Risk factors, helmet effect on the biomechanics of the impact and computational simulation of bicycle accidents

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Abstract

The need of a cheaper way of transportation allied with modern eco societies thinking, results in an increasing of bicycle popularity. In Europe, bicycle accidents are the second category with the lowest fatality reduction, next to motorcycle category in the last years. Portugal is the European country with higher mortality per km ratio, in 2013, making this popularity growth alarming.

Portugal´s bicycle accidents, from 2010 to 2015, were analyzed with an ordered logistic regression in order to identify the risk factors associated with the injury outcome. Of the 8592 accidents analyzed, over 60 years old and un-helmeted cyclists are more likely to suffer severe injuries when involved in an accident. Alcohol, night period, rural areas, collisions with trucks, surface good grip, single vehicle accidents, maneuvers and other weather conditions are also likely to increase the severity of the injury outcome.

The main reasons for helmet non-usage are head overheating and itchiness. Its use, among in the inquired 100 people sample, is more likely for women, ages between 41-60 and higher annual cycling distance. Helmet does not difficult cyclists´ visual or earing skills.

Helmet or high visibility vest use does not translate in closer pathing overtakes, comparing to unhelmet cyclists. Motor vehicle drivers´ behavior regarding overtaking probably cannot be changed by modifying cyclist´s appearance. The tests were performed using an Arduino device to measure store data.

From 2 real cases analyzed using PC-Crash, proper helmet use might reduce fatality chances head injuries aggravation.
Key Words: **Bicycle helmet, Cycling risk factors, Helmet use, Overtaking distances, Helmet effectiveness**

I. Introduction

Motivation

Road fatalities are systematically one of main issues regarding Human safety. Nowadays, about 1.25 million of people dies in road accidents [1]. In Portugal and across the Europe, the financial crisis resulted in a popularization of bicycle use [2]. In 2013, Portugal was the European country with higher mortality per km ratio. According to D. Shinar *et al.* [3], only 10% of all bicycle accidents are reported to the authorities.

Bibliographic Research

Helmet use reduce the frequency and severity of head injuries in bicycle accidents [4]–[8]. Agreeing to N. Persaud *et al.* [9], helmeted cyclists are more likely to survive in case of an accident. Its use reduces the chances of skull fracture [10]–[13], intracranial injuries [10], [13]–[15] and facial fractures [16]. Helmet effectiveness varies across the face [17].

Mandatory helmet use can lead to the reduction of bicycle users [18], special children and young adults [19] and its implementation is not a synonym of accidents reduction, in terms of number and severity, since helmeted cyclist are normally more careful, respectful of the law cyclists and therefore with lower risk of accident [5]. By forcing helmet use, cyclist can engage in a risk compensation behave and increase their chances of accident and severe injuries [20]. Nevertheless, according to Robert Bauer *et al.* [21], mandatory helmet use in children results in na increase of helmet use and decrease of head injuries in children.

In the presence of helmeted cyclists, motor vehicles drivers can induce the presence of an experienced cyclists and therefore decrease precaution levels [22]. However, Olivier, J. e Walter [23] and Walker I. [24] concluded that the presence of the helmet did not have a significant impact on overtaking distances.

Older [25]–[27] cyclists are more likely to suffer severe injuries. Rural environment accidents results in a severe injury outcome [26]–[28].

Fedy Ounia e Mounir Belloumi [29] determined that good weather accidents are more likely to result in a severe injury outcome and that the number of accidents increase in summer season.

Riding a bicycle under the effect of alcohol or other drugs increase the probability of severe injuries, according to Chiara Orsi *et al.* [30].

II. Theoretical background

Bicycle helmet consists in successive energy-absorbing layers made up of foam [31], an external shell, made up of high quality plastic, that also absorbs impact energy, ventilation system, to ensure the head cooling [32] [33] and restrain and fixation systems [34] [35]. Helmet should be homologated according with the current standard [36].

The two main standards are the European standard EN 1078 and United States Standard CPSC. The main reason for their existence is to ensure quality helmets on the market, capable of resisting establish minimum criteria.

Helmet function is to absorb energy and reduce the linear and rotational accelerations of the cyclist head. HIC criteria measures de head acceleration and predicts the severity of the injury outcome [37]. Values of HIC above 700 severe head injuries are expected [38].

$$HIC = \left[\left(\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a\, dt\right)^{2.5}(t_2-t_1)\right]max$$

The injury outcome is evaluated with the AIS index [39]:

Table 1 - AIS level and head injury

AIS	Injury
1	Possible minor concussion
2	Possible skull fracture, loss of consciousness, nasal fracture
3	High probability of skull fracture, loss of consciousness. No severe brain damage. Possible face fracture
4	Skull fracture, high probability of severe brain damages
5	Skull fracture and head deformation, internal bleeding
6	Massive brain and skull destruction. Death

HIC criterion can be related with AIS value, according to the Figure 1, where the victim is considered to be unhelmeted [40].

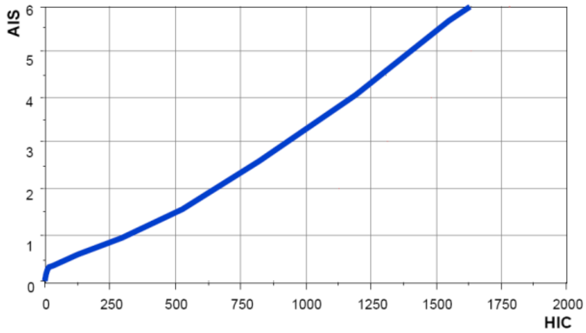


Figure 1 - Unhelmeted HIC and corresponding AIS

The Figure 2 relates the AIS outcome and the HIC criterion, when the victim is helmeted [40]:

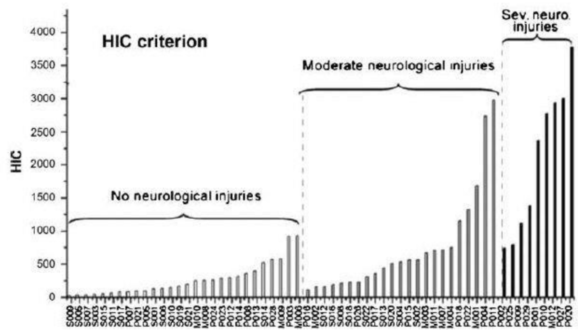


Figure 2 - Helmeted HIC and corresponding AIS

The Figure 3 relates the HIC criterion with the probability of skull fracture [41]:

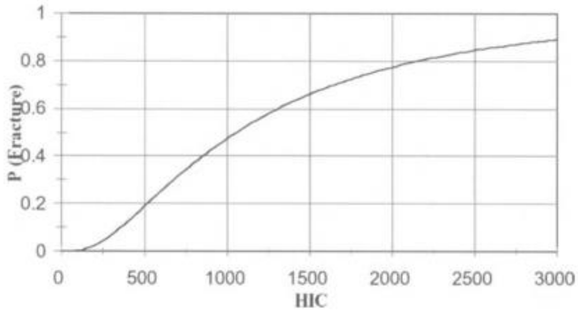


Figure 3 - HIC and corresponding skull fracture probability

HIP criterion measures both linear and rotational acceleration to measure the probability of mild traumatic brain injury, according to the next equation [42]:

$$HIP = C_1 a_x \int a_x dt + C_2 a_y \int a_y dt + C_3 a_z \int a_z dt + C_4 \alpha_x \int \alpha_x dt + C_5 \alpha_y \int \alpha_y dt + C_6 \alpha_z \int \alpha_z dt$$

$$C_1 = C_2 = C_3 = 4.5\, Kg;\ C_4 = 0.016\, Nm\, s^{-2};$$

$$C_5 = 0.024\ Nm\ s^{-2};\ C_6 = 0.022\ Nm\ s^{-2}$$

The relation between the HIP criterion and the probability of head traumatic injury is given by the following figure [42]:

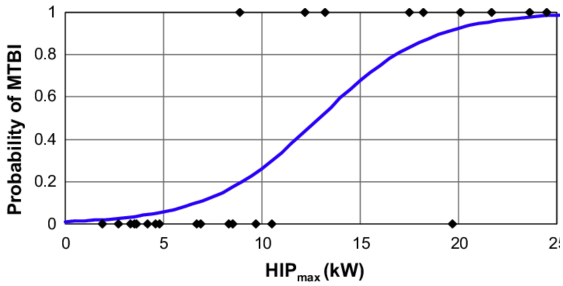


Figure 4 - mTBI probability and HIP value

GAMBIT criterion combines linear and rotational to measure brain injury probability, according to the next equation [43]:

$$GAMBIT = \left[\left(\frac{a(t)}{a_c}\right)^{2.5} + \left(\frac{\ddot{\varphi}(t)}{\ddot{\varphi}_c}\right)^{2.5}\right]^{1/2.5}$$

The next figure correlates the GAMBIT criterion with the probability of irreversible head injury [44]:

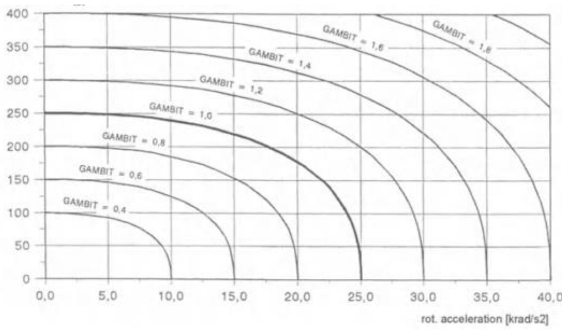


Figure 5 - GAMBIT value and irreversible head injury probability

III. Statistical results

III.I – ANSR data statistical analysis

With data provided by ANSR a retrospective analysis was done to the victims of accidents involving cyclists in the period between 2010 and 2015. The data base included 8972 accidents, which resulted in 192 cyclist's deaths.

With descriptive statistic it was made an analysis of the severity index (number of deaths in 100 accidents with victims), SI, of the cyclists' injuries in order to understand the main factor associated with higher mortality in the study sample.

In order to determine the risk factors associated to the increase of injuries severity in cyclists in Portugal, an ordered logistic regression was applied to the ANSR data, using the statistical analysis software *IBM Statistics SPSS.*

Descriptive analysis

Regarding the type of accidents, between 2010 and 2015, single vehicle accidents SI is higher than collisions.

Across the period studied, the SI decreased, having its lower value in 2015 and its higher in 2011.

There wasn´t a significant variation of the SI during the four annual seasons, day of the month or day of the week.

Night period (0h-6h) had the higher SI, when compared to other periods of the day, with 5 deaths in 100 accidents with victims.

Bad weather conditions caused more deaths per 100 accidents with victims, compared to good weather conditions.

For grip conditions, the SI was higher for good surface grip conditions, 2 times compared to bad grip conditions. This results can be contradictory to the weather conditions results.

Accidents in outside towns resulted in more deaths than those occurred inside towns, with 6 deaths per 100 accidents with victims. Outside intersections accidents also resulted in higher SI. Highways, principal and complementary itinerary registered the higher SI in the road type category.

Regarding human factors, it was found higher SI for accidents involved over 61 years old. The SI of the gender Male were also the higher value of the category, compared to female gender.

Reversing the direction registered the higher SI in the cyclists´ maneuver category.

Concerning the helmet usage, there wasn´t any difference between helmeted and unhelmeted cyclists. However, since helmet is not mandatory in Portugal, most of the accidents included in the data were mark as exempt. If considered as unhelmeted, this new class had the higher SI.

Regarding cyclists´ BAS, the values between 0.2-0.5g/l or above 1.2g/l registered the higher SI.

Collisions with trucks has the higher SI, when compared with collisions with cars, motorcycles or bicycles.

Finally, for others driver´s injuries, the higher SI was for unharmed motor vehicle drivers.

Risk factors associated with injury severity outcome

In order to make a statistical inference to the Portuguese population, an ordered logistic regression was applied to the ANSR data, using the statistical analysis software IBM Statistics SPSS. The statistical method were chosen because of the different importance (multilevel) among the classes of the dependent category, Cyclist´s injury. Therefore, in this analysis death of a cyclist is more important than a severe injury and this is more important than minor injury. The odd ratio (OD) is an association between the independent variables and the dependent variable that allows describing the association between the variables with a confidence interval of 95%. In this analysis are only presented values with statistical significance (p<0.005 or p<0.01), related with the p-value. The results are presented in Table 2:

Regarding the type of accident, it was found 61.07% of higher risk of increasing injury severity for single vehicle accidents, compared to collisions with cars and collisions with pedestrians. This fact may be explained the low levels of accident report in Portugal (only 13.2%). The majority of reports may occurred when it was a collision with an insured vehicle. The insurance requires the presence of the authorities and therefore reports. Single vehicle accidents only are reported in case of fatal or severe injury, changing the OR results.

Bad surface grip conditions results in 22.14% of lower chances of severe injuries than good grip conditions.

After a detailed analysis to the descriptive analysis it was found a correlation in the reduction of the risk of injury aggravation between bad grip conditions and bad weather. The controversial results obtained in this analysis may be explained by the class aggregation made to obtain better statistical significances.

Relatively to the accident location, inside towns accidents have a lower chances of severe injuries (49.1% of risk reduction), than outside town accidents.

Worst luminosity conditions corresponds to a 43.86% increase of severe injury chances, comparing to good luminosity conditions.

Highways, main and complementary itineraries are more likely to result in severe injuries than the other types of road (221.37% increased risk compared to streets).

Older than 60 years old cyclists are more likely to suffer severe injuries in case of an accident, with an increased risk of 113.51%, compared to 0 to 40 years old cyclists.

During a maneuver, cyclists are 35.15% more likely to sustain a severe injury than a regular forward ride.

Helmet non-use corresponds to a 136.14% increased risk of severe injuries, compared to helmet use.

BAS between 0.5-0.8 g/l have the highest risk of severe injuries with a 347.92% increased risk, compared to BAS between 0.0-0.05 g/l.

Collision with trucks have the highest risk of severe injuries, with a 134.8% increased risk, compared to collision with cars.

When the other driver gets severely injured, cyclists have more risk to sustain severe injuries. The risk increases 1611.8% when compared to unharmed drivers.

Table 2 - Results from the ordered regression (OR (CI of 95%) and statistical significance)

Variables	Classes	OR	Confidence interval of 95%		P-value	Chance variation
Type of Nature	Single vehicle accidents	1.617	2.371	1.103	.014	61.70%
	Collision + Collisions with pedestrians					
Grip	Other road conditions	0.779	1.049	0.578	.100	-22.14%
	Clean and dry road					
Weather	Other weather conditions	1.542	2.255	1.055	.025	54.21%
	Good weather					
Location	Inside urban area	0.509	0.656	0.395	.000	-49.11%
	Outside urban area					
Luminosity	Night	1.439	1.779	1.164	.001	43.86%
	Day					

Variables	Classes	OR	Confidence interval of 95%		P-value	Chance variation
Road type	Other typed of roads	1.594	2.175	1.168	.003	59.41%
	Highways, Complementary itinerary and Principal itinerary	3.214	6.291	1.642	.001	221.37%
	National road	1.541	1.942	1.223	.000	54.11%
	Street					
Cyclist age group	≥ 61	2.135	2.652	1.719	.000	113.51%
	41-60	1.580	1.924	1.298	.000	58.02%
	0-40					
Cyclist´s action	Maneuvers	1.351	1.646	1.110	.003	35.15%
	Regular driving					
PTW driver's safety accessories	Exempt	2.004	3.218	1.247	.004	100.36%
	Without safety accessories	2.361	4.546	1.227	.010	136.14%
	With safety accessories					
PTW driver's alcohol	Not tested	7.878	9.453	6.566	.000	687.80%
	> 1.2 g/l	2.576	3.604	1.841	.000	157.57%
	0.8 - 1.2 g/l	3.013	6.058	1.499	.002	201.31%
	0.5 - 0.8 g/l	4.479	11.792	1.701	.002	347.92%
	0,0 - 0.5 g/l					
Other vehicle category	Without other vehicle involved	0.829	2.479	0.278	.738	-17.06%
	Other type of vehicles	1.077	3.815	0.304	.909	7.66%
	Bicycle and bicycle with motor	0.113	0.360	0.035	.000	-88.71%
	Moped and Motorcycle	0.405	0.829	0.198	.013	-59.52%
	Truck	2.348	3.479	1.585	.000	134.80%
	Car					
Other vehicle driver's injuries	Without other vehicle involved	0.953	3.006	0.302	.935	-4.68%
	Severe injury	17.118	72.220	4.057	.000	1611.8%
	Minor injury	4.483	7.844	2.562	.000	348.32%
	Unharmed					

III.II – Helmet use analysis

100 cyclists were inquired in person with the purpose of understanding the reasons of use or non-use of the helmet, using a TU COST 1101 inquiry.

Helmet Use

Among the inquired people, 40% always wear helmet, 2% wear it sometimes and 58% rarely or never wear it.

Helmet use varied according to the cyclist age, gender and annual cycling distance:

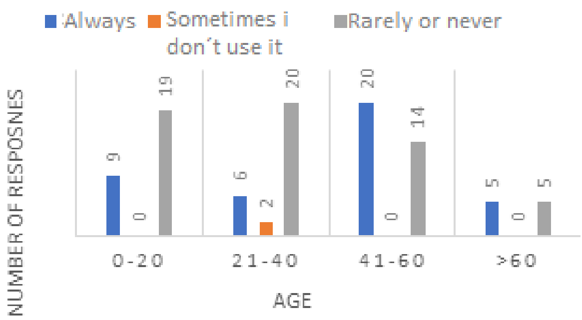


Figure 6 - Helmet use and age

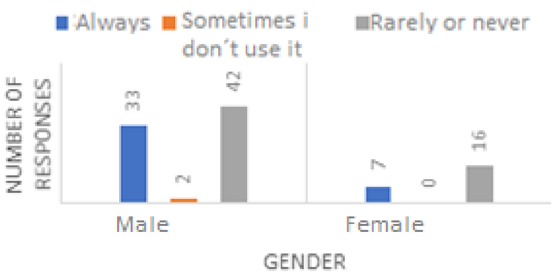


Figure 7 - Helmet use and gender

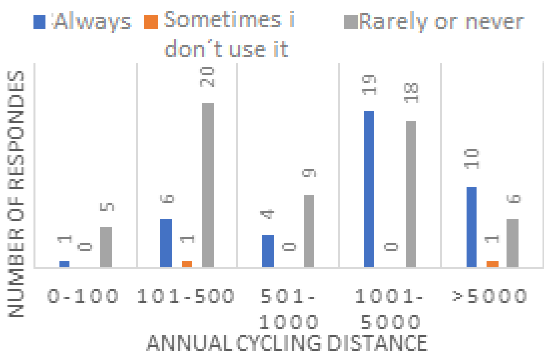


Figure 8 - Helmet use and annual cycling distance

Giving the sample inquired, ages between 41 and 60, the gender male and higher annual cycling distances had the higher helmet use percentage.

In case of mandatory helmet use law implementation, 15% admitted not to use despite being acting against the law.

The main reasons for the non-usage of helmet were head overheating, itchiness and carelessness. In the other hand, the main reasons for helmet use were safety feeling, state of habituation and automobilists´ unsafe driving.

Cyclist´s road safety

50% of the sample have experienced a bicycle accident, at least once. 36% considered bicycle driving much more dangerous, compared to driving a car.

Helmet use side effects

For this chapter of the analysis, only inquired people who always use helmet were taken to account. Round 5 admitted to have audition problems caused by the helmet and 2% confessed to have vision problems caused by the helmet. 40% attributed the sweat to the helmet presence. 2% suffer headache after its use and 21% admitted to feel discomfort caused by the buckle.

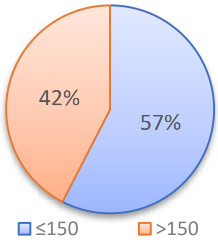
Helmet use and overtaking distances

An Arduino device was used to measure and store data regarding overtaking distances. The Portuguese law states that the minimum lateral overtaking distance is 150 cm Based on the studies Walker I. [24] and Shtogryn D. [2], a route was defined and performed, at the same speed and traffic density, not using helmet, using a black and white helmet and using a safety vest with the word “POLITE” on it. The tests were performed in a 6.2 km route in the national road EN10. The 3 different outfits are presented in the next figure:

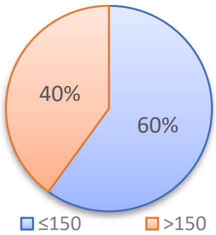
Figure 9 - Outfits tested

The results obtained are presented below, in terms of percentage of legal and illegal overtakes:

Without helmet



With helmet



With safety vest

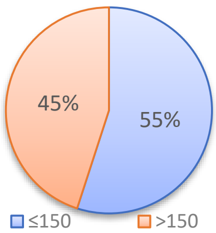


Figure 10 - Percentage of legal and illegal overtakes

IV. Real Bicycle accidents reconstruction

The helmet effectiveness in the reduction of head injuries severity and death probability, is discussed using the police information about 2 real accidents in Portugal involving cyclists. Both cases resulted in the death of the cyclist, according to INMLCF caused by fatal head injuries. For each case, a scientifically analysis were done using PC-Crash based on the police and witnesses information. This paper briefly explain them.

In the first case, a collision occurred between the right of a van and the left side of the unhelmeted cyclist/bicycle, during an overtake, as show in the following figures:

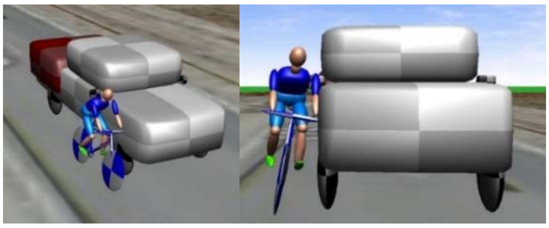


Figure 11 - Inicial collision

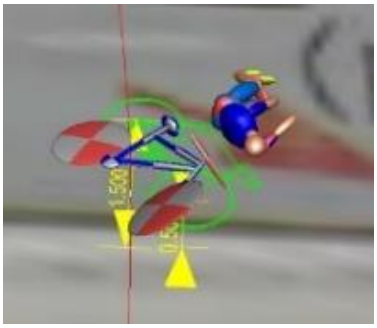


Figure 12 - Cyclist and bicycle final positions

The lack of damages in both vehicles after collision make unlikely high car speed. Given the type of road and several tests in PC-Crash, the velocity determine for the van was 50km/h and for the bicycle was 15km/h. For this last one, the cyclist´s BAS (2.02 +/- 0.26 g/l) makes unlikely higher or lower speeds. The high level of BAS was, probably, one of the accident cause. After numerous simulations, the relative impact positions were, initially, between the cyclist´s shoulder blade and the right side of the car hood/right rear view mirror. After analyzing different collisions spots, it was determined that the motor vehicle´s driver did not respect the minimum overtaking distance, causing the accident.

Using a matlab algorithm and the head acceleration it was calculated the HIC value. The result, 54.69, is related with an AIS score of 0 or 1 (Figure 1). According to James Newman et al. [45] the TBI probability is less than 5% and HIC is proximately 0 and HIP and GAMBIT values are less than 4.70 and 0.22 for helmeted impacts with the same head acceleration. So, by using helmet, the probabilities of skull damages were reduced to approximately 0% (Figure 3), mTBI to less than 20% (Figure 4) and irreversible head injuries to 11% (Figure 5). In this case, it´s not known for sure why the cyclist died, given the low probable AIS score, but helmet use would be crucial to decrease the injury severity and probably avoid the cyclist’s death.

In the second case, the cyclist was turning to his left when a passenger car is illegally overtaking him. After several PC-Crash simulations, it was determine that the car was moving at 93 km/h at the impact instant. Numerous of tests were performed to correctly obtain compatible car deformations and cyclist and bicycle final positions. The Figure 13 shows the impact instant (on the left) and the intervenients´ final positions (on the right):

Figure 13 - Impact moment and final positions

The cyclist suffer 4 different head impacts as shown below:

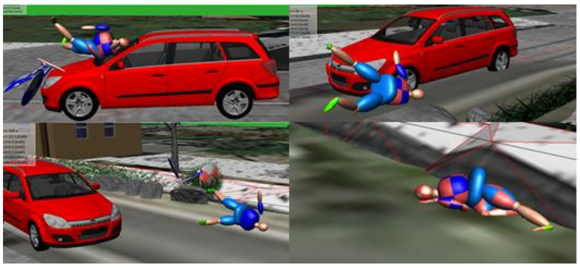


Figure 14 - 4 head impact´s moments, organized chronologically from the left to the right and top to bottom

The helmet final position was different from the cyclist final position. This fact proves that the helmet separated from the head during one of the head impacts. Given the acceleration difference between the 4 collisions of the head, it was concluded that the helmet disengaged from the cyclist during the first impact, the one with higher head accelerations.

Therefore, the first impact was analyzed as if the cyclist was wearing helmet and the following impacts as the cyclist was not wearing helmet.

The first impact resulted in a 1053.55 m/s^2 acceleration. Once again, according to James Newman et al. [45], this impact resulted in a 86% probability of TBI. The following table presents the HIC, HIP and GAMBIT values and the respectively analysis. Is worth knowing that the unhelmeted HIC value was calculated using a matlab algorithm.

Table 3 - Injury criteria analysis

Criterion	Reference vale	Value obtained	Analysis
HIC	700	Unhelmeted: 1190.94	According to Figure 1 and 2, the conclusion was that the helmet reduced the probability of head injury and death. From Figure 3, helmeted HIC presents 10% risk of skull fracture and unhelmeted presents over 50% risk of the same injury
		Helmeted: 430.60	
HIP	10 KW	Helmeted: 19.18	The HIP suggests a probability of mTBI between 80% and 100%
GAMBIT	1.0	Helmeted: 0.53	GAMBIT value indicates a 25% probability of irreversible head injury

All criteria considered, helmet use reduced the chances of head injury and its severity. However, there was still a high probability of mTBI.

The analysis of the next impacts is difficult because there´s no way to know for sure the physical damages of the cyclist head after the first impact. However, if the helmet was still attached to the cyclist´s head, the probability of head injury was 56%, which still is a high value. Consequently, it is concluded that the 3 impacts after the first one, only aggravated the injury previously suffer.

It´s worth knowing that the acceleration of the first impact shouldn't be enough to break the helmet or its buckle. Therefore, it is assumed that the helmet was not being used correctly.

V. Conclusion

From the statistical analysis, using the ANSR database, it is concluded that the risk factors associated to the use of bicycle in Portugal are single vehicle accidents, outside town, highways, main and complementary itineraries and night period (bad light conditions) cycling. Over 60 years old, maneuvers, BAS from 0.5 g/l to 0.8 g/l, truck collisions and severe injuries of the other driver are more likely to result in cyclists´ severe injuries.

It is concluded that increasing car´s velocity results in the aggravation of cyclists´ injuries in case of an accident. It is suggested campaigns to sensitize motor vehicle drivers for the vulnerability of cyclists in case of an accidents. The same measure should be applied to sensitize cyclists for the consequences of drink alcohol and drive.

The helmet is always used by 40% of the in the sample inquired. Its use was not related with decreasing visual and hearing capabilities. 40% of who always wear helmet, relates the increase of sweat to the helmet presence and 21% find the helmet buckle uncomfortable. This fact may explain the reason why some people don't tighten the buckle.

Helmet usage was related with age, gender and annual cycling distance. Ages between 0-20 and 21-40 were less likely to use helmet. This result demonstrates the need of education for the benefits of helmet use among children and young adults. The biggest the annual cycling distance the highest was the probability of helmet use. This fact is explained by the high levels of experience of those who cycle the most. The greater the experience, the greater the cyclist self-awareness to cycling dangerous and helmet use benefits. Since the main reason for the helmet use were the habituation regarding its use, it's suggested the implementation of mandatory helmet use law for children, in order to make them used to it and perpetuate its use in future generations.

From the investigation of overtaking distances and the influence of helmet use, it is concluded that the helmet use produces no difference in the overtaking distances. There wasn´t a significant difference in helmeted and unhelmeted results. Furthermore, the presence of a reflective safety vest did not influenced the overtaking distances. Therefore, it is concluded that the cyclist probably cannot manipulate overtaking distances by changing their appearance.

From the 2 real cases analysis, it is concluded that helmet use could probably save the cyclist life in the first accident and reduce the fatality chances in the second one. Both accidents results of illegal motor vehicle driving, where cyclist´s road space was not respected. The second case shows how important is the right use of the helmet in order to guarantee its maximum effectiveness. To minimize helmet misuse and maximize its usage among the population, it is suggested design and comfortability improvements.

Cyclists´ road safety in Portugal, in a time of popularization of the bicycle, will depend on the effect of safety in numbers. To achieve this, it is necessary to introduce laws that protect the cyclist from collisions, in which he is the most vulnerable intervenient and the best way for protection is defensive cycling and helmet use.

Acronyms

HIC – Head Injury Criterion

ANSR – Associação Nacional de Segurança Rodoviária

AIS – Abbreviated Injury Scale

BAS - Blood Alcohol Scale

HIP – Head Impact Power

INMLCF – Instituto Nacional de Medicina Legal e Ciência Forense

SI – Severity Index

mTBI – Mild Traumatic Brain Injury

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