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Influence of Road Safety Barriers on the Severity of Motorcyclist Injuries in Horizontal Curves

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Abstract: Motorcyclist safety remains a significant problem, and the overall safety of motorcyclists has been improved at a much slower rate in the last decade compared to passenger and commercial vehicles. Because motorcyclists are not protected by the vehicle frame, fatalities or severe injuries are often related to hitting a roadside object or safety barrier. The main objective of this study is to investigate relations between the presence and type of road safety barriers and the consequences of motorcycle crashes on rural roads. For this purpose, we analysed Croatian rural road-crash data from 2015–2019, tested several factors as single predictors, and combined them using binary logistic regression. The results show that run-off-road crashes and nighttime driving are significant risk factors. There was no significant positive impact of the presence of safety barriers on the crash consequences due to the unsuitability of the barriers for motorcyclists, which proves the fact that the functionality of existing safety barriers should be upgraded. The results of this study could be further used by researchers, road designers, and experts to improve road infrastructure safety on rural roads.

Keywords: motorcyclist; safety barriers; crash; horizontal curve

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1. Introduction

Road safety is a significant social problem, given that around 1.35 million people die yearly in road crashes (the eighth leading cause of death for people of all ages), with millions suffering severe injuries [1]. More than half of road fatalities are amongst pedestrians, cyclists, and powered two-wheelers (PTWs), i.e., vulnerable road users (VRUs). When it comes to PTWs, these are divided into motorcycles and mopeds. Motorcycles are two- or three-wheeled motor vehicles with an engine size up to 125 ccs or a maximum speed exceeding 45 km/h, while mopeds are two- or three-wheeled motor vehicles with an engine size of a maximum of 50 ccs and a maximum speed that does not exceed 45 km/h [2]. Due to their economic advantages (fuel efficiency/cost of ownership), flexibility in manoeuvring and parking, and ecological aspects (less emission than cars), PTWs are widespread. They extend from recreational and leisure to commercial activities [3,4].

Although motorcycles have many advantages, there are also downsides, primarily related to safety. The biggest safety issue concerning motorcycles is that these are single-track low-weight vehicles with powerful engines capable of higher acceleration and a higher top speed than most other vehicles. Moreover, motorcyclists do not have a vehicle shell protection compared to other vehicles, and the motorcycle's balance highly depends on the rider's skill. Due to a relatively small contact area between the road surface and the motorcycle (tyres), any loss of friction between the front or rear tyre and the road surface, for example, when turning or negotiating a curve, is likely to have a significant negative impact on the handling. In addition, their relatively small size makes them less detectable and predictable to car drivers, while their low weight is a disadvantage in collisions with other vehicles that are heavier.

The information above suggests that road crashes involving motorcyclists can often have severe consequences. The crash statistics support this, as 15.5% of road fatalities in the EU involve motorcyclists [2]. The situation is even worse in developing countries, and the statistics vary from 20% to 70%, depending on the country and region [5,6].

Moreover, in the EU, the relative proportion of motorcycle fatalities within the total number of road fatalities increased slightly from 14.3% in 2010 to 15.5% in 2018 [2]. In addition, costs per fatality/injured motorcyclist are significantly higher than those for passenger-vehicle drivers [7].

For motorcyclists, the highest number of road fatalities occurs on rural roads, with a noticeable increase from 53% in 2010 to 57% in 2018 in the European Union (EU27) [2]. Data from Great Britain's Department for Transport show similar trends, where more than 65% of all motorcyclist fatalities occurred on rural roads in 2016–2019 [8]. In general, rural roads represent roads with changing geometry, which are often not maintained timely and properly, impacting the safety of motorcyclists.

Hazardous sections of rural roads from motorcyclists' perspectives are curves. This is mainly because motorcycles require certain riding skills, and riders can easily lose control over the motorcycle when steering and navigating through curves [9]. Moreover, in horizontal curves, a motorcyclist's roadway perception and visibility are degraded [10]. This is especially evident on rural roads [11]. Studies show that the crash frequency increases as the horizontal curve radius decreases [12,13]. In other words, motorcyclists are more prone to steering errors in horizontal curves than in other road sections, and depending on the terrain configuration, their visibility is often significantly reduced.

Standard safety measures, which are often implemented in the curves, are road safety barriers. Road safety barriers are part of the road restraint systems (RRSs) intended to prevent the vehicle from leaving the roadway and protect from the opposite-direction traffic [14]. Considering strength and deflection, the most common classification of road safety barriers concerns flexible (e.g., cable/wire-rope barriers, weak post W-beam barriers), semi-rigid (e.g., strong post or blocked-out W-beam barriers and blocked-out three-beam barriers), and rigid barriers (e.g., concrete barriers) [15]. Although conventional road safety barriers perform well for occupants of passenger cars and trucks, their effects on other road user groups, especially motorcyclists, usually result in more severe injuries [16,17].

When investigating the motorcyclist's injury type and severity following the impact against a road safety barrier, there are two types of pre-crash configurations: sliding crash and upright-posture crash [18]. Results of the study conducted by Grzebieta et al. (2013), wherein both sliding and upright crash configurations were evenly represented, showed that the thorax region had the highest incidence of injury and the highest incidence of maximum injury in fatal motorcycle-to-barrier crashes. The second highest was the head region. According to Roque and Cardoso (2013), the upper and lower extremities were the most injured body regions in all motorcycle crashes. Motorcyclists involved in road-safety-barrier crashes were 2.15 times more likely to suffer a severe injury to the thoracic region than motorcyclists not engaged in that type of crash [14].

According to the research review by Gabauer (2016), motorcycle-to-barrier crashes cause more severe injuries and an increased fatality risk compared to crashes involving only an impact with the ground [19]. Those mentioned above were also concluded in a study conducted in Wyoming. It was found that barrier crashes were at risk of being more severe than all other single-motorcycle crashes [20]. Of course, the impact speed and angle in motorcycle-to-barrier crashes greatly influence the level of injuries. Higher impact speed will increase the likelihood and severity of head, neck, chest, and femur injuries [17,21,22]. Moreover, Daniello and Gabler (2012) noted that various road-safety-barrier designs might influence the risk of injuries. However, because of the lack of detail in their dataset, a more exclusive correlation could not be determined [22]. Nevertheless, it was found that steel W-beam safety barriers are not always considered fully satisfactory for motorcyclists' safety, especially when there is only one (upper) W-beam without the additional motorcycle protection system (MPS).

Furthermore, other studies found that injury risk is slightly increased for W-beam metal barriers due to the steel stiffness of the barrier posts and lack of absorption of the kinetic energy from the motorcycle during the crash [16,19]. Impact angle also has a significant effect; however, this effect differs depending on the type of road safety barrier. For concrete barriers, low impact angles usually do not cause severe injuries to motorcyclists due to the sliding of the rider to the concrete barrier and the impact energy absorption, even for high-velocity impacts [22]. On the other hand, for more perpendicular angles, the absence of the direct impact of the rider and concrete barrier results in decreased femur and pelvis injuries. However, low energy-absorbing capability in high-impact angles causes high head injury levels as an outcome of the secondary impact on the road [22]. In addition, the results of the study conducted by Daniello and Gabler (2011) showed that 40.1% of people involved in motorcycle crashes with W-beam barriers were dead or severely injured. This was almost the same as those involved in a motorcycle crash with a cable barrier (40.4%). In comparison, a lower percentage of fatalities or serious injuries (36.5%) occurred in motorcycle–concrete-barrier crashes [21].

From the above, it is evident that road crashes involving motorcyclists are a significant problem, given the frequency and severity of the consequences, as well as the lack of research focused on current road infrastructure safety practices. Namely, most of the studies focused on investigating how different types of safety barriers affected types of injuries of motorcyclists as well as their severity when crashing with them. However, the scientific and expert research were mainly conducted in the United States and Australia, where the road geometry and safety-barrier standards and practices are different compared to Europe. Therefore, the main motivation for this study is to investigate how the traditional approach to safety barriers, which is based on characteristics of cars and not motorcycles, impacts the severity of motorcycle crashes on typical European two-way rural roads, which, due to the changing road geometry and limited maintenance budget, have been highlighted as most challenging for motorcyclists. The main research question is whether the presence of such traditional safety barriers has any positive effect on the reduction in the severity of motorcycle crashes compared to the situation when safety barriers are not present at all. For the purpose of this study, we used a Croatian dataset in order to analyse and identify trends in frequency, location, causes, and consequences of motorcycle crashes and to investigate possible impacts of the presence of road safety barriers on motorcyclist safety, i.e., injury severity. Beyond the aforementioned, the second hypothesis of this study is that higher speed and smaller curve radius correlate with more severe motorcyclist injuries, regardless of the presence of road safety barriers.

Although the analysis is conducted on a dataset from Croatia, the results are applicable for other countries that have similar geographical and climatic characteristics and road features.

2. Materials and Methods

2.1. Data Collection

Data on run-off-road crashes on Croatian state roads from January 2015 to December 2019 were examined to achieve defined objectives. According to the 2018 public road classification, the network of state roads in the period above was approximately 7175 km long. These are secondary level roads, mostly two-lane two-way roads in rural areas (average lane width 3.2 m), with some sections passing through the urban areas. The data related to the crashes, crash participants, and vehicles were collected by the police, i.e., the Croatian Ministry of the Interior, for research made available to the authors. In reports, crash consequences are divided into material damage, mild injuries, severe injuries, and fatalities.

For this study, only crashes on rural roads, i.e., outside the urban area, were considered. Several filters were set to exclude the influence of other factors. First, only crashes that involved the motorcyclist as one of the participants were selected. After that, crashes that, according to available data, were described as run-off-road crashes, were singled out. Furthermore, to investigate the impact of road safety barriers on the safety of motorcyclists, only those crashes in which the motorcycle was the only vehicle involved were segregated. Finally, since road safety barriers on selected roads are generally installed in horizontal curves where run-of-road crashes are most common due to centrifugal force, crashes that occurred in horizontal curves were singled out.

The next step was to examine each crash's location and determine if a road barrier was present at the crash site and which type of road barrier it was (steel W-beam or concrete safety barrier). In addition, the following data were recorded: curve radius, speed limit, crash consequences, time of the day, and the presence of road markings. The barrier type was determined by examining the crash location or using Google Street View, a method used in some earlier studies [19,23]. It has to be noted that the examined road safety barriers were not equipped with any type of MPS. Horizontal curve radii for the location of analysed crashes were measured based on the road axis using the official Croatian Roads Ltd. GIS website for each horizontal curve.

2.2. Data Analysis

Descriptive statistics were used to describe road safety current state involving motorcycles and select factors for further analysis. In addition, the binary logistic regression method was used to test different predictors, i.e., their significance in predicting motorcyclist crash consequences. Generally, binary logistic regression is a useful tool for interpreting the influence of one or more independent input variables on the dependent variable, which is categorical, with two possible outputs. The approach has been applied in several studies which modelled the impact of crash factors on crash consequences [24–27].

In this case, the occurrence of crashes with severe or fatal consequences was used as the dependent variable (two possible outcomes: crash outcome was severe or fatal consequence or crash outcome was not severe or fatal consequence), with several independent variables used as potential predictors of the likelihood of crash occurrence. The strength of association between variables was measured using Cramer's φ coefficient, and its level of statistical significance was determined using the chi-square test. Since the outcome variable takes two possible values, its conditional distribution is based on binomial probability distribution and logit transformation, with regression coefficients representing the change in the logit associated with one unit change in the predictor. In order to ease the interpretation, regression coefficients were transformed into odds ratios, i.e., ratios of the odds outcome when a variable is present to the odds when it is absent, associated with one unit increase in predictor [28].

SPSS software (Statistical Package for the Social Sciences), version 24, was used for running the analyses conducted in this study.

3. Results

According to the observed dataset (described in Section 2.1), 29,403 crashes occurred, regardless of the type of vehicles involved. One or more motorcycles were involved in 1693 crashes, accounting for 5.8% of the total number of crashes. The share of motorcyclists involved in crashes that ended in fatalities and seriously injured was 44.9%. This fact has once again confirmed that motorcyclists are vulnerable road users and that further efforts are needed to improve their safety. In the continuation of this chapter, the analysis (descriptive statistics and prediction) of only those crashes that involved motorcyclists is presented. The number of crashes used in the further analysis is described in Table 1.

Table 1. Number of observed crashes.

Crash Type	Number of Cases
All crashes where one or more motorcyclists were involved	1693
Single-vehicle motorcycle crashes	558
Single-vehicle motorcycle crashes in curves	371
Single-vehicle run-off-road motorcycle crashes	383
Single-vehicle run-off-road motorcycle crashes in curves	289

3.1. Descriptive Analysis

3.1.1. Single- and Multi-Vehicle Motorcycle Crashes

As mentioned above, almost half of the 1693 crashes involving motorcycles resulted in fatalities or severe injuries (44.9%), 37.9% resulted in mild injuries, and only 17.1% resulted in material damage. Most crashes involving motorcycles occurred on curved road sections (38%), followed by straight road sections (33.1%), and different kinds of intersections (25.5%). When looking at the type of crash in which at least one motorcycle was involved, the largest share related to run-off-road crashes and accounted for more than a quarter of all crashes involving motorcycles (25.9%). Regarding the number of vehicles that took part in a crash, the highest percentage (55.4%) were two-vehicle crashes (of which at least one was a motorcycle), while single-motorcycle crashes accounted for 36.3% of all crashes.

3.1.2. Single-Vehicle Motorcycle Crashes

For further analysis, 558 single-vehicle motorcycle crashes with sufficient data were analysed. Crashes that lacked some of the data, such as GPS coordinates, road characteristics, etc., were excluded from the analysis. More than half of all analysed crashes resulted in fatalities or severe injuries, and 66.5% of all single-vehicle motorcycle crashes occurred in curves (Table 2). Due to fewer crashes at sections other than curves and straight road segments, all other road sections were merged into one category named "Other" (e.g., bridge, tunnel, intersection etc.).

Table 2. Consequences and road characteristics of single-vehicle motorcycle crashes (n_{crash} = 558).

	n	(%)
Severe injuries or fatalities		
No	260	(46.6)
Yes	298	(53.4)
Total	558	(100.0)
Road characteristics		
Curve	371	(66.5)
Straight road	119	(21.3)
Other	68	(12.2)
Total	558	(100.0)

Other variables observed were the types and circumstances of single-vehicle motorcycle crashes. According to the available data, the most significant share (68.6%) was run-off-road crashes (Table 3). The main crash circumstance was inappropriate speed (75.2%), while 82.8% of the crashes occurred during the daytime.

Table 3. Type of crash and crash circumstances (n_{crash} = 558).

	n	(%)
Type of crash—merged categories		
Run-off-road	383	(68.6)
Collision with fixed objects	36	(6.5)
Pedestrian strike or animal run	39	(7.0)
Other	100	(17.9)
Total	558	(100.0)
Inappropriate speed		
No	138	(24.8)
Yes	419	(75.2)
Total	557	(100.0)
Visibility conditions		
Daytime	462	(82.8)
Nighttime (9:01 PM till 7.00 AM)	96	(17.2)
Total	558	(100.0)

3.1.3. Single-Vehicle Run-Off-Road Motorcycle Crashes in Horizontal Curves

Because 66.5% of all single-motorcycle crashes occurred in the horizontal curves, those crashes were selected to investigate the influence of road barriers on motorcyclist safety. As stated earlier, due to specific characteristics of motorcycles, steering and navigating through the horizontal curves represents the most challenging driving task for motorcyclists. Hence, only single-vehicle crashes were observed to exclude the potential influence of other vehicles. Severe injuries or fatalities were the most common outcomes of these crashes, while a road barrier was present in 40.5% of the crashes (Table 4). The total number of crashes here refers to single-vehicle and run-off-road crashes in curves.

Table 4. Crash consequences of single-vehicle run-off-road motorcycle crashes and the presence of a road barrier in horizontal curves (n_{crash} = 289).

	n	(%)
Crash consequences		
Material damage	31	(10.7)
Mild injuries	89	(30.8)
Severe injuries	142	(49.1)
Fatalities	27	(9.3)
Total	289	(100.0)
Road barrier		
No	172	(59.5)
Yes	117	(40.5)
Total	289	(100.0)

An additional variable was created for more detailed analysis to indicate the type of barrier when it was present on crash sites (Table 5). The analysis showed that most barriers were made of steel (35.9%). It must be noted here that all steel W-beam barriers were grouped together, regardless of whether they had a distance spacer. Similar was done with concrete barriers. After merging all concrete barriers ("New Jersey" style barriers and concrete walls), it was concluded that such barriers existed only in 3.5% of the crashes.

Table 5. Road barrier type (n_{crash} = 289).

	n	(%)
Road barrier and type		
No barrier	172	(59.5)
Steel W-beam safety barrier	102	(35.3)
Concrete safety barrier	10	(3.5)

No data about barrier type	5	(1.7)
Total	289	(100.0)

Moreover, some extra road characteristics on the crash locations were noted, which are shown in Table 6. Only on 13.8% of curves were there no edge road markings present, while the centreline was present in almost 99%.

Table 6. Road characteristics (n_{crash} = 289).

	n	**(%)**
Edge lines		
No	40	(13.8)
Yes	249	(86.2)
Total	289	(100.0)
Centreline		
No	4	(1.4)
Yes	285	(98.6)
Total	289	(100.0)
More than two lanes		
No	264	(91.3)
Yes	25	(8.7)
Total	289	(100.0)

As in previous cases, the most common crash circumstance noted in the database was the inappropriate speed (91% of crashes). In observed curve-located crashes, the speed limit ranged from 30 to 90 km/h, with a mean of 53.1 (SD = 13.09), and the most frequent was 50 km/h. For further analysis, the speed limit was categorised as either 50 km/h and below or above 50 km/h. Regarding curve radius, the mean value was 164.83 m (SD = 230.71, Max = 2400, Min = 19), and the categorisation of radii used in the analysis is shown in Table 7. For two crashes, it was impossible to determine the radius; therefore, the number of observed crashes is 287. The curve radii presented in Table 7 were determined due to the relatively small crash sample and the speed–radius ratio used in the Croatian Rulebook [29].

Table 7. Speed limit and curve radius (n_{crash} = 287).

	n	**(%)**
Speed limit above 50 km/h		
No	171	(59.2)
Yes	118	(40.8)
Total	289	(100.0)
Curve radius (m)		
≤74 m	93	(32.4)
75–174 m	118	(41.1)
175–349 m	49	(17.1)
≥350 m	27	(9.4)
Total	287	(100.0)

3.2. Statistical Analysis

Of the individual circumstances that preceded the motorcycle-involving crashes, the most prominent is excessive or unadjusted speed, which was the case in 38.7% of the crashes, followed by the disregard of right-of-way (17.0%). Regarding the visibility conditions, 89.1% of the crashes occurred during the daytime.

When each predictor was analysed separately, statistically significant risk factors for severe crash consequences were curve, as well as run-off-road crashes, single-vehicle crashes, inappropriate speed, and nighttime driving. In an analysis that considered all predictors simultaneously (i.e., controlling for their inter-relations), run-off-road and single-vehicle crashes were no longer significant risk factors of severe crash consequences. This analysis indicated curve crashes, inappropriate speed, and nighttime driving as significant risk factors (Table 8).

Table 8. Prediction of severe injuries or fatalities—all types of motorcyclist crashes (n_{crash} = 1693).

Predictor	Severe Injuries or Fatalities									
	No		**Yes**		**Single Predictor**			**All Predictors**		
	n	**(%)**	***n***	**(%)**	***OR***	**(95% CI)**	***p***	***OR***	**(95% CI)**	***p***
Curve										
No	642	(61.2)	407	(38.8)	1			1		
Yes	290	(45.0)	354	(55.0)	**1.93**	**(1.58, 2.35)**	**<0.001**	**1.33**	**(1.05, 1.69)**	**0.018**
Run-off-road										
No	753	(60.0)	501	(40.0)	1			1		
Yes	179	(40.8)	260	(59.2)	**2.18**	**(1.75, 2.72)**	**<0.001**	1.36	(0.98, 1.91)	0.069
Single vehicle										
No	655	(60.8)	423	(39.2)	1			1		
Yes	277	(45.0)	338	(55.0)	**1.89**	**(1.55, 2.31)**	**<0.001**	0.94	(0.69, 1.29)	0.719
Inappropriate speed										
No	653	(63.2)	380	(36.8)	1			1		
Yes	275	(42.1)	378	(57.9)	**2.36**	**(1.93, 2.89)**	**<0.001**	**1.78**	**(1.37, 2.31)**	**<0.001**
Nighttime										
No	856	(56.8)	652	(43.2)	1			1		
Yes	76	(41.1)	109	(58.9)	**1.88**	**(1.38, 2.57)**	**<0.001**	**1.72**	**(1.25, 2.37)**	**0.001**

Note. *OR* = odds ratio, 95% CI = 95% confidence interval for odds ratio, *p* = level of statistical significance.

Table 9 describes shares of road characteristics associated with single-vehicle motorcyclist crash consequences. Although most single-vehicle motorcycle crashes occurred on curved road sections, further analysis using the Cramer's φ coefficient showed no statistically significant association between road characteristics and crash consequences (φ = 0.07, $\chi^2(6)$ = 2.34, i = 0.886).

Table 9. Association between crash consequences and road characteristics (n_{crash} = 558).

Road Characteristics	Material Damage		Mild Injuries		Severe Injuries		Fatalities		Total	
	n	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**	**n**	**(%)**
Curve	44	(11.9)	123	(33.2)	171	(46.1)	33	(8.9)	371	(100.0)
Straight road	14	(11.8)	46	(38.7)	51	(42.9)	8	(6.7)	119	(100.0)
Other	7	(10.3)	26	(38.2)	31	(45.6)	4	(5.9)	68	(100.0)
Total	65		195		253		45		558	

As stated, to identify risk factors for crashes resulting in severe consequences (i.e., severe injuries or fatalities), prediction of severe consequences was made using binary logistic regression. Analyses at the level of each predictor separately (i.e., without considering its relationship with other predictors) indicated that statistically significant risk factors for severe crash consequences were run-off-road crashes, inappropriate speed, and nighttime driving. When all predictors were considered simultaneously, inappropriate speed was no longer a significant predictor of severe injuries or fatalities. At the same time, run-off-road crashes and nighttime driving remained significant risk factors (Table 10).

Table 10. Prediction of severe injuries or fatalities of single-vehicle motorcyclist crashes (n_{crash} = 558).

Predictor	Severe Injuries or Fatalities									
	No		Yes		Single Predictor			All Predictors		
	n	(%)	*n*	(%)	*OR*	(95% CI)	*p*	*OR*	(95% CI)	*p*
Curve										
no	93	(49.7)	94	(50.3)	1			1		
yes	167	(45.0)	204	(55.0)	1.21	(0.85, 1.72)	0.292	0.96	(0.65, 1.42)	0.832
Run-off-road										
no	101	(57.7)	74	(42.3)	1			1		
yes	159	(41.5)	224	(58.5)	**1.92**	**(1.34, 2.76)**	**<0.001**	**1.76**	**(1.18, 2.62)**	**0.005**
Inappropriate speed										
no	77	(55.8)	61	(44.2)	1			1		
yes	182	(43.4)	237	(56.6)	**1.64**	**(1.12, 2.42)**	**0.012**	1.36	(0.88, 2.09)	0.169
Nighttime										
no	226	(48.9)	236	(51.1)	1			1		
yes	34	(35.4)	62	(64.6)	**1.75**	**(1.11, 2.76)**	**0.017**	**1.73**	**(1.09, 2,75)**	**0.021**

Note. *OR* = odds ratio, 95% CI = 95% confidence interval for odds ratio, *p* = level of statistical significance.

Most crashes in total, as well as those which resulted in severe or fatal consequences, occurred when there was no safety barrier on the road. Similarly, in the analysed dataset, 59.5% of all crashes occurred in locations with no road safety barrier. On the other hand, when we look at the ratio between the number of crashes with severe and fatal consequences and the total number of crashes in horizontal curves when safety barriers were and were not present, the ratio above is almost equal. Furthermore, using Cramer's φ coefficient and χ^2 test, the impact of the presence of the road barrier on crash consequences was tested. The initial results showed no statistically significant association (φ = 0.11, $\chi^2(3)$ = 3.53, p = 0.317) between presence / non-presence of road barrier and crash consequences (Table 11).

Table 11. Association between crash consequences and the presence of a road barrier (n_{crash} = 289).

Road Barrier Present	Material Damage		Mild Injuries		Severe Injuries		Fatalities		Total	
	n	(%)	n	(%)	n	(%)	n	(%)	n	(%)
No	15	(8.7)	59	(34.3)	83	(48.3)	15	(8.7)	172	(100.0)
Yes	16	(13.7)	30	(25.6)	59	(50.4)	12	(10.3)	117	(100.0)
Total	31		89		142		27		289	

The type of road safety barrier and other factors were considered predictors of severe injuries and fatalities. However, none of the factors came out as a statistically significant predictor in single-vehicle motorcyclist crashes in curves. There was no significant impact of road safety barriers on the crash consequences, regardless of the driving speed, curve radii, or the presence of road markings (Table 12). Nevertheless, the division of the curve radius to less than 250 m vs. 250 m and above was marginally statistically significant in interaction with the presence of a safety barrier, indicating that repeating the analysis with a larger crash sample could show some significance.

Table 12. Prediction of severe injuries or fatalities in single-vehicle run-off-road motorcyclist crashes in curves (n_{crash} = 289).

Predictor	Severe Injuries or Fatalities									
	No		Yes		Single Predictor			All Predictors		
	n	(%)	*n*	(%)	*OR*	(95% CI)	*p*	*OR*	(95% CI)	*p*
Road barrier and type										

no barrier	74	(43.0)	98	(57.0)	1			1		
Steel W-beam safety barrier	38	(37.3)	64	(62.7)	1.27	(0.77, 2.10)	0.348	1.32	(0.76, 2.27)	0.323
Concrete safety barrier	6	(60.0)	4	(40.0)	0.50	(0.14, 1.85)	0.301	0.48	(0.13, 1.84)	0.286
Inappropriate speed										
no	13	(50.0)	13	(50.0)	1			1		
yes	107	(40.7)	156	(59.3)	1.46	(0.65, 3.27)	0.360	1.27	(0.54, 3.02)	0.586
Nighttime										
no	102	(42.1)	140	(57.9)	1			1		
yes	18	(38.3)	29	(61.7)	1.17	(0.62, 2.23)	0.624	1.23	(0.61, 2.48)	0.560
Speed limit above 50 km/h										
no	69	(40.4)	102	(59.6)	1			1		
yes	51	(43.2)	67	(56.8)	0.89	(0.55, 1.43)	0.627	0.72	(0.42, 1.22)	0.221
Curve radius (m)										
≤ 74 m	41	(44.1)	52	(55.9)	1			1		
75-174 m	47	(39.8)	71	(60.2)	1.19	(0.69, 2.07)	0.534	1.23	(0.67, 2.23)	0.506
175-349 m	17	(34.7)	32	(65.3)	1.48	(0.73, 3.04)	0.280	1.91	(0.81, 4.51)	0.138
≥ 350 m	13	(48.1)	14	(51.9)	0.85	(0.36, 2.00)	0.709	1.03	(0.39, 2.73)	0.951
Edge lines										
yes	101	(40.6)	148	(59.4)	1			1		
no	19	(47.5)	21	(52.5)	0.75	(0.39, 1.47)	0.409	0.84	(0.41, 1.71)	0.622
More than 2 lanes										
no	108	(40.9)	156	(59.1)	1			1		
yes	12	(48.0)	13	(52.0)	0.75	(0.33, 1.71)	0.493	0.62	(0.25, 1.58)	0.317

Note. OR = odds ratio, 95% CI = 95% confidence interval, *p* = level of statistical significance.

4. Discussion

As predicted in the beginning, the analysis highlighted curves as one of the most dangerous and demanding road sections concerning motorcycle crashes and the severity of their consequences, given that 38% of crashes involving motorcycles occurred on curved road sections. This is also consistent with previous studies that indicated that horizontal curves are spots where the frequency of motorcyclist crashes is the highest [30] and where consequences are most severe [19]. One of the reasons for such statistics is related to the characteristics of the motorcycle. Namely, motorcycles are most commonly single-track vehicles with a small contact area between the road surface and tyres and, as such, require a particular riding skill, especially when driving and navigating through horizontal curves [9]. Moreover, an additional problem for motorcyclists in horizontal curves is related to the perception and visibility of the environment [10]. Finally, motorcycles do not offer riders physical protection when crashes happen.

Further support for the abovesaid is that most of the analysed crashes were run-off-road (25.9%), meaning that motorcycle stability issues in riding are significant. Riding mistakes are often caused by either inappropriate speed (riding above the speed limit) or speed unadjusted to conditions on the specific road sections, such as curves, which leads to losing control over the motorcycle. Overall, the analysis indicated that 38.7% of motorcycle crashes are related to speeding (inappropriate or unadjusted speed), according to the police reports from the crash sites. Several studies analysed in recent literature reviews highlighted that speed is one of the main contributing factors to motorcycle-related road crashes [3,31,32]. Moreover, our analysis shows that more than half of single-motorcycle crashes resulted in fatalities or severe injuries. This is primarily due to the inappropriate riding speed since speeding significantly affects the injury severity and because motorcycles do not provide physical protection to the rider [33].

Even though our analysis showed that 66.5% of single-motorcycle crashes occurred in curves, further analysis showed no statistically significant correlation between road characteristics (curved or straight section) and the crash consequences. However, this finding should be taken with caution as it may result from a limited and uneven sample size. Namely, Vlahogianni, Yannis, and Golias (2012), in their literature review, concluded that the radius and length of each horizontal curve significantly influence the frequency and severity of motorcycle crashes [31]. Furthermore, Gabauer and Li highlighted a horizontal curve radius of 249.94 m (820 ft) or less as being a significant predictor of motorcycle-to-barrier crashes [34]. In addition, they found that approximately 40% and 73% of curves with motorcycle-to-barrier crashes have a radius of less than 318.2 m (1044 ft) and 853.4 m (2800 ft), respectively. In other words, small and medium radius curves were found to be more likely to be where motorcycle-to-barrier crashes occur. It has to be noted that, when we analysed curves with radii less than 250 m vs. 250 m and above, the effect was marginal in interaction with the presence of a road safety barrier. This is also, to some extent, consistent with the literature, suggesting that smaller radii indicate higher crash frequency [35,36]. Therefore, a deeper investigation that includes a larger sample should be conducted.

Since the main goal of this paper was to investigate the potential impact of road safety barriers on motorcyclist safety, the focus was therefore brought to single-vehicle crashes. This was done to exclude the potential impact of other vehicles. The analysis of all motorcycle crashes showed that most of them occur in curves. In addition, curves are the most common location for road-safety-barrier installation on rural roads. As before, severe injuries and fatalities made the most significant share of these crashes' consequences (more than 58%), and an inappropriate speed was the most common circumstance, according to the police reports.

Given that none of the road safety barriers were motorcyclist friendly, i.e., equipped with MPS, the initial testing results were as expected, i.e., the initial hypothesis was confirmed. The results showed no statistically significant relation between crash consequences and the presence of road safety barriers or the barrier type. Further analysis also included other variables, such as curve radius, number of lanes, non-compliance with speed limits, time of day, and presence of edge road markings. All these factors, combined with the road barrier type, were considered possible predictors in predicting fatalities and severe injuries. However, after the analysis, none of the factors were a significant predictor.

Suppose we focus on the primary goal of this manuscript. In that case, we can see that implemented road safety barriers designed primarily for cars did not significantly benefit motorcyclists when they crashed compared to the situation where there were no barriers at all. Moreover, no statistically significant differences between individual types of barriers were found. The most common barrier type in this study were steel W-beam barriers, which have several issues concerning motorcyclists. The major issue is related to the fact that such barriers have exposed poles that a motorcyclist may hit when sliding on the pavement after losing control of the motorcycle, which may cause extremely severe injuries or a fatality [37]. Another issue may occur when motorcyclists slide under the barrier beam with their body, hitting the beam with their head or sliding entirely under it and falling into a chasm or hitting another fixed object. Therefore, some studies indicate that concrete safety barriers are more favourable for motorcyclists since they do not have exposed barrier posts and motorcyclists cannot slide under them [21,38]. However, this study could not make a more detailed comparison between steel W-beam and concrete barriers due to the relatively small and uneven sample size.

Overall, the findings indicate no statistical differences in the consequences of motorcycle crashes where road safety barriers without MPS were or were not present. This further supports the finding by Bambach et al. (2015), highlighting that appropriate road safety barriers should be placed in the proper places [39]. Proper design and placement of road safety barriers provides an additional safety layer during motorcycle crashes. This may significantly reduce the risk of fatal and severe injuries compared to situations where motorcyclists hit trees, poles, or other objects due to a lack of barriers next to the road [40]. In other words, although safety barriers that are unadjusted to motorcyclist can be dangerous objects themselves, they still provide protection from other fixed roadside objects such as trees or poles [41]. This is also in accordance with our findings, since, although no positive impact of barriers was detected, no negative impact was detected either. Therefore, the development and implementation of MPSs are imperative, especially in horizontal curves [42], to accomplish a noticeable positive impact on crash consequence severity. According to [38], a positive effect is gained using a continuous MPS when a motorcyclist collides with a barrier both in upright and sliding positions. Good practices in EU countries with similar road characteristics and geometry, such as Slovenia [43] or Austria [44,45], present additional proof that such thinking can bring significant benefits. Nevertheless, further before–after and cost–benefit analyses are recommended to confirm the efficiency of the MPS and its types.

Although the study provided valuable results, it has certain limitations that must be considered. First, the analysis should be conducted on a bigger sample to ensure more reliable results. Since this analysis was performed on a relatively small crash sample, within which different types of safety barriers are represented unevenly, the results should be interpreted cautiously. Another limitation is the crash database that was used, which has inevitable shortages, mainly related to the quality and accuracy of the data. The quality and level of detail of data collected through police crash examination and reports differ from country to country, and sometimes within the country, since it can depend on the subjective observation of the police officer, which ultimately complicates the comparisons between similar studies [46,47]. Furthermore, additional variables could be identified as a part of better data collection, including the length of the curve arc, transverse slope, longitudinal inclination, skid resistance, AADT, etc. Motorcyclist characteristics, such as age, gender, or riding experience, could also be included in the analysis. Finally, it is recommended to investigate the impact of road elements on the consequences of crashes and how motorcyclists perceive certain aspects of road infrastructure to effectively prevent motorcyclist crashes and reduce their number.

Nevertheless, the significance of the results is manifested in the fact that there is no positive impact of the currently implemented safety barriers on the safety of motorcyclists. It also opens opportunities for future research comparing the consequences of crashes involving motorcyclists hitting motorcyclist-friendly barriers, since the installation of such barriers is in progress in Croatia. One of our goals for future research projects is to conduct a before–after analysis to conclude to what extent the motorcyclist-friendly safety barriers, and possibly other safety-enhancing solutions, reduce the motorcyclist crash severity.

Another recommendation for road authorities and crash investigators arising from this study is the use of uniform crash report forms, which would enable the collection of more precise and detailed information, including location and road equipment specifications. In this way, very valuable information could be obtained for further research, leading to the improvement of the safety of motorcyclists. A more detailed crash report could be further used to determine the most useful safety barriers and to set up the MPS evaluation criteria [48,49]. In addition, this could enable comparative analyses from different countries, i.e., areas with different geographical and cultural characteristics, to make sure that the best practices are used.

5. Conclusions

Motorcyclist safety is one of the most significant issues in road traffic, considering the severity of crash consequences and fatality rate. The specifics of riding a motorcycle differ from other motorised vehicles, so some parts of the road are more demanding for motorcyclists. This paper aimed to analyse Croatian road crash statistics related to motorcycles and investigate the impact of road safety barriers on the severity of motorcyclist injuries. For that purpose, a crash dataset that consists of all crashes that occurred on the Croatian secondary road network (state rural roads) from January 2015 to December 2019 was analysed.

Overall, horizontal curves on rural roads stand out as one of the riskiest situations for motorcyclists. The most common crash type is run-off-road, primarily resulting in motorcyclists hitting fixed roadside objects. After analysing crashes and road characteristics, no significant impact of road safety barriers on the crash consequences was found. Since the most common road safety barrier was steel W-beam barriers without any MPS, the results indicate that, from the perspective of motorcycle crash consequences, it is the same whether those barriers were present or not. The results of this study indicate a need for enhancing motorcyclist safety, especially in tourist countries such as Croatia, and that one solution indeed lies in implementing appropriate road safety barriers while considering the specific characteristics of different road users.

As said, no positive impact of the existing road safety barriers without MPS on mitigating the severity of motorcyclist crashes has been proved. Hence, this remains an incentive for experts in the field of road safety and road authorities to implement error-forgiving solutions for motorcyclists. This was also a recommendation given as one of the conclusions of the thorough literature review from 2022 [50]. Recognisable road design, as well as forgiveness of the environment, are some of the safe-system principles aimed at eliminating road deaths, and improvement of road restraint systems is certainly one way to achieve sustainable road safety. Furthermore, focusing on the specific crashes occurring on roads helps in detecting possible intervention options. However, in practice, it will not be possible to achieve the set goals without further scientific research.

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