Injury analysis and reconstruction of Powered Two Wheelers accidents

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Abstract - The number of road accidents in Portugal has decreased significantly in the last decades, however, this tendency is not similar in all types of transportation. In the most recent years and by European standards, Portugal is still one of the leading countries concerning the number of fatalities in Powered Two Wheelers (PTW) accidents. To this effect, the in-depth investigation of PTW accidents is crucial and so, a thorough statistical analysis concerning the main factors influencing PTW riders injury severity accidents was undertaken regarding the 2007-2010 period in the National Road Safety Authority (ANSR) injured riders database using the software SPSS. In addition, to determine the importance of absent factors in the database analysis, such as velocity, a set of 53 real accidents involving PTW were also investigated and computationally reconstructed using the software PC-Crash. Lateral collisions between a motorcycle, its rider and the side of three different passenger cars were also simulated, varying the motorcycle impact angle and velocity in order to estimate the PTW deformation energy and the rider's injuries, as this accident configuration stands out in terms of frequency and even severity. The results of this detailed study are presented.

NOTATION

a linear acceleration
AIS Abbreviated Injury Scale
E_D deformation energy
HIC Head Injury Criterion
m mass length
t time
v velocity

INTRODUCTION

The 2009 global status report on road safety conducted by the World Health Organization [1] states that injuries resulting from road traffic accidents are a public health problem and an impediment to development, being expected, if immediate measures are not implemented, that road accidents will become the 5th leading cause of death in the world by 2030. Despite the recent year's reduction in road accident numbers verified in Portugal, it has not been reflected so distinctly among Powered Two-Wheelers (PTW), which still represent concerning numbers of road accidents and among PTW, motorcycles stand out in terms of accidents severity.

Figure 1 shows the evolution in the number of deaths linked with PTW in the European Union with 15 Member States (excluding Luxembourg because of its small numbers) up to the available 2010 data according to the latest CARE database statistics [2]. From this perspective is clear that even having a continuous improvement since 2000, Portugal still constitutes one of the worst cases in terms of PTW accidents in the most recent years, lagging behind the European average and around the same level as or below larger countries.

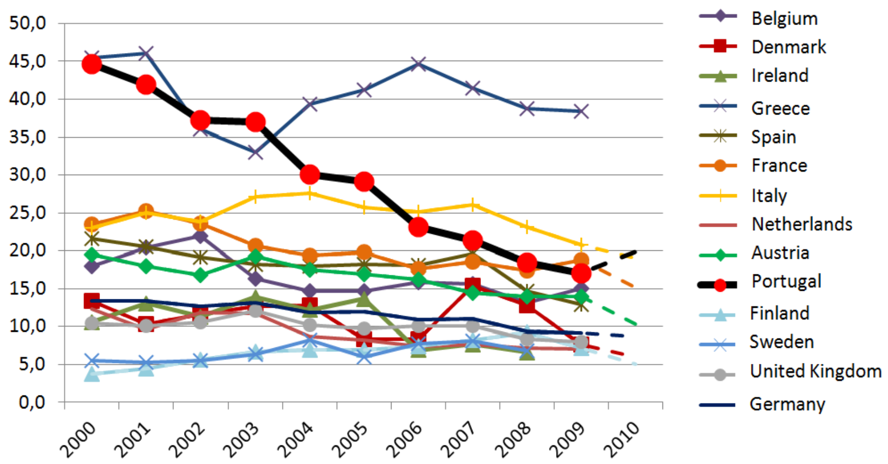


Figure 1. Number of fatalities with PTWs for a million of habitants (2000-2010), source CARE [2].

In 2010 alone, in mainland Portugal, 35426 casualties in road accidents occurred, resulting 741 deaths, from which 24% were PTW riders and passengers, with motorcycles standing out as the transport mode that presents the largest ratio of fatalities per 100 accident victims, overcoming even passenger cars, though the number of motorcycles in Portuguese roads is much lower [3]. It follows that PTW accidents severity in Portugal is a real problem that demands the development and implementation of specific road safety measures. Through the statistical analysis of road accidents one can determine patterns and identify the determinant factors in the occurrence and severity of accidents, and in this particular case, of PTW accidents. The in-depth study of these specific accidents, resorting to scientific methods and namely, the use of computational models, allows the increase of knowledge in this particular field in order to evaluate tendencies, isolate problems and areas where taking actions is a priority and supports the development of effective countermeasures to improve PTW users' safety.

STATISTICAL ANALYSIS OF PTW ACCIDENTS

A retrospective analysis of the ANSR's database of PTW users injured in accidents occurred between 2007 and 2010 in mainland Portugal [4] was carried in order to characterize the PTW accidents severity problem in Portugal and determine the main factors among vehicle, human, environmental and geographical factors, as well as the accident's nature potentially associated with severe injury risk. After the exploratory statistical analysis, drawing on ANSR's database, an ordinal regression was applied using the statistical analysis software SPSS, version 19.0 to identify factors affecting PTW riders injury severity in accidents and estimate their effect. This constitutes a first approach on the application of regression methods in accident analysis and it is relevant to emphasize that there were not found previous studies undertaken in Portugal considering this kind of analysis applied to PTW accidents and its risk of accident or injury severity. The detailed explanation of the procedures considered is available in the respective report [5].

PTW accidents in Portugal from 2007 to 2010

The main results to withdraw from this analysis relate to the vehicle and the accident's typology. Among PTW, motorcycles with an engine displacement larger than 50 cm^3 and not limited to 25 kW in power or 0,16kW/kg in power to weight ratio have the highest severity index (number of deaths per 100 injured PTW users) as is shown in Figure 2.

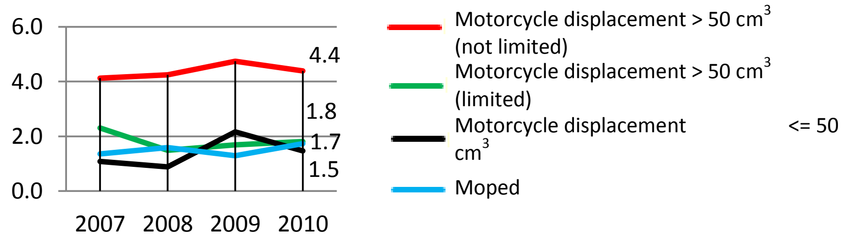


Figure 2. Severity index per PTW type, 2007- 2010.

Motorcycle riders between 25 and 34 years old and with 1 to 5 years of driving license have associated the largest number of fatalities when it comes to motorcycle accidents occurred in 2010. In the same way, for mopeds the largest number of deaths is associated with drivers of 55 years old or older and with 20 or more years of license. In 2010 also, the majority of PTW accidents occurred during the day, but the highest number of deaths is associated with accidents that happened at night. The same is verified about the weekend. In this same year the vast majority of accidents with injured PTW riders occurred in urban areas, but despite this and the fact that 57,7% and 61,5% of fatalities among motorcycle and moped drivers happened inside urban areas, the severity index is higher outside urban areas.

The motorcycles accident typology with the largest number of victims and severely or fatally injured PTW users in 2010 was “Lateral collision with another moving vehicle” followed by “Running off the road” (ROR) as can be seen in Figure 3. This was also true for moped accidents with the exception that head-on collisions overcame running off the road accidents.

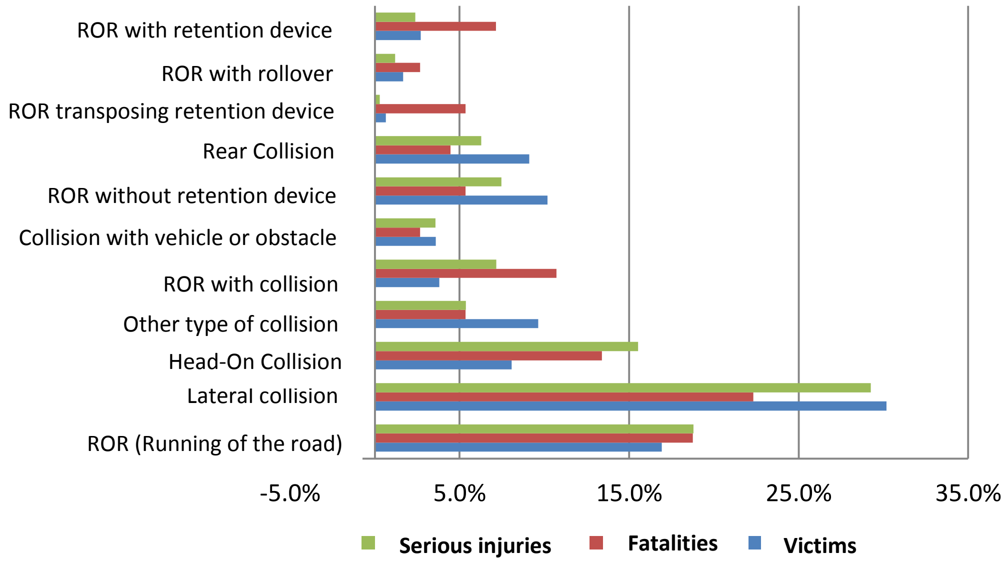


Figure 3. Victims by type of accidents with PTWs during 2010.

On the whole, the largest number of victims among users of PTWs in 2010 was due to lateral collisions.

Risk factors affecting PTW riders’ injury severity in accidents

Degrees of injury severity resulting from a crash are included in the ANSR database [4] thereby enabling the construction of a categorical variable that captures different ranks of severity following the same strategy as Albalate and Fernández-Villadangos [6]. Thus, the dependent variable contains 3 increasing degrees of severity according to police reports following the crash: no severe, severe, and fatal. The ordinal regression was then applied using a number of potential determinants as explanatory variables of injury severity to estimate the determinants of differences in the degree of accident

severity. The sample considered included only PTW drivers injured in accident, as some of the factors largely depend on human behaviour.
The theoretical background concerning regression models and in particular, ordinal regression models, is described more in detail in the literature [7] [8] and the major decisions involving the model building for ordinal regression and the optimization process are extensively described in Dias and Daniel [5].
The association between the factors in analysis and the dependent variable was measured by the resulting Odds Ratio (OR), a measure of effect size describing the strength of association between the variables and a confidence interval of 95% was considered. The statistical significance ($p<0,05$) of the results was given by the associated p-value.
The results obtained point out an association between the rider's injury severity in a PTW accident and the type of PTW as severe injuries are more likely if the PTW is a motorcycle. Actually, according to the ordinal regression model the probability of severe injuries to a driver if he has an accident riding a motorcycle is 66,2% (OR=0,662, p=0,000) higher than if he was riding a moped. The results also show that factors such as gender, helmet use, action of the rider before the accident, day of the week, time of year and light conditions affect casualty severity. If the rider is of female gender, there is more than twice the probability (OR=2,130, p=0,000) that injuries are less severe than the case of a male rider. The other factors affect injury severity raising the probability of suffering severe injuries, namely, when the rider doesn't wear a helmet (OR=0,174, p=0,000), the accident occurs at night (OR=0,624, p=0,000), weekend (OR=0.668, p=0.000) or between July and September (O=0.857 p=0.009), and the PTW was changing direction to the left (OR = 0.773, p=0.012), changing lane, (OR=0.668, p=0.000), driving in the direction of the oncoming traffic (OR=0.319, p=0.000), or crossing lanes (OR=0.388, p=0.000).

IN-DEPTH STUDY OF PTW ACCIDENTS

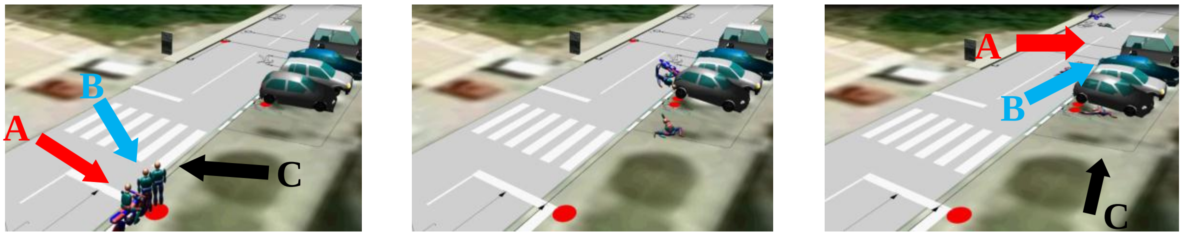
The statistical analysis of accidents allows the evaluation of road safety through time and the identification of problems, standing out as an essential tool to monitor the performance of the safety measures applied. However, fundamental information necessary to raise the level of detail and understanding of PTW accidents such as pre-impact speed, accidents cause and responsibility for its occurrence is absent, as police authorities are limited to the information they can get on the crash site. So, there is a demand for an in-depth study that enables the analysis of factors absent in a statistical analysis.
The methodology applied on the in-depth study of PTW accidents is based on the MAIDS methodology [9], following the same objectives, but in its application is similar to the study undertaken by Clarke *et al.* [10]. The computational reconstitution of accidents is treated as an optimization process, where velocities and pre-impact positions are variable parameters. The procedures include the analysis of post-accident records handled by the police authorities, such as the accident sketch, pictures of the site and vehicles, as well as autopsy reports. The next step involves building the accidents computational layout based on this data and performing the computational simulations. Then one can estimate precisely the pre-impact conditions, such as speed, position and course of the vehicles.
For the computational reconstitution of the accidents the software PC-Crash, version 8.0, an accidents reconstitution software validated among the scientific community, is used and on the present study, a set of 16 real accidents involving PTWs were investigated and computationally reconstructed using the software PC-Crash, being subsequently added to 37 previously studied accidents, resulting in a sample of 53 PTW accident cases ranging from 1998 to 2008. Given the relative small dimension of the sample when compared to other similar studies [9] [10], the statistical methods applicable to test the strength of the results is limited, so as the conclusions obtained.
The main results obtained are that sport and high capacity motorcycles riders stand out as a potential risk group and it is also noted that lateral collisions are the typical accident configuration in terms of frequency and even severity.

In-depth investigation of PTW accidents

The computational simulations of two real accidents investigated are briefly described.

Accident I

A scientific study was developed regarding a first collision in a straight road between a sports motorcycle Yamaha YZF-R6 and a pedestrian, followed by a second collision between the same motorcycle and two pedestrians on the sidewalk of an intersection located 91,39m after the first location. Due to the absence of relevant information to perform the first collision's reconstitution, only the second part of the accident was considered to this effect (figure 4). The determined velocity for the motorcycle was 113±5 km/h, which had a critical contribution to the pedestrians' injuries severity. In figure 4, the motorcycle driver is identified by A and each of the pedestrians by B and C.

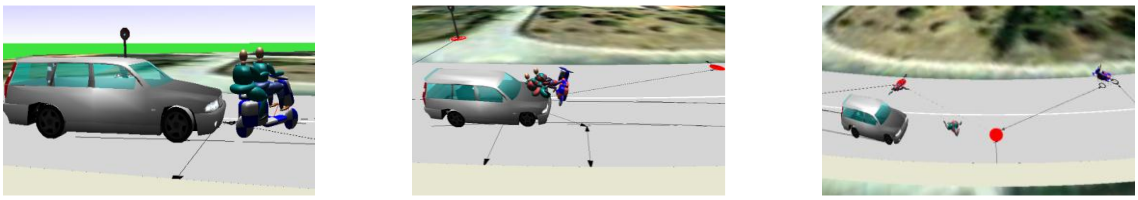


T = 0.00s Starting positions   T = 0.84s Impact moment   T = 3.17s Final positions

Figure 4. Computer simulation of the impact between the motorcycle and the pedestrians.

Accident II

A scientifically detailed study was performed regarding a rear collision between the right-front area of a passenger car and the rear of a motorcycle (figure 5). Involved in the accident were a passenger car Volvo V70 and a motorcycle Vespa 50 transporting 2 occupants. An important remark is that all the participants in the accident where under the influence of alcohol. The passenger car driver had a Blood Alcohol Concentration (BAC) of 1,44 g/l, the motorcycle driver, 0,43 g/l and the motorcycle passenger 1,15 g/l. The determined velocity of the motorcycle was 10±2 km/h and for the car, 56±5 km/h. In the first impact moment the motorcycle had an angle of 36,5º (counter-clockwise) relative to the road axis while the other vehicle was practically straight (2º). It was concluded that the accident was due to the influence of alcohol in the passenger car's driving and also because of an abrupt change of direction to the left by the motorcycle driver.



T = 0.00s Starting positions   T = 1.20s First Impact moment   T = 3.41s Final positions

Figure 5. Computer simulation of the rear collision.

IMPACT BIOMECHANICS AND INJURY CRITERIA

Impact biomechanics studies the forces acting on the human body, namely, impact forces, the effects produced by these forces and ways to reduce or eliminate the structural and functional damages on the body deriving from an impact situation [11]. In order to evaluate the PTW rider biomechanical behaviour in an impact and analyse the injuries severity based on acceleration levels obtained in the collision simulation, the software PC-Crash can be used. In its base there are the multibody dynamics fundaments, which are explained in detail in the literature [12] and on the software applied technical manual [13]. In practical terms, the injury level evaluation is done by using injury criteria applied to acceleration data withdrawn from the multibody models representing the human body in the impact simulation.

Injury criteria are a set of physical parameters correlated with the severity of the injury inflicted in the body area in analysis that indicate the potential for inducing injuries from the impact. These criteria are essential in the development of safety devices and for evaluating their efficiency. Concerning a fundamental vital area of the human body, the head, criteria to assess injuries severity in an impact such as HIC (Head Injury Criterion) are available.

Head Injury Criterion

HIC is a criterion based on the head linear acceleration evaluated, for example, from biomechanic models, in a given interval, that is computed based on the following expression:

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

In this expression (equation 1) the acceleration pulse a(t) at the head's center of mass is measured in multiples of the acceleration of gravity [g] in the time interval (t_2-t_1) that maximizes the HIC value. The maximum HIC value admitted, beyond which the resultant injuries are expected to be severe and permanent, requires t2 and t1 not to lay more than 15ms apart for a direct impact or an interval (t_2-t_1) of 36ms for an indirect one, with a HIC tolerance limit of 700 (HIC_{15}) and 1000 (HIC_{36}) for each case and considering the 50th percentile male [11] [14].

Abbreviated Injury Scale

The Abbreviated Injury Scale (AIS) is a criterion based on an anatomic scale divided in six different levels that define the kind of injury and respective severity level for each part of the human body and the higher the AIS value, the higher the respective injury severity, culminating in death. There is a direct correlation between HIC and AIS that enables the conversion of the head acceleration levels determined in computational simulations into injury severity [11] [14], which is presented in figure 6.

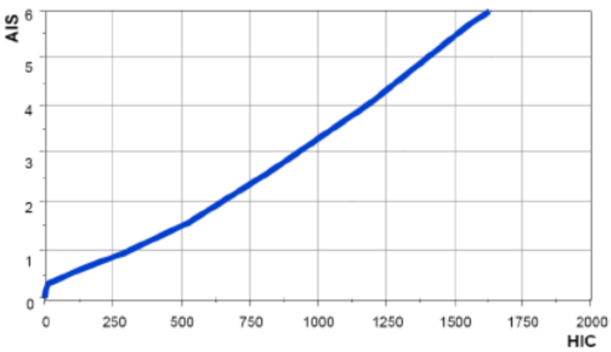


Figure 6. HIC and AIS correlation.

COMPUTATIONAL SIMULATIONS OF PTW LATERAL COLLISIONS

Given the importance of lateral collisions in PTW riders' injury severity, using the software PC-Crash, version 9.0, side impacts were simulated. The International Standard ISO13232 specifies the minimum requirements for research into the feasibility of protective devices fitted to motorcycles and is applicable to impact tests involving two-wheeled motorcycles with either a stationary and a moving vehicle or two moving vehicles. It was accessed in an indirect way through the work of Deguchi [15] and Mukherjee et al. [16] and constituted the starting point of the lateral collisions study as it defines a lateral impact between the motorcycle at a velocity of 13,4m/s (≈50 km/h) and the side of the stationary passenger car. Based on this pre-configured impact configuration, lateral collisions between a motorcycle, its driver and the side of three different passenger cars selected according to their characteristics, namely their ascending values of mass and height, were simulated by varying the motorcycle impact angle (0º and 45º) and velocity (50 km/h and 120 km/h).
In the initial stage of the impact analysis, the rigid body motorcycle model with no driver was applied in the kinematic analysis of the collision and estimate of the vehicle's deformation energy. Afterwards, the impact biomechanics analysis was undertaken applying multibody models in the computational simulation in order to obtain the rider's head acceleration and determine the corresponding HIC. For the rider's model, the anthropometric dimensions considered were a mass of 78,4kg and height of 1,755m, which correspond to the 50th percentile adult male [11] and the computational simulations were carried out considering a restitution coefficient of 0,1, a friction coefficient for the ground of 0,8, a friction coefficient between the motorcycle and the pavement of 0,6 and a friction coefficient between the human body and the ground of 0,8 [17].
The vehicles and multibody models considered and previously referred are shown next in Figures 7 and 8.

Figure 7. Model of motorcycle without rider and multibody models of motorcycle and rider.

Figure 8. Passenger car models considered, chosen by ascendig value of mass and height.

As PC-Crash doesn't allow the integration of helmet models in the simulations, an evaluation of helmet use influence on injury severity accounting for parameters like motorcycle velocity and passenger car type was done considering an empiric head injury reduction factor based on statistical results [15] to evaluate indirectly the potential reduction on the head injuries if the driver used an helmet, as presented next.

$$HIC_{Helmet} = 0.31 \times HIC_{No\ Helmet}, \quad \text{if AIS} < 6 \qquad [2]$$
$$HIC_{Helmet} = 0.58 \times HIC_{No\ Helmet}, \quad \text{if AIS} = 6 \qquad [3]$$

Results in terms of deformation energy and injury severity

A summarized exposition of the results obtained for the direct impact (0º) simulations between the motorcycle with or without rider at 50 km/h and the stationary vehicle 1 will be presented next. The complete characterization of the lateral collisions simulated, as well as all the detailed exposition of the results obtained is present in the resulting report [19]. So, the next figure shows the direct impact between the motorcycle and vehicle 1 simulation from which the deformation energy involved in the collision was estimated.

a) b) c)

Figure 9. Frames a), b) and c) of the impact simulation using the motorcycle model without rider.

Once the post impact velocities (V_f) of each vechicle are determined and as the pre-impact velocities (V_i) and vehicle masses are known initial conditions, applying the principle of conservation of energy (equations [4] and [5]) one can estimate the deformation energy ($E_{De}f$) transferred to vehicle A and B.

$$\Delta KINETIC\ ENERGY + \Delta POTENTIALENERGY + (Other\ \ types\ of\ energy) = 0 \qquad [4]$$

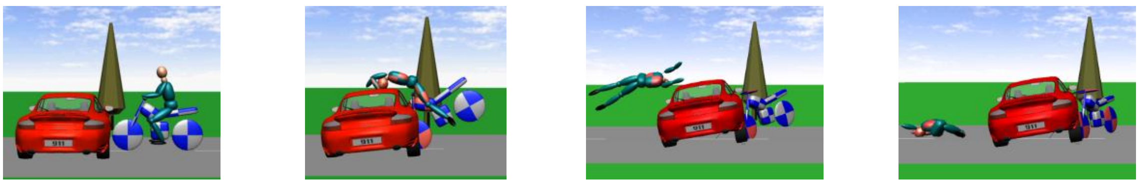
$$\frac{1}{2} m_A v_{Ai}^2 + \frac{1}{2} m_B v_{Bi}^2 = \frac{1}{2} m_A v_{Af}^2 + \frac{1}{2} m_B v_{B_f}^2 + E_{Def} \qquad [5]$$

For the current example, the initial conditions and results obtained are presented in Table 1.

Table 1. Mass, pre and post impact velocity and deformation energy for each vehicle.

Vehicle	Mass (kg)	V_i (km/h)	V_f (km/h)	E_{Def} (kJ)
Motorcycle	201	50,0	8,5	18,8
Vehicle 1	1552	0	6,0	2,2

It comes from this results that the energy transferred to the passenger car in this impact is about 11,6% of the energy transferred to the motorcycle.
Figure 10 shows an example of the simulation performed maintaining the previous conditions but applying multibody models of the motorcycle and its rider to assess the rider's injuries severity.



a) b) c) d)

Figure 10. Frames a), b), c) and d) of the impact simulation using the motorcycle and human body multibody models.

The highest acceleration pulse detected in the model's head in this simulation happens at t=0,170s, the instant in which the rider's head hits the car roof and is equivalent to 808,3 m/s^2 (82,4g). For this impact the resulting value of HIC is 566, below the 700 limit for the maximum time interval of 15 ms and corresponding to an AIS of 2, equivalent to moderate head injuries. If the rider used an helmet, the estimated potential reduction of head injuries severity results in a HIC value of 176 and an AIS of 1, reducing the injuries severity to a minor level.
Among all the cases studied, it was found that the largest share of the collision's deformation energy is transferred to the motorcycle and that there is a high probability of severe injuries to the rider. In this collision configuration the direct association between the impact velocity and the motorcycle rider's injury severity was verified. The results also suggest that helmets offer a potential reduction of injuries to the head in a 50 km/h collision, but at the top speed of 120 km/h, it has a null efficiency in terms of preventing fatal injuries.
In Table 2 the results obtained for the several impact simulations performed in terms of the passenger cars and motorcycle deformation energy (**ED_{PC}** and **ED_M**) divided according to the motorcycle's impact velocity (**V_{Mi}**) and angle (**θ**).

Table 2. Deformation energy estimated for the simulations involving each passenger car.

		Vehicle 1		**Vehicle 2**		**Vehicle 3**	
V_{Mi} (km/h)	**θ (º)**	**ED_{PC}(kJ)**	**ED_M(kJ)**	**ED_{PC}(kJ)**	**ED_M(kJ)**	**ED_{PC}(kJ)**	**ED_M(kJ)**
50	0	2,2	18,8	2,1	18,8	1,7	18,8
	45	1,2	16,9	1,2	16,9	0,9	17,0
120	0	12,2	107,7	12,0	107,7	9,7	107,7
	45	5,3	90,3	5,0	90,3	4,0	91,1

In tables 3 to 5, the HIC and AIS indices are presented for each vehicle type.

Table 3. HIC and AIS for the lateral collision between the motorcycle and vehicle 1.

		Motorcycle – Vehicle 1				
V_{Mi} (km/h)	**θ (º)**	**HIC_{15}/HIC_{36}**	**AIS**	**HIC_{Helmet}**	**AIS_{Helmet}**	**Limit HIC_{15}/HIC_{36}**
50	0	566 / -	2	176	1	700 / 1000
	45	139 / -	1	43	1	
120	0	32644 / -	6	18934	6	
	45	- / 2628	6	1524	6	

Table 4. HIC and AIS for the lateral collision between the motorcycle and vehicle 2.

		Motorcycle – Vehicle 2				
V_{Mi} (km/h)	**θ (º)**	**HIC_{15}/HIC_{36}**	**AIS**	**HIC_{Helmet}**	**AIS_{Helmet}**	**Limit HIC_{15}/HIC_{36}**
50	0	748 / -	2	232	1	700 / 1000
	45	- / 574	2	178	1	
120	0	15427 / -	6	8948	6	
	45	- / 2844	6	1650	6	

Table 5. HIC and AIS for the lateral collision between the motorcycle and vehicle 3.

		Motorcycle – Vehicle 3				
V_{Mi} (km/h)	**θ (º)**	**HIC_{15}/HIC_{36}**	**AIS**	**HIC_{Helmet}**	**AIS_{Helmet}**	**Limit HIC_{15}/HIC_{36}**
50	0	505 / -	2	157	1	700 / 1000
	45	1026 / -	3	318	1	
120	0	15139 / -	6	8781	6	
	45	4556 / -	6	2643	6	

CONCLUSIONS AND FUTURE DEVELOPMENTS

Conclusions

The human factor is the main cause for PTW accidents resulting in death or severe injuries to its driver, especially linked to speeding. Sport and large engine displacement motorcycle drivers are identified as a potential risk of severe injuries group due to the conjunction between the vehicle's performance in terms of maximum speed and the drivers' risk-taking behaviours.
Lateral collision and more specifically, the impact between the PTW and the side of the other vehicle (OV) when the OV is changing direction to the left appeared as a typical accident configuration in terms of frequency and even severe/fatal injuries to the rider, to which excess speed in the case of motorcycles and low conspicuity for mopeds must contribute.
At high velocity impacts, the main protective equipment available to PTW riders – the safety helmet – is insufficient to prevent injuries, however, helmet non-use is a crucial factor affecting injury severity increase in a PTW accident. PTW accidents resulting in more severe injuries to the rider also present a significant correlation with certain environmental factors, namely the night period, weekends and the time of the year (July to September). The rider's gender is also an important factor affecting injury severity in an accident as female riders appear significant related to lower severity.
In addition, the results obtained suggest a potential association between high injury severity of PTWs casualties if the accident occurs in urban areas, streets inside urban areas and national roads and if the rider is aged between 20 and 29 years old or owns a driving license for one to six years.
The detailed comprehension of severe accidents involving PTWs, injuries mechanisms and their distribution in the rider, translated into measurable data reveal themselves to be a valuable instrument to have a based perspective on the problem and identify the primary measures to apply, as well as in monitoring their efficiency. Preventive actions should combine education, law enforcement and engineering. Educational policies should influence and guide driving training and mainly the rider's attitude more intensively by increasing their information about risk exposure and the responsibility of their actions. Police control interventions should be focused in reducing high risk behaviours, mainly, high speed driving and intensified in times and locations identified as critical. Engineering can act in the development of systems that increase PTWs' users' safety in case of an accident, like airbags or improvement of the helmet's impact resistance and energy absorption capability and even in prevention, by increasing the PTWs conspicuity. Accidents investigation and computational reconstitution is also important to clarify the responsibility in their occurrence, causes and to support safety measures.

Future developments

In the scope of future developments it would be of great interest to set up partnerships with the Mathematics Department at Instituto Superior Técnico in order to apply advanced statistical analysis methods to road accidents data and develop improved statistical models to determine the main risk factors associated with severe accidents in Portugal; to carry out studies towards the characterization of the PTW rider in Portugal to identify the major flaws in driving abilities and attitudes that affect the accidents' occurrence; the increase of the real accidents investigated database, collecting simultaneously, as done in the MAIDS study [9], information on riders and PTWs not involved in accidents to provide comparative data and determine the relative risk in the population; to reformulate the ANSR's database in such a way that it includes specific PTW parameters such as the vehicle style and power to weight ratio and start a registry of the kilometre-based distance travelled by PTW riders to determine their effective hazard exposure; to develop optimization methods to multibody systems applied in accidents reconstitution, as the current optimization method is very time-consuming and highly dependent on the user's interaction; to perform side-impacts' and other collision configurations between motorcycles and passenger cars characterization studies, including the vehicle's structural deformation (using the software Madymo, for example) to better define injury mechanisms and levels in the rider.

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