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Infrastructural and Human Factors Affecting Safety Outcomes of Cyclists

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Abstract: The increasing number of registered road crashes involving cyclists during the last decade and the high proportion of road crashes resulting in severe injuries and fatalities among cyclists constitutes a global issue for community health, urban development and sustainability. Nowadays, the incidence of many risk factors for road crashes of cyclists remains largely unexplained. Given the importance of this issue, the present study has been conducted with the aim of determining relationships between infrastructural, human factors and safety outcomes of cyclists. **Objectives:** This study aimed, first, to examine the relationship between key infrastructural and human factors present in cycling, bicycle-user characteristics and their self-reported experience with road crashes. And second, to determine whether a set of key infrastructural and human factors may predict their self-reported road crashes. **Methods:** For this cross-sectional study, a total of 1064 cyclists (38.8% women, 61.2% men; *M* = 32.8 years of age) from 20 different countries across Europe, South America and North America, participated in an online survey composed of four sections: demographic data and cycling-related factors, human factors, perceptions on infrastructural factors and road crashes suffered. **Results:** The results of this study showed significant associations between human factors, infrastructural conditions and self-reported road crashes. Also, a logistic regression model found that self-reported road crashes of cyclists could be predicted through variables such as age, riding intensity, risky behaviours and problematic user/infrastructure interactions. **Conclusions:** The results of this study suggest that self-reported road crashes of cyclists are influenced by features related to the user and their interaction with infrastructural characteristics of the road.

Keywords: cyclists; bicycle users; risky behaviours; human factors; infrastructure; self-reported road crashes; road safety

1. Introduction

Road crashes have been a substantial concern for public health agencies (government, public entities, healthcare system, etc.) and society for the last half century. However, despite the bicycle being older than every motorized vehicle as a transport mode, the problem of cyclists' injuries or fatalities as a result of road crashes has been accentuated as a public health problem during the last few years [1]. Consequently, the amount of evidence available for explaining, predicting and preventing road crashes involving cyclists is relatively scarce, especially in developing countries where bicycle usage has exponentially increased [2]. On the other hand, although high-income countries have a broader and longer tradition of using bicycles [3,4], the mechanisms by which human and infrastructural factors act on crash causation are not completely understood.

Considering that, especially in cities, the number of bicycle users, their average daily journeys and distances travelled have been constantly growing and the need for analysing the factors that affect cyclists' crash rates is increasingly relevant [5,6]. For instance, in the case of Spain, in the period 2008–2013, 25,439 cyclists were involved in crashes resulting in injuries or fatalities [7,8]. Furthermore, only in 2015, from the total of 59,148 road crashes involving injuries or fatalities, 3.85% (2277) of them involved cyclists, leaving as a result 48 dead cyclists—47 men and 1 woman [9]. As for the zones in which crashes occur, urban centres have a higher percentage of crashes (70.7%) and injury or fatality victims (67.4%), compared to country roads, which report 29.3% of crashes and 32.6% of victims. Moreover, 47.2% of severe injuries of cyclists occur on conventional urban roads [7].

Although the overall rates of road crashes (especially involving motorized vehicles) have been decreasing in the last 40 years, the number of cyclist injuries and fatalities as a result of road crashes has been systematically increasing [10]. The reasons for this increase are worth researching and should not be disregarded. In addition, the subsequent health and financial costs of road crashes involving cyclists are considerably elevated [11], especially considering two facts: first, compared to crashes suffered by motor vehicle-users, cyclists have a greater physical vulnerability, even when they were properly using passive-safety elements [12,13]; and second, in most countries cyclists do not need to have crash insurance [14] and often their medical care is subsidized by public healthcare systems [11].

Bicycle-using is widely promoted as a cheap, environmentally responsible and alternative transport mode to conventional motorized vehicles [15] and this has resulted—in many cases—in a disproportionate and sometimes disorganized growth of bicycle users. This situation has implied a significant increase in the need for studies seeking to explore different road system factors associated to road crashes suffered by cyclists, including infrastructure [12,16] and rider behaviour [17]. In this sense, one factor with a greater attributed influence on traffic injuries suffered by cyclists is risky cyclist behaviour [18]. It is estimated that 40% of the crashes suffered by cyclists are preceded by one or more risky cyclist behaviours, especially traffic violations or distracted riding [17]. Furthermore, risky behaviour on the road may be influenced by several variables, such as problematic interactions with other road users, infrastructure problems and the lack of a cycling culture among the population [19–23].

Nevertheless, research linking risky cyclist behaviour with road crashes is scarce [24,25], compared to the number of empirical studies explaining traffic crashes involving motorized vehicle drivers. Generally, this limits our capacity to design evidence-based cyclist injury prevention programs [26–28]. In this regard, it is necessary to identify human and infrastructural factors influencing cyclist safety outcomes to support road safety [29–31].

Objectives

The objectives of this study focus on first, the relationship between key infrastructural and risk-related human factors present in cycling, characteristics of cyclists and their crash rates. And second, whether infrastructural and human factors on the road are associated with traffic crash rates reported by cyclists, through a predictive model for explaining traffic safety outcomes.

2. Methods and Materials

2.1. Sample

Participants in this study were bicycle users (*n* = 1064) of 20 different countries from Europe, South America and North America, comprised of 413 women (38.8%) and 651 men (61.2%), with an average of $M = 32.83$ ($SD = 12.63$) years of age. The mean time participants used a bicycle per week was M = 6.71 (SD = 6.34) h, i.e., M = 0.96 h or 57.6 min per day. The average length for each bicycle journey was M = 47.60 (SD = 42.68) min, or M = 0.80 h.

2.2. Study Design and Procedure

For this cross-sectional study, participants completed an online questionnaire. A cross-sectional design was selected to maximize sample size in a narrow timeframe of data collection. Participants were informed that their responses would be anonymous and only used for research purposes. The importance of answering honestly to all questions was emphasized, as well as the non-existence of wrong or right answers. Participants were required to indicate their voluntary informed consent before proceeding with the questionnaire. Surveys were fully completed by n = 1064 cyclists, with a 42.6% response rate from approximately 2500 questionnaires that were initially delivered.

2.3. Description of the Questionnaire

The questionnaire was written in Spanish and consisted of various sections: Its initial part addressed individual/demographic variables, such as age, gender and city of residence and cycling-related factors, such as the frequency, length and habits associated to bicycle-using.

The second part examined participants' self-reported risky behaviours on the road using the Cyclist Behaviour Questionnaire (CBQ) [26], which is specifically designed for measuring high-risk riding behaviours (errors and violations) among bicycle users. This Likert scale is composed of 44 items, distributed in three factors: *Violations* (V), consisting of 16 items, *Errors* (E), composed by 16 items and *Positive Behaviours* (PB), consisting of 12 items. A global score of "Risk Behaviours" was built through the summing of Errors and Violations reported by respondents. The entire questionnaire used a frequency-based response scale of 5 levels: 0 = never, 1 = hardly ever, 2 = sometimes, 3 = frequently, 4 = almost always.

The third part of the survey measured participants' perceptions about infrastructural conditions and other road users. Firstly, a set of Likert-type items was used to measure the following factors in a scale from 0 (none existing) to 4 (highly present in their habitual cycling experience): the avoidance of cycling under adverse weather conditions, signalizing and infrastructure problems on roads frequented by participants, density of traffic and complexity of urban roads, perceived respect for priority at intersections and overcrowding of bicycle use in their cities/towns of residence. Secondly, a set of dichotomous items (Yes/No) addressed potential negative interactions participants recently experienced in terms of: problematic interactions with other road users, problematic interactions with obstacles on the road and the perception of environmental overstimulation through visual elements present on their circulation roads.

Finally, the fourth part of the questionnaire consisted of a series of questions related to participants' road crash rates (regardless of severity) suffered over a period of five years (e.g., *how many crashes have you suffered when cycling in the last 5 years?*).

2.4. Ethics

This study was granted ethics clearance by the Research Ethics Committee for Social Science in Health of the University Research Institute on Traffic and Road Safety at the University of Valencia. This study was deemed in accordance with the ethical principles of the Declaration of Helsinki. The study used an informed consent statement containing ethical principles, data treatment details, explaining the objective of the study, the mean duration of the survey, the personal data treatment and the voluntary nature of the study, which was presented to participants before undertaking the questionnaire. The informed consent statement also advised that identifying data would not be used as participation was anonymous.

2.5. Statistical Analysis (Data Processing)

Basic descriptive analyses were performed in order to obtain raw and standardized scores for study variables. Further, descriptive statistics (means, standard deviations) and Pearson's (bivariate) correlational analysis were performed to obtain, respectively, basic study factors and associations between study variables. The association between independent study variables and self-reported road crash rates of cyclists (dependent variable) was tested using logistic regression (Logit), using a significance parameter of $p < 0.05$. All statistical analyses were performed using ©IBM SPSS (Statistical Package for Social Sciences), version 23.0 (IBM, Armonk, NY, USA).

3. Results

3.1. Descriptive Statistics and Study Variable Scores

The mean of self-reported cycling crashes suffered in the last 5 years was $M = 0.65$ ($SD = 0.98$). Regarding risky behaviour, the mean for self-reported risky behaviours when cycling (scale 0–4) was $M = 1.26$ ($SD = 0.73$) and avoidance of cycling under adverse weather conditions (scale 0–4) was $M = 2.75$ ($SD = 1.25$). The mean score obtained for perceived signalizing and infrastructure problems of roads frequented by participants (scale 0–4) was $M = 3.44$ ($SD = 0.80$). Perceived density of traffic and complexity of urban roads (scale 0–4) had a mean value of $M = 3.38$ ($SD = 0.91$). The perceived respect for priority at intersections (scale 0–4) scored a mean of $M = 1.29$ ($SD = 1.17$). In addition, the perceived overcrowding of bicycle' use in city/town of residence (scale 0–4) presented a mean value of $M = 2.27$ ($SD = 1.14$), as shown in Table 1.

Regarding categorical (dichotomous) indicators, 83.6% of cyclists reported frequent problematic interactions with other road users. Furthermore, 84% of participants had problematic interactions with obstacles on the road. On the other hand, only 34.7% of respondents reported perceiving environmental overstimulation through billboards or visual elements on the road.

3.2. Correlation Analysis

The bivariate (Pearson) correlation analysis (see Table 1), allowed identification of significant associations between infrastructural and human demographic factors and traffic safety outcomes. Specifically, age was negatively and significantly related to average hours riding per week, self-reported risky behaviours on the road and self-reported road crashes suffered in the previous five years. On the other hand, age was positively correlated with avoidance, perceived overcrowding of bicycle use and environmental overstimulation. Regarding risky behaviours, significant associations were found for perceived complexity of urban roads [−], perceived respect for priority in crossings [−], avoidance [−] and for self-reported road crash rates [+]. Self-reported road crash rates were also associated with intensity [+], overcrowding of bicycle use [+], avoidance [+] and perceived respect for priority in crossings by other road users [−].

Table 1. Descriptive statistics and bivariate correlations between study variables.

Continuous Variables		**Mean**	**SD**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
1	Age of Users	32.83	12.630	−0.177 **	−0.274 **	−0.040	0.176 **	0.102 **	−0.222 **	0.161 **	0.024	0.048	0.171 **	−0.197 **	−0.190 **
2	Hours Riding per Week	6.71	6.341	1	0.206 **	0.058	−0.097 **	−0.033	0.107 **	−0.199 **	−0.024	−0.040	−0.090 **	0.286 **	0.228 **
3	Own Risky Behaviours	1.26	0.734		1	0.038	−0.170 **	−0.115 **	0.049	−0.247 **	0.033	0.018	0.044	0.341 **	0.306 **
4	Signalizing and Infrastructure Problems	3.44	0.801			1	0.203 **	−0.169 **	−0.028	0.053	0.102 **	0.115 **	0.026	0.035	0.040
5	Traffic Density and Complexity of Urban Roads	3.38	0.913				1	0.042	−0.050	0.155 **	0.026	0.093 **	0.087 **	−0.012	−0.023
6	Respect for Priority at Intersections	1.29	1.172					1	0.182 **	0.047	−0.086 **	−0.069 *	0.053	−0.066 *	−0.087 **
7	Overcrowding of Bicycle Use in City/Town of Residence	2.27	1.249						1	0.008	0.021	−0.022	−0.004	0.133 **	0.128 **
8	Avoidance (Weather Conditions)	2.75	1.136							1	0.000	0.047	0.103 **	−0.211 **	−0.170 **
Categorical Variables (0/1)		**Frequency**	**Percent**												
9	Problematic Interactions with other Road Users	890	83.6%								1	0.471 **	0.135 **	0.007	0.054
10	Problematic Interactions with Obstacles in the Road	893	84.0%									1	0.130 **	−0.017	−0.018
11	Environmental Overstimulation (Billboards)	695	34.7%										1	−0.053	−0.046
Self-reported road crashes		Mean/Frequency	SD/Percent												
12	Self-reported road crashes (5 Years)	0.65	0.983											1	0.794 **
13	Self-reported road crashes (Yes/No)	425	39.9%												1

** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed).

3.3. Logistic Regression (Logit)

The significant model, conducted through a stepwise regression (forward) technique, was fitted using variables contained in Table 2 showing its Beta coefficients, significance level and Confidence Intervals (CI) at 95%. The final model (contained at the fifth step) had an overall accuracy percentage of 66.7%, explained 19.5% of the variance between subjects (with a Nagelkerke's R-square coefficient of R^2 = 0.195) and showed a −2 Log likelihood coefficient of 1282.77 after 3 iterations, with a level of significance of $p < 0.001$.

Some of the variables contained in the model decreases the Odds Ratio (OR) of belonging to Group 1 (i.e., to have suffered at least one self-reported road crash in the last five years during bicycle riding). These variables are: the age of cyclists, where an increase in one year of age decreases the OR by 1.3% [$Exp(B)$ = 0.978, $CI_{Exp(B)}$ = 0.975, 0.999], the respect for the priority of cyclists at intersections, for each additional year of age decreases the OR by 12.9% [$Exp(B)$ = 0.879, $CI_{Exp(B)}$ = 0.778, 0.993] and the avoidance of riding under adverse weather conditions, for every additional year of age explains a subsequent decreasing of OR by 19.4% [$Exp(B)$ = 0.823, $CI_{Exp(B)}$ = 0.727, 0.933].

Table 2. Logistic Regression (Logit) Model. Dependent variable: Self-reported road crash suffered along the last 5 years (Dichotomous, with 1 = probability of success).

Step	Variable	B	S.E.	Wald	df	Sig.	*Exp*(*B*)	95% C.I. for *Exp*(*B*)	
								Lower	Upper
Step 1 [a]	Age of Users	−0.018	0.006	8.927	1	0.003	0.982	0.971	0.994
	Hours Riding per Week	0.061	0.013	23.905	1	0.000	1.063	1.037	1.090
	Own Risky Behaviours	0.733	0.105	48.366	1	0.000	2.082	1.693	2.560
	Constant	−1.165	0.277	17.762	1	0.000	0.312		
Step 2 [b]	Age of Users	−0.014	0.006	5.544	1	0.019	0.986	0.974	0.998
	Hours Riding per Week	0.059	0.013	21.898	1	0.000	1.061	1.035	1.087
	Own Risky Behaviours	0.743	0.106	49.064	1	0.000	2.102	1.707	2.588
	Overcrowding of Bicycle Use in City/Town of Residence	0.175	0.058	9.082	1	0.003	1.191	1.063	1.334
	Constant	−1.678	0.327	26.299	1	0.000	0.187		
Step 3 [c]	Age of Users	−0.013	0.006	4.646	1	0.031	0.987	0.975	0.999
	Hours Riding per Week	0.054	0.013	18.375	1	0.000	1.056	1.030	1.082
	Own Risky Behaviours	0.695	0.107	41.905	1	0.000	2.003	1.623	2.472
	Overcrowding of Bicycle Use in City/Town of Residence	0.185	0.058	10.050	1	0.002	1.203	1.073	1.349
	Avoidance	−0.180	0.063	8.148	1	0.004	0.835	0.738	0.945
	Constant	−1.157	0.373	9.628	1	0.002	0.314		
Step 4 [d]	Age of Users	−0.012	0.006	3.734	1	0.053	0.988	0.976	1.000
	Hours Riding per Week	0.054	0.013	18.102	1	0.000	1.055	1.029	1.081
	Own Risky Behaviours	0.683	0.108	40.222	1	0.000	1.981	1.603	2.446
	Respect for Priority at Intersections	−0.126	0.062	4.138	1	0.042	0.882	0.781	0.995
	Overcrowding of Bicycle Use in City/Town of Residence	0.209	0.060	12.203	1	0.000	1.232	1.096	1.385
	Avoidance	−0.183	0.063	8.323	1	0.004	0.833	0.736	0.943
	Constant	−1.071	0.376	8.123	1	0.004	0.343		
Step 5 [e]	Age of Users	−0.013	0.006	4.666	1	0.031	0.987	0.975	0.999
	Hours Riding per Week	0.055	0.013	18.791	1	0.000	1.056	1.031	1.083
	Own Risky Behaviours	0.713	0.109	42.536	1	0.000	2.041	1.647	2.529
	Traffic Density and Complexity of Urban Roads	0.162	0.079	4.182	1	0.041	1.176	1.007	1.375
	Respect for Priority at Intersections	−0.129	0.062	4.314	1	0.038	0.879	0.778	0.993
	Overcrowding of Bicycle Use in City/Town of Residence	0.211	0.060	12.427	1	0.000	1.235	1.098	1.389
	Avoidance	−0.194	0.064	9.289	1	0.002	0.823	0.727	0.933
	Constant	−1.589	0.456	12.162	1	0.000	0.204		

[a] Variable (s) entered on step 1: Own Risky Behaviours; [b] Variable (s) entered on step 2: Overcrowding of Bicycle Use in City/Town of Residence; [c] Variable (s) entered on step 3: Avoidance; [d] Variable (s) entered on step 4: Respect for Priority at Intersections; [e] Variable (s) entered on step 5: Traffic Density and Complexity of Urban Roads.

On the other hand, there is a set of included variables increasing the OR: the number of weekly riding hours, whereby each additional hour increased the OR by 5.5% [$Exp(B)$ = 1.056, $CI_{Exp(B)}$ = 1.031, 1.083], the overcrowding of cycling in city/town of residence, signifying an increase in the OR of 21.1% [$Exp(B)$ = 1.235, $CI_{Exp(B)}$ = 1.098, 1.389], the level of traffic density and complexity which increased the

OR by 16.2% [$Exp(B)$ = 1.176, $CI_{Exp(B)}$ = 1.007, 1.375] and finally, the self-reported risky behaviours when cycling, increasing the OR by 71.3% [$Exp(B)$ = 2.041, $CI_{Exp(B)}$ = 1.647, 2.529]. Figure 1 represents the observed groups and probabilistic predictions based on the variables contained in the model.

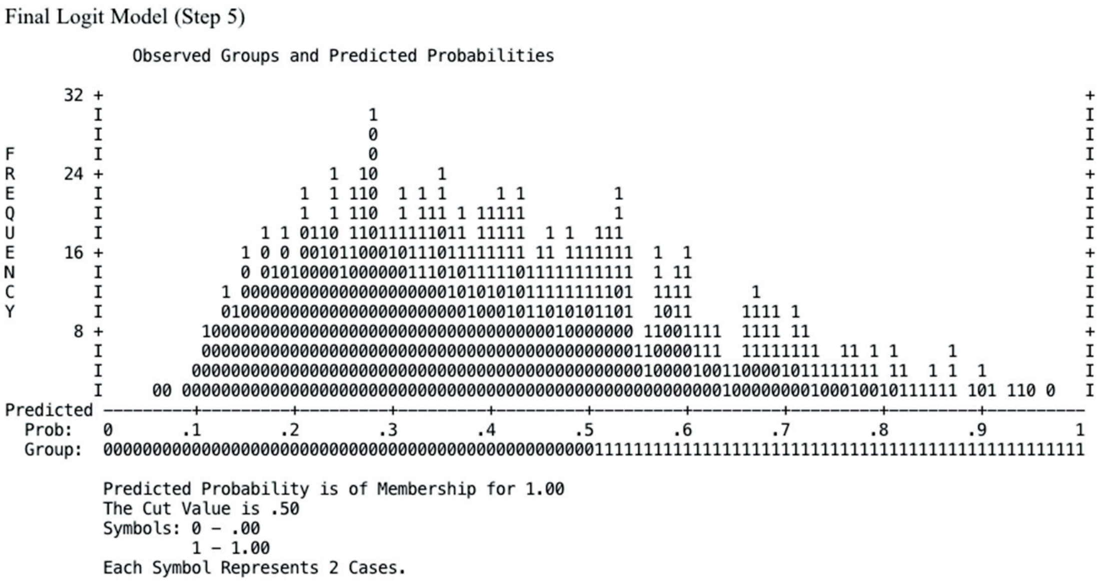

Figure 1. Observed groups (*Logit*) and probabilistic predictions, corresponding to 1's = Positive cases and 0's = Negative cases.

4. Discussion and Conclusions

The results of this study support the existence of a relationship between infrastructure characteristics, human factors and negative road safety outcomes reported by the international sample of cyclists participating in this research.

Regarding our first objective, it is worth mentioning that the observed directionality of associations between human factors and infrastructure variables, resulted consistently with other studies previously performed with samples of cyclists [4,32] and diverse groups of road users, especially drivers with high exposure to diverse road risks [33,34]. Specifically, it is worth remarking on the associations reported between age of cyclists and road crash rates in the last 5 years which were in accordance with other empirical sources [35,36], i.e., cyclists with less age tend to accumulate higher crash rates (regardless of severity) when riding compared with those with a higher age/riding experience. Furthermore, age was also correlated with risk-related perceptions (linked to infrastructural and interactional factors) and risky behaviours on the road. This finding further supports that not only young drivers are at elevated risk [37–39] but also young cyclists tend to present a higher crash risk when riding [40,41]. In addition, intentions, attitudes and perceptions of users have also been correlated to the age, experience and other human factors of cyclists and may play a crucial role for the design of cyclist-related policies [42]. Finally, behavioural factors such as avoidance and problematic interaction with environmental elements of the road correlated with cyclists' age and hours spent cycling per week.

As for our second objective, this study identified the impact of human and infrastructure-related factors on self-reported road crashes suffered by cyclists, i.e., those reporting road crashes when cycling during the previous five years. In this regard, demographic factors of cyclists were shown to have a substantial influence on safety records, the perceived complexity of urban roads for cycling, traffic density, the respect given for the priority of certain road users and the overcrowding of cycling in their city/town of residence. All significant variables related to infrastructure were shown to have an increasing effect on cyclists' self-reported involvement in a road crash while riding. Accordingly, the existing literature has shown how transportation infrastructure plays a key role on road safety [43]. For instance, Reynolds et al. [44] stated that improvements in transportation infrastructure may enhance the prevention of crashes and injuries and a successive promotion of a safety culture, inclusive for all road users. More research and system-wide efforts are necessary to address the urban policy failures in safely integrating cyclists in the transport system.

Human factors, personal characteristics and risky riding behaviours, significantly predicted self-reported road crashes. Whilst age and exposure to cycling are sufficiently documented as variables linked to cyclists' crash risk [6,15,19], much is unknown regarding the nature of cyclists' risk-taking behaviour. In this sense, investigations targeting the full spectrum of cyclists' risky behaviours and predictors of cyclists' risky behaviours are likely to support the development of countermeasures (i.e., public policy and road design) [45].

It is important to remember that cyclists' safety is a complex issue. Previous studies have reported that integration of cyclists into the transport system has been complicated by poor infrastructure, insufficient legal protections and enforcement, lack of evidence-based road safety education, low empathy from other road users and a lack of perceived risk by cyclists [29,46]. In addition, scholarly literature has described the dominance of motor transport [47], often as an urgent policy issue as the main barrier to create a safe space for cyclists. Unfortunately, the lack of action to safely integrate cyclists into the transport system prevents society from earning the long-term benefits of cycling to the environment, public health and sustainability.

One of the main lessons from this study is that cyclists' safety must be approached as a complex problem that requires a multi-faceted systems approach. This means that multiple actors at different levels of the transport system should cooperate and coordinate its effort [48]. As mentioned by [49], a systems-based approach to safety should consider equipment and surroundings (such as the bicycle and infrastructure), actor activities (including behaviour of other road users), operational management (such as riding training), local government (including parents of young riders), regulatory bodies (such as police) and government policy (such as infrastructure standards), in the development of countermeasures.

5. Limitations of the Study

Although sample size was considerably large and statistical parameters were overall accurately and positively tested, some potential biasing sources and facts related to the data collection and analysis should be mentioned. First, being an international study, the specific conditions governing traffic dynamics of cyclists belonging to different countries may substantially vary [50,51], considering relevant factors such as the aforementioned status of road safety education [46], absence of legislation and normative regulations for cyclists [52], the use of helmets and reflecting accessories [18], infrastructure-related issues [44]. Furthermore, this research only uses self-reported risky cyclists' behaviour while, in reality, they could also engage in protective behaviours such as self-regulation.

This research used self-reported road crash data but not police or hospital crash data [53]. Although these self-reports might suffer from inaccuracies, it is important to remember that crash and injury data do not necessarily register all the information necessary to explore the complexity of cyclists' safety. Self-reported data are a cost-effective road safety tool typically used when archived data is not accessible [54]. In this sense and depending on the attributed complexity of each study, cyclists' road risk estimation methods may require the implementation of different research methods in future research.

Finally, it is worth addressing the high rate of underreported road crashes, not only in institutional records but also for the case of self-reporting-based studies. Regarding the first, a substantial part of registered traffic crashes involving cyclists, especially those not implying major material losses or injuries, may not be reported [55]. As for the later, a potentially large part of their road crashes suffered may be not reported by cyclists [56], highlighting the lack of a standardized and/or well-known definition of the concept among participants.

6. Practical Applications

This study, based on self-reported cyclist data, provides a useful conceptualization of the impact of human and infrastructural issues that may influence the road safety outcomes of cyclists. In this sense, policy makers and practitioners could consider the reported data as a useful empirical framework for the building of applied interventions aimed at addressing risk factors explaining road crashes. Also, the authors consider that this work represents a useful experience for the statistical approach to the public health problem of traffic injuries among cyclists, suggesting new questions about how to strengthen a sustainable and responsible promotion of alternative transport modes.

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