of PTWs can come up against certain potentially difficult aspects of roadway use and users. Generally, the drivers of other vehicles, not very accustomed to the presence of motorcycles (in higher-income countries the proportion of PTWs per veh-km is much less than that of other vehicles), may fail to detect them, creating conflicts and crashes (Wulf et al., 1989). Indeed, this type of observational error is commonly called "looked but failed to see" and is a contributing factor in over a third of PTW crashes (Brown et al., 2021; Morris et al., 2018). It is important, therefore, to include the volumes of traffic distinguishing between light and heavy vehicles.

The total length of the network analyzed was, in 2015, 26,394 km; of these, 11,942 correspond to high capacity motorways, and 14,428 to conventional roads. Given the difference in the risk of having an accident depending on the road type (Abdul Manan et al., 2013; Eustace et al., 2011; Shaheed et al., 2013; Shankar and Mannering, 1996; Walker et al., 2011), the proportion of high capacity motorways was considered as a measure of the composition of the road network. Along general lines, the mortality of motorcycle drivers is greater in conjunction with a higher roadway capacity and speed (Li et al., 2009), although this finding may be altered by considering exposure to risk.

The relationship between economic fluctuation and road safety has been profusely studied, and an overall reducing trend for crash rates has been tied to adverse economic cycles (Elvik, 2015; Wegman et al., 2017; Wijnen and Stipdonk, 2016). This association has likewise been identified in the case of PTWs (French and Gumus, 2014; Pulido et al., 2021; Wilson et al., 2009), reflecting changes in mobility deriving from the economic cycle. Aside from this, socioeconomic variables may serve to approach diverse underlying mechanisms that can affect road safety, such as the composition of traffic and the vehicle stock (Wijnen and Stipdonk, 2016). Because of this, included as variables are: unemployment rate, the price of gasoline, and per capita GDP. Outstanding among the risk factors previously related to driver behavior is age (Dubois et al., 2020; Geedipally et al., 2011; Hefny et al., 2012; Keall and Newstead, 2012; Rolison et al., 2013; Theofilatos and Yannis, 2014a; Xin et al., 2017a; Yannis et al., 2005), for which reason it was also included.

Meteorological factors are usually considered in PTW studies owing to their impact on the state of the roadway surface, most often whether dry or wet (Alnawmasi and Mannering, 2019; de Lapparent, 2006; Eustace et al., 2011; Jung et al., 2013; Quddus et al., 2002; Schneider and Savolainen, 2011; Shaheed and Gkritza, 2014; Shankar and Mannering, 1996; Wang et al., 2016; Waseem et al., 2019), or else as an indirect measure of exposure such as motorcycle activity or riding season (Branas and Knudson, 2001; French and Gumus, 2014; Houston and Richardson, 2008; McCartt et al., 2011; Morris, 2006; Shaheed et al., 2013; Wilson et al., 2009). Precipitation is the factor most commonly used, and was included here as an independent variable.

Finally, certain legislative aspects were considered through three dummy type variables making reference to the following legal changes affecting PTW traffic: 1) reform of the Penal Code in 2007 (Organic Law 15/2007), 2) modification of the Demerit Point System and the sanction procedure in 2009 (Law 18/2009 and Real Decree 818/2009), and 3) transitory reduction in the generic speed limit on high capacity roads in 2011 (Real Decree 303/2011). The latter was intended to save energy, and lasted only two months.

To configure the database corresponding to all these variables, data from Spain's 43 provinces was gathered for the period 2007–2015, giving a balanced data panel with a total of 387 observations. Table 3 lists the definitions and data sources.

Displayed in Table 4 are the main descriptive statistics. The monetary variables were converted to 2015 constant prices using two indexes: cost of construction index for civil engineering of the *Ministry of Transport, Mobility and Urban Agenda* (for variables related to roadway investment) and the Index of Consumer Prices (for the per capita GDP and price of gasoline).

3. Results and discussion

3.1. Results of the models

Table 5 shows the four estimated models. Eleven of the 14 independent variables are seen to give significant results in all (except for maintenance expenditure and the price of gasoline in model NB2, and the proportion of motorways in model RPNB-3). The results also show consistency in the sign of the relationship under the different models analyzed.

The parameter of dispersion (α) of the negative binomial distribution likewise gives statistically significant results with all four models, confirming the overdispersion of crash data and justifying the use of this distribution instead of the Poisson one.

In terms of fit, the RPNB-1 yields better results than NB2 for all the selection criteria. Model RPNB-1 increases the ρ^2 by 2.46%, and gives lower values for AIC and BIC. It moreover improves the prediction accuracy by 18.18% for MAD and by 8.99% for RMSE, while the LR test shows a better fit for model RPNB-1. Deserving mention is the fact that RPNB-1 is the equivalent of the standard random-effects model where the effects are normally distributed (Anastasopoulos and Mannering, 2009; Hilbe, 2011). For this reason, the RPNB-1 was also compared with its random-effects version following a beta distribution —although the fit was no better in this case.

The model RPNB-2 considers three random parameters: *intercept*, price of gasoline, and per capita GDP. Results indicate that the standard deviation of the three random parameters is significantly different from zero. Thus, a part of the unobserved heterogeneity previously captured in the intercept of the RPNB-1 is now captured by the other two random coefficients. In addition to assuming a normal distribution for these coefficients, the lognormal and the uniform distributions were also tested. Notwithstanding, the RPNB-2 does not appear to improve the statistical fit of model RPNB-1. Both measures of MAD and RMSE show just a slight improvement. Meanwhile, the AIC and the BIC respectively rise from 2984.5 to 3051.8 to 2987.3 and 3062.5. Also noteworthy is that the LR test does not favor the choice of RPNB-2 over RPNB-1.

Table 3
Definition and sources of the variables selected to explain PTW crashes.

VARIABLE	DEFINITION	UNIT	SOURCE
CRASH	Crashes	Number	Dirección General de Tráfico (DGT) (2022)
EXPOSURE	Total length travelled by PTWs	Millions of Veh-Km	Ministerio de Transportes, Movilidad y Agenda Urbana (MITMA) (2021)
STOCK	Investment in construction accumulated per kilometer. Year in course plus 9 previous years, with a depreciation rate of 2%.	Thousands of €/Km (Constant 2015)	MITMA (2021b), MITMA (n.d.), Ministerio de Hacienda y Función Pública (2022), Ministerio de Fomento (n.d.), Sociedad Estatal de Infraestructuras del Transporte Terrestre (SEITTSA) (n.d.)
INVEST	Investment in construction per kilometer	Thousands of €/Km (Constant 2015)	
MAINTAIN	Expenditure on maintenance per kilometer	Thousands of €/Km (Constant 2015)	
LIGHT V	Total length travelled by light vehicles	Millions of Veh-Km	Transportes, Movilidad y Agenda Urbana (MITMA) (2021)
HEAVY V	Total length travelled by heavy vehicles	Millions of Veh-Km	
MOTORWAY	Proportion of high-capacity roads	%	MITMA (2021b)
GDP	Per capita GDP	Thousands of € (Constant 2015)	Instituto Nacional de Estadística (INE) (2019)
AGE	Median age	Years	INE (2019b)
UNEMPLOY	Unemployment rate	%	INE (2016)
GAS	Price of gasoline	Cents of €/litre (Constant 2015)	Ministerio para la Transición Ecológica y el Reto Demográfico (2020), INE (2021)
PRECIPIT	Annual precipitation	mm	Agencia Estatal de Meteorología (AEMET) (2022)
PENAL	Reform of Spain's Penal Code (LO 15/2007)	Dummy. 1 for the years 2008 and 2009, 0 for the rest	Boletín Oficial del Estado (BOE) (Government of Spain, 2007)
DPS	Modification of the sanction procedure (Law 18/2009) and modification of the traffic regulation (RD 818/2009).	Dummy. 1 for the years 2010–2013, 0 for the rest	BOE (Government of Spain, 2009a; 2009b)
SPEED	Reduction of the generic speed limit (temporary measure) (RD 303/2011).	Dummy. 1 for the year 2011, 0 for the rest	BOE (Government of Spain, 2011)

Model RPNB-3 furthermore permits a correlation to be drawn among the three random parameters defined in RPNB-2 under the normal distribution assumption. All the Cholesky matrix elements are found to be statistically significant, supporting evidence of their contribution to the randomness of the parameters. In this case, the goodness-of-fit measures give mixed results. For one, measurements like the ρ^2 and the AIC obtain the best results with this model. The ρ^2 increases to 0.4509, and the AIC of 2981.7 is the least of all the values obtained with the models analyzed. In addition, the BIC penalizes the greater structural complexity of this model, showing higher results than RPNB-1 and RPNB-2. Even so, the LR test appears to favor selection of the model RPNB-3. And in view of the prediction accuracy, the following improvements are seen over the

Table 4
Main descriptive statistics of the variables.

Variable	N	Mean	S.D.	Min.	Max.
Crash	387	36.91	**45.39**	**2.00**	**271.00**
Exposure	387	20.11	**26.59**	**1.92**	**187.80**
Stock	387	1484.00	**1213.91**	**196.64**	**7561.465**
Invest	387	117.08	**155.76**	**0.25**	**1254.34**
Maintain	387	42.09	**25.24**	**1.38**	**150.98**
Light V	387	2402.34	**2154.25**	**540.60**	**14017.54**
Heavy V	387	392.36	**283.87**	**105.05**	**1780.90**
Motorway	387	44.45	**17.14**	**12.78**	**92.29**
GDP	387	21.66	**4.20**	**14.67**	**35.48**
Age	387	41.94	**3.37**	**35.09**	**50.59**
Unemploy	387	19.50	**8.15**	**3.03**	**42.31**
Gas	387	127.88	**11.94**	**70.31**	**145.72**
Precipit	387	532.23	**294.83**	**126.60**	**2176.00**
Penal	387	0.22	**0.42**	**0**	**1**
DPS	387	0.44	**0.50**	**0**	**1**
Speed	387	0.11	**0.32**	**0**	**1**

RPNB-1: 12.15% in the MAD and 13.82% in RMSE.

The random-parameter models clearly provide for better fit and predictive capacity as opposed to the fixed-parameter version. More specifically, RPNB-3 incorporates six more parameters (than the FPNB) for estimation purposes, and obtains a better fit and predictive capacity. On the other hand, the RPNB-1 produces the best improvement in the goodness of fit of the model, incorporating only one extra parameter for estimation. The statistical performance of the models studied here for PTW crashes is found to be in line with previous data regarding *all-vehicles crashes* (Caliendo et al., 2019; Chen and Tarko, 2014; Hou et al., 2018), where RPNB-3 slightly outperformed the RPNB-1. At any rate, these results also underline the fact that model RPNB-1 would be a good alternative to RPNB-3 in those cases requiring a simpler model in terms of calculation and/or interpretation. Regarding the incorporation of heterogeneity in the means and variances in the RPNB-3 model, no statistically significant results were obtained.

Finally, to avoid misleading inferences caused by the presence of statistically insignificant variables in the model, the best specified model RPNB-3 (4) was re-estimated with statistically significant variables alone. The results of this final model are shown in Table 8. Given in Table 6 and Table 7 are the elements of the Cholesky matrix (used to calculate variance-covariance of the random parameters) of the models (4) and (5).

Additionally, all models proposed underwent a sensitivity analysis to determine the robustness of the results. Table 9 offers the findings for the main variables of interest: cumulative investment in construction, investment in the current year, and maintenance expenditure. Only the results corresponding to the model RPNB-3 (5) are given for the sake of clarity, and because no considerable variations were detected, with these or the remaining variables, in the other models.

3.2. *Discussion of the variables*

- Economic resources dedicated to motorways

The variables of economic resources for motorways —cumulative investment in construction, in the year underway, and expenditure in maintenance— proved to be significant in all the models. As for the two investment-related variables (investment in construction over the past ten years and annual investment), their coefficients are seen to be consistent for the four models studied here. Yet the relationship of these two variables with respect to anticipated crashes per one million veh-km is of the opposite sign. Accordingly, in the short term —reflected by annual investment— spending on construction shows a beneficial effect on the reduction of PTW crash statistics. In the long term, however —cumulative investment— this effect appears to turn around and cause a direct residual association with crash occurrence, though with a

Table 5
Estimation results for fixed- and random-parameter negative binomial panel count data models.

Variables	(1)	(2)	(3)	(4)
	NB2	RPNB-1	RPNB-2	RPNB-3
Stock *(in thousands of € per km)*	**.00011**** (2.15)	**.00013***** (3.11)	**.00013***** (3.00)	**.00018***** (4.89)
Invest *(in thousands of € per km)*	**−.00070***** (-3.18)	**−.00073***** (-3.02)	**−.00073***** (-3.05)	**−.00075***** (-3.62)
Maint *(in thousands of € per km)*	−.00115 (-0.49)	**−.00270*** (-1.87)	**−.00271*** (-1.90)	**−.00251*** (-1.89)
Light V *(in million veh-km)*	**.00009**** (1.98)	**.00008***** (2.88)	**.00008***** (2.84)	**.00009***** (3.54)
Heavy V *(in million veh-km)*	−.00043 (-1.56)	**−.00070***** (-4.37)	**−.00073***** (-4.44)	**−.00068***** (-4.27)
Motorway *(in %)*	**−.00790**** (-2.25)	**−.00450*** (-1.89)	**−.00425*** (-1.80)	−.00217 (-0.96)
GDP *(in thousands of €)*	**−.05585***** (-3.22)	**−.04458***** (-4.45)	**−.03906***** (-3.88)	**−.02370**** (-2.38)
St.dev. of parameter density function	—	—	.00816*** (7.47)	.09135*** (18.47)
Age *(in years)*	**−.03443**** (-2.22)	**−.04768***** (-5.28)	**−.04510***** (-5.03)	**−.06433***** (-7.43)
Unemploy *(in %)*	**−.03506***** (-5.44)	**−.04030***** (-7.39)	**−.03979***** (-7.29)	**−.03225***** (-5.84)
Gas *(in cents of € per litre)*	.00302 (0.74)	**.00650**** (2.16)	**.00656**** (2.19)	**.00721**** (5.28)
St.dev. of parameter density function	—	—	.00176***	.014112* (1.93)
Penal *(dummy)*	−.01468 (-0.22)	−.00347 (-0.04)	−.00179 (-0.02)	−.03415 (-0.46)
DPS *(dummy)*	**−.19700**** (-2.45)	**−.23741***** (-2.90)	**−.23740***** (-2.94)	**−.27972***** (-3.75)
Speed *(dummy)*	.02387 (0.34)	.01693 (0.13)	.01609 (0.13)	.00871 (0.07)
Precipit *(in mm)*	.00015	.00010 (1.05)	.00010 (1.06)	.57247D-04 (0.62)
Intercept	**3.94348***** (4.74)	**3.93641***** (6.59)	**3.69782***** (6.23)	**3.87940***** (6.72)
St.dev. of parameter density function	—	0.29143*** (11.57)	0.07931*** (3.44)	3.79332*** (18.67)
ln (Exposure)	1 (exposure)	1 (exposure)	1 (exposure)	1 (exposure)
Dispersion parameter for Negative Binomial distribution				
Alpha	.21697***	6.82904***	6.89976***	8.12130***
Other Statistical Information				
Observations	387	387	387	387
LL (0)	−2714.9	−2714.9	−2714.9	−2714.9
LL (β)	−1506.3	−1475.3	−1474.7	−1468.9
Adj. McFadden ρ^2	0.4393	0.4504	0.4498	0.4509
AIC	3044.7	2984.5	2987.3	2981.7
BIC	3108.0	3051.8	3062.5	3068.8
Prediction Accuracy				
MAD	15.29	12.51	12.44	10.99
RMSE	32.60	29.67	29.53	25.57
Likelihood Ratio test				
Estimated parameters	16	17	19	22
Vs model		NB2	RPNB-1	RPNB-2/ RPNB-1
Chi-Square		62.14***	1.20	11.62***/ 2.82**
Degrees of freedom		1	2	3/5
Preferred model		RPNB-1	RPNB-1	RPNB-3

***p < .01, **p < .05, *p < .1. Z-Statistics in parenthesis.

Table 6

Diagonal and off-diagonal elements of the Cholesky matrix of model (4).

	Intercept	*GDP*	*GAS*
Intercept	3.7933***[1.00]		
GDP	0.0895***[0.98]	0.0181***[1.00]	
GAS	−0.0135***[-0.96]	0.0040***[-0.88]	0.0009***[1.00]

***p < .01, correlation of random parameters in brackets.

Table 7

Diagonal and off-diagonal elements of the Cholesky matrix of model (5).

	Intercept	*GDP*	*GAS*
Intercept	3.9978***[1.00]		
GDP	0.0956***[0.98]	0.0180***[1.00]	
GAS	0.0139***[0.96]	−0.0037***[0.90]	0.0010***[1.00]

***p < .01, correlation of random parameters in brackets.

Table 8

Estimation results for selected RPNB-3 model, marginal effects and elasticities.

Variables	(5)	MARGINAL EFFECTS	ELASTICITY
	RPNB-3		
Investment in construction accumulated per kilometer—*Stock*— *(in thousands of € per km).*	0.00017*** (4.54)	0.00038	0.23632
Investment in construction per kilometer—*Inver*— *(in thousands of € per km).*	−0.00078*** (−3.90)	−0.00169	−0.09155
Expenditure on maintenance per kilometer—*Maint*— *(in thousands of € per km).*	−0.00282** (−2.53)	−0.00608	−0.11860
Total length travelled by light vehicles—*Light V*— *(in million veh-km).*	0.99851D-04*** (4.16)	0.00022	0.23988
Total length travelled by heavy vehicles—*Heavy V*— *(in million veh-km).*	−0.00072*** (−4.69)	−0.00155	−0.28233
Per capita GDP—*GDP*— *(in thousands of €).*	−0.01727* (−1.81)	−0.03726	−0.37420
Standard deviation of parameter density function	0.09727** (19.67)		
Median age—*Age*— *(in years).*	−0.06116*** (−7.38)	−0.13190	−2.56484
Unemployment rate—*Unemploy*— *(in %).*	−0.03360*** (−7.00)	−0.07247	−0.65540
Price of gasoline—*Gas*— *(in cents of € per litre).*	0.00789*** (5.65)	0.01701	1.00860
Standard deviation of parameter density function	0.01739** (2.38)		
Modifications of the sanction procedure and the traffic regulation—*DPS*— *(dummy).*	−0.25769*** (−4.27)		
Intercept	3.48528***		
Standard deviation of parameter density function	3.9978*** (19.67)		
ln (Total length travelled by PTWs, *in million veh-km*)	1 (*exposure*)		
Alpha	8.18084***		
Observations	387		
LL (0)	−2775.5		
LL (β)	−1469.3		
Adj. McFadden ρ^2	0.4641		
AIC	2974.6		
BIC	3045.8		
MAD	10.01		
RMSE	25.47		
Estimated parameters	18		
Vs model	RPNB-3 (4)		
Chi-Square	0.87		
Degrees of freedom	4		
Preferred model	RPNB-3 (5)		

***p < .01, **p < .05, *p < .1. Z-statistics in parenthesis.

magnitude some 3 to 4 times lesser than the short term effect. This change in sign of the influence of investment in construction might be attributed to an effect of risk compensation (Peltzman, 1975; Sánchez González et al., 2018). Certain previous studies have justified that PTW riders could adopt a riskier behavior in the face of situations more linked *in theory* to situations of relative road safety, for instance: when the prevailing conditions are perceived as excellent (Perez-Fuster et al., 2013), the roadway is dry (Shaheed et al., 2013), or other similarly favorable factors are perceived (Geedipally et al., 2011; Xin et al., 2017a). A future analysis could explore this aspect, and the change in sign, in the long term. Expenditure in roadway maintenance keeps a negative sign, which is significant for the three models of random parameters; model NB2 does not give a result significantly different from zero. These findings therefore evidence the beneficial effects of maintenance expenditure on PTW road safety.

So as to contextualize the above results, over the past decade there has been a serious decrease in road investment and road quality, not only in Spain but in most European countries (European Investment Bank, 2018). This has led to the existence of a growing road maintenance backlog (European Parliament: DG for Internal Policies, 2014) with inevitable consequences for road safety. Most road improvement projects point to a positive cost-benefit ratio when a reduction in the number of crashes is considered as a return (Claros et al., 2022), which should also be the case when economic resources are being allotted for roadway maintenance. In the case of Spain, the Spanish Road Association (AEC) estimates at 73,370 €/km the cumulative deficit by central and regional administrations for conservation (AEC, 2020). Authors Rojo et al. (2018) point out that savings in maintenance costs do not constitute a real economic benefit if one takes into account the traffic crashes associated with a poor state of the roadway. Therefore, the results of the present study statistically justify all these aspects. Both investment in construction and expenditure in maintenance have proven to be beneficial in terms of reducing PTW accidents. These results agree with other studies highlighting this effect of economic resources for all vehicles, whether through investment in construction (Nguyen-Hoang and Yeung, 2014; Sánchez González et al., 2020; Sun et al., 2019) or else expenditure on maintenance (Fridstrøm and Ingebrigtsen, 1991; Navarro-Moreno et al., 2022a; Nguyen-Hoang and Yeung, 2014; Sánchez González et al., 2018). Moreover, taking into account that part of the road investments are dedicated to improving the layout (e.g. eliminating curves) and intersections (eliminating level crossings), the result obtained for the investment in construction is in line with Montella et al. (2012), who noted that the majority of PTW crashes took place on non-straight sections (47.8%) and at intersections (51%); and with Theofilatos and Ziakopoulos (2018) and Manan et al. (2018), who found additional crash risk for PTW riders in curves. Finally, given that both part of the investment in construction and part of the maintenance expense are used to improve road surface quality and road markings too, the results obtained in this study regarding economic resources dedicated to roads are in line with Manan et al. (2018) as well, who found that the quality of these elements contributes to reducing the risk of accidents for PTW users.

- Light and heavy vehicle traffic

Regarding the traffic variables considered, the volume of light vehicle traffic shows a direct relation with increased PTW crashes. In the absence of specific studies on PTWs, this finding comes to support studies that consider traffic of all vehicle types as an independent variable (Abdul Manan et al., 2013; Gabauer and Li, 2015; Xin et al., 2017b). To explain this association, one might invoke infraction of the *motorcycle's right of way* as the main cause of accidents between cars and motorcycles (Pai, 2011); similarly, an increase in light vehicle traffic could lead to more multi-vehicle PTW crashes. Schneider et al. (2010)

Table 9
Sensitivity analysis.

CRASH	(i) T = 11	(ii) T = 9	(iii) d = 1%	(iv) d = 3%	(v) Random effects
Stock	.00017***	.00016***	.00016***	.00017***	.00014***
Invest	−.00076***	−.00076***	−.00076***	−.00077***	−.00071***
Maint	−.00292***	−.00293***	−.00281**	−.00285**	−.00308***

Note: Columns (i) and (ii) use different numbers of years (T) in calculating cumulative investment in construction. Columns (iii) and (iv) use different indexes of depreciation (d) in calculating cumulative investment. Column (v) incorporates random effects for province and year.
***p < .01, **p < .05, *p < .1.

likewise found an increase in single-vehicle motorcycle crashes when traffic was greater, which may be explained by a change in the behavior of PTW riders in the presence of passenger vehicles on high-volume roads. It would also be necessary to account for the capacity of drivers to distinguish an object from an environmental display, a concept known as *conspicuity*; it is reportedly low for automobile drivers when they try to detect a motorcycle (Hancock et al., 1990). Low motorcycle conspicuity has been contrasted in terms of the observer characteristics, or cognitive conspicuity (Rogé et al., 2012; Wulf et al., 1989), and of the physical features of the object observed, or sensory conspicuity (Gershon et al., 2012; Gershon and Shinar, 2013). All the above situations are applicable to the present study, and consequently one may expect an increase in the frequency of crashes involving PTWs when an increase in light vehicle traffic occurs.

The results indicate a relationship of a negative sign for heavy vehicle traffic. This result is in line with the data referring to vehicles involved in PTW crashes shown in Montella et al. (2012), according to which trucks were only involved in 6.5% of PTW crashes, and with the finding of Theofilatos and Ziakopoulos (2018), who found that an increased proportion of trucks led to slighter injuries. The obtained reduction in crash frequency might owe to a greater precaution on the part of PTW riders when facing an increase in heavy vehicle traffic. Still, there is a gap in knowledge about the effects of PTW maneuvers when passing heavy vehicles (Vlahogianni, 2014), and in the patterns of PTW maneuvers and interactions with heavy vehicles in mixed traffic fluxes (Das and Maurya, 2017). It is furthermore necessary to contextualize the realm of study, as the roadway network analyzed carries more than 60% of all Spain's heavy traffic, the percentage of heavy vehicles ranging from 13% to 16% during the period of study (Ministerio de Fomento, 2016). Thus, in areas with great volumes of traffic, the presence of a higher proportion of heavy vehicles has been linked to decreased mean velocity (Chen et al., 2020; Zhang et al., 2019), which may imply heightened safety in general, and of PTW users in particular. This finding regarding motorcycle-heavy truck interaction and its implications for road safety should be further explored in future research.

- Composition of the motorway network

The proportion of high capacity roads has a relationship with a negative sign in all the models, yet with RPNB-3 it is no longer significant. This result can be explained by bearing in mind that some design factors, such as physically divided carriageways, large curve radiuses, limited points of access, or a lesser number of roadside objects, could contribute to PTW safety on this type of road (Daniello and Gabler, 2011; Shankar and Mannering, 1996). In addition, on motorways there is a heightened cognitive conspicuity between PTWs and passenger cars, which allows for the mutual interpretation of movements and may prevent the "fail to see" crash. Such compatibility between PTWs and passenger cars does not occur on two-lane rural highways; as this makes it easier to interpret the other's maneuvers in motorways (Walker et al., 2011) an improvement in safety would ensue.

- Socioeconomic and demographic characteristics

Out of the socioeconomic and demographic variables considered, per capita GDP, average age, and unemployment rate showed significant associations with a negative sign in all the models. The level of mean income of a society and traffic crashes could be linked by one or more of these four mechanisms (Wijnen and Rietveld, 2015): the volume of traffic, composition of traffic, user behavior, and/or investment to heighten safety. Since both the volume of traffic and its composition have been considered within the models, the relationship of a negative sign between per capita income and accidents might be attributed to changes in the behavior of users, or improvements toward road safety. Thus, a higher income level would contribute to a decrease in the number of crashes in an array of manners: transfer of high-risk and low-cost motorcycles to low-risk and high-cost passenger cars (Poi et al., 2021), more awareness of risky behavior through better education (Law et al., 2013), or more resources available for safety programs such as police enforcement or media advertising (Guria, 1999). Encountering an inverse relation is therefore in line with the existence of a *motorcycle Kuznets curve* between economic development and PTW road safety (Nishitateno and Burke, 2014; Sirajudeen et al., 2022).

This type of curve, an inverted U, ties in the first place a higher income to an increase in crashes (in poorly developed countries); and after a certain point, the relationship is reversed: greater wealth is associated with a decrease in accidents. For this reason, Spain offers an interesting study context —it has reached the crossroads of low/high income with regard to the rest of the EU, and the fact that the GDP has grown could imply better road safety education and higher demand for road improvement (Law et al., 2013), eventually translating as fewer crashes.

Age also showed an inverse relation with respect to crashes, in line with the literature consulted, wherein this factor is underlined as one of particular relevance for the safety of PTW riders (Allen et al., 2017; Bjørnskau et al., 2012; Hefny et al., 2012; Theofilatos and Yannis, 2014a; Yannis et al., 2005). In turn, Elvik (2010) explored the theoretical framework of this association, attributing the greater risk of young men and women to a mixture of biological factors, overconfidence in one's capacities, and a rebellious spirit. Young people moreover tend to have a lower socioeconomic level, meaning a risk up to 2.5 higher than riders who come from higher socioeconomic spheres (Zambon and Hasselberg, 2006).

The unemployment rate also exerts an inverse influence on PTW crashes. It may be that higher unemployment means reduced volumes of traffic and variations in its composition. An inverse relationship between unemployment and road accidents is well reflected in the literature (Economou et al., 2008; Gerdtham and Ruhm, 2006; He, 2016; Neumayer, 2004; Ruhm, 2000; Safaei et al., 2021; Wagenaar, 1984; Wegman et al., 2017). Authors Wegman et al. (2017) furthermore identified as underlying reasons a strong reduction in high-risk drivers, particularly very young ones, and certain changes in driver behavior. In Spain, during the period of study, the aftereffects of the Great Recession provoked a sharp increase in the rate of unemployment among youth, much more so than for any other age group (Bell and Blanchflower, 2011). If we recall that young motorcycle riders have a greater probability of involvement in a crash (Theofilatos and Yannis, 2014a), any rise in unemployment would imply a decrease in PTW crashes. Finally, the increase in unemployment and the deterioration of economic conditions in general could bring about a change in drivers' behavior —being afraid of economic sanctions for traffic infractions, they might adopt a more cautious attitude towards driving (Pulido et al., 2021).

As for the price of gasoline, which gave a significant relationship with a positive sign under models RPNB-1, RPNB-2 and RPNB-3, one might assume that more expensive gasoline makes PTWs more attractive as an alternative to cars (Wilson et al., 2009; Zhu et al., 2015), especially in developed countries where the use of motorcycles was historically low (Zhang and Burke, 2021). What is more, rising fuel prices affect most of all the users with limited economic resources, who happen to be the ones generally showing riskier driving behavior (Hasselberg et al., 2005; Zambon and Hasselberg, 2006). All these explicative factors can be applied to the study area dealt with here, supporting the results reported. Studies that relate the rising price of gasoline to an increase in PTW crashes (Hyatt et al., 2009; Safaei et al., 2021) point out as a limitation the lack of specific consideration of PTWs' exposure. Because our study includes it, our findings contribute new and robust evidence to the corpus of literature by accounting for exposure to risk —a fundamental variable for road safety studies— with regard to the direct relationship between gasoline price and an increase in PTW crashes. According to Hou et al. (2021), a correlation with a positive sign between the random parameters of per capita GDP and the price of gasoline (Table 7) signals that unobserved heterogeneity interactions bear a homogeneous impact on the frequency of PTW crashes. One example would be that a joint increase in gas prices and per capita GDP would increase PTW users of a lower socioeconomic level (associated with more dangerous conduct). But also, the income growth would make possible access to higher displacement motorcycles, thus further raising the odds of unsafe motorcyclist actions in certain age groups (Dubois et al., 2020).

- Legislative variables

When focusing on Spain's road safety regulations, only the variable *DPS* showed significant results, a beneficial effect on PTW crash reduction. This variable represents two legislative modifications that came into effect toward the end of 2009: a change in the sanction procedure (Government of Spain, 2009b) and a modification of the rules for circulation (Government of Spain, 2009a). These two updates affected the Demerit Point System adopted in 2006 and restricted access to certain PTW licences. In light of the results obtained here and elsewhere, implementation of a DPS system effectively improves road safety (Abay, 2018; De Paola et al., 2013; Lee et al., 2018; Zambon et al., 2007), though its efficacy may wear off over time (Castillo-Manzano and Castro-Nuño, 2012; Izquierdo et al., 2011). Therefore, periodic updating of this norm is deemed necessary to maintain a beneficial impact on road safety. The variable *Penal Code* —representing stiffer sanctions for traffic offences (Government of Spain, 2007)— also shows a negative sign, but it is not significant. Lastly, the variable *Speed* —referring to the briefly modified speed limit on Spanish motorways during 2011 (Government of Spain, 2011)— was not significant in any model. At this point, we may hypothesize that the influence of these two legislative norms is partly captured by the variable *DPS*, which also included stiffer sanctions.

- Meteorology

In the end, no significant results were harvested for mean annual precipitation under any of the models. In more general road safety studies, a positive sign between precipitation and increased crashes is frequently reported (Theofilatos and Yannis, 2014b). However, this association may change in sign depending on the level of temporal aggregation of the data (Eisenberg, 2004) or even the type of roadway (Bergel-Hayat et al., 2013).

4. Conclusions

This article presents a macro level study of how the economic resources spent on roadways may influence the occurrence of crashes involving Powered-Two-Wheelers (PTWs) on interurban roads. The realm of study is Spain's national highway network, distributed over 43 provinces, and it covers the time period from 2007 to 2015. A *fixed parameters negative binomial (FPNB) model* was formulated, along with three configurations of *random parameters negative binomial (RPNB) models*. The correlated RPNB was found to give the best general fit and a greater predictive capacity than the other models. Also noteworthy is the utility of the random-intercept negative binomial model, equivalent to the classic random-effects model, as an efficient alternative that is easier to interpret.

Overall, the results indicate a reducing effect on PTW crashes for annual investment in road construction, an effect apparently attenuated when cumulative investment over the past ten years is considered. The change in sign of this relationship over time may reflect an effect of risk compensation, documented in previous studies. Expense in roadway maintenance likewise demonstrated a positive contribution, toward a reduced number of crashes. Other variables included in the study that showed a reducing effect on the number of crashes are the proportion of high-capacity roadways, per capita GDP, age, unemployment rate, and the implementation of the demerit point system. Contrariwise, the price of gasoline is linked to an increase in crashes involving PTWs.

As main novelties and contributions of this research, the following points can be highlighted: i) For the first time, the effect of the economic resources dedicated to road on PTWs' crash risk is analyzed. For that purpose, two variables —not considered previously in the literature on PTW safety— related with highway investments (investment in construction and maintenance expenditure) are considered; ii) the use of a variable of exposure to risk specifically for PTWs and relative to the traffic volume; and iii) the application of diverse random parameter negative binomial models in a study of PTW safety with specific exposure data (previous studies having applied only the fixed parameter negative binomial model).

Diverse policy implications can be derived from the results presented here. First, it is shown that dedicating economic resources to roadway construction and maintenance has beneficial repercussions for traffic safety involving PTWs. Such investment would therefore contribute to an improved road infrastructure quality for a country, in addition to aiding the fulfillment of road safety and public health policy. According to the results obtained regarding investment in roadway construction, building high-capacity roads should be taken into account when aspiring to greater road safety for PTWs. In turn, given that an adverse economic cycle can mean an overall increase in PTWs, and that these vehicles in particular entail greater risk, it is wise to reinforce educational road safety campaigns, above all among certain sectors of the population, namely young drivers or those with lower income. Finally, modification of the demerit point system (DPS) has proven to have a beneficial effect in Spain, reducing PTW crashes. Hence, periodical updating of the demerit point system (in view of changing driver characteristics, types of roads and accidents, the number of registered motorcycles, etc.) is needed to guarantee the engagement of drivers with traffic regulations.

For future research, it would be useful to carry out similar studies, distinguishing between roadway types (motorway or conventional two-lane roads) in order to identify differences in the effects of economic resources invested according to road type. This would call for knowing the volume of PTWs circulating on each type of road, data not currently available. The network analyzed in the present study pertains to the central administration of Spain, which is the only source of traffic data specifically for PTWs. This network contains a greater proportion of motorways than conventional roads, and takes in over 50% of total vehicle traffic (MITMA, 2020). Given that 65%–84% of traffic deaths in Spain occur on two-way roads, and that most of these conventional networks depend on regional, provincial or local administrations (DGT, 2020), a thorough study of PTW road safety at these other levels would surely provide welcome, more precise evidence. Finally, a more exact breakdown of the economic resources destined to roadway construction and maintenance, according to the specific activities involved, might help identify which measures are most effective when striving to improve PTW road safety.

CRediT authorship contribution statement

José Navarro-Moreno: Conceptualization, Methodology, Software, Data curation, Formal analysis, Writing – original draft, Visualization. **Juan de Oña**: Conceptualization, Validation, Supervision, Formal analysis, Writing – review & editing. **Francisco Calvo-Poyo**: Conceptualization, Validation, Supervision, Formal analysis, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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