

Pedestrian Reconstruction Tools Applied to Pedestrian Accidents in Portugal

Ricardo J.F. Portal*, João M.P. Dias*

* IDMEC – Institute of Mechanical Engineering, IST – Technical University of Lisbon, PhD. Student of Mechanical Eng. Dep., Av. Rovisco Pais, 1049-001 Lisbon, Portugal, e-mail: ricardo.portal@dem.ist.utl.pt, jdias@dem.ist.utl.pt

Abstract - Pedestrian accidents are one of the major concerns related with road accidents around the world. Portugal has one of the highest rates of pedestrian fatalities in Europe. In this paper an overview conditions were the pedestrian accidents occurred in Portugal is presented. In the last years, a project related with the pedestrian accidents has run in Portugal for the period 2004-2006 where 603 people died, 2097 have been severely injured and about 17000 slightly injured. Within this project all the pedestrian accidents in this period have been analysed providing global information about a wide range of aspects, since location, driver and pedestrian characteristics, weather and road conditions, among others. In addition, 50 in-depth accidents have been investigated and the data collected according the Pendant methodology. For this in-depth methodology detailed information about the accident has been collected, including injuries, vehicle damage, road conditions and road user's behaviour and actions. An accident reconstruction has been carried for each case including the determination of the speeds and driver actions, and the analysis of the contributing factors for the accident.

Depending of the accident complexity, different methodologies have been used to analyse these accident, from the classical analytical equations such as Simms and Woods, to the use of detailed computational pedestrian models as those included in the commercial software's PC-Crash[®] or Madymo[®]. Also one of the goals of our investigation is the development of multibody models and methodologies for the reconstruction of pedestrian accidents. Some of these tools integrated in the commercial software Cosmos Motion[®] are presented. The advantages of the different approaches are compared and discussed for some of the accidents investigated. With these tools the impact speed can be determined from the projection distance with analytical tools or PC-Crash[®], but more complex tools should be used to determine speed from the injuries, what is especially important for fatal accidents. The influence of the vehicle geometry and stiffness characteristics is another aspect analysed, where the influence of the vehicle stiffness has been determined using a combined multibody-finite elements approach within the software Madymo[®].

NOTATION

CARE	European Road Accident Database
SafetyNet	European Road Safety Observatory
ANSR	<i>Autoridade Nacional Segurança Rodoviária</i> (Portuguese Authority for Road Safety)
PARA	Project " <i>Peões, Atropelamentos e Reconstituição de Acidentes</i> " (car-to-pedestrian accident reconstruction)
V	Striking velocity
μ	Average coefficient of friction for pedestrian sliding on the ground
d_T	Throw distance
h	Pedestrian centre of mass's height
a	Acceleration
M_{EP}	Vehicle and pedestrian mass relation
d_f	Distance travelled by the pedestrian during fall
d_s	Distance travelled by the pedestrian during slide
V_s	Impact velocity at the pedestrian rest position

INTRODUCTION

In 2006, according to the CARE Database [1], 42953 fatalities occurred on European road accidents (EU-27). The last accident data available, SafetyNet [2], shows that, in 2005, accidents related to pedestrians represents 17.5% in the total number of road traffic European fatalities (EU-18), Figure 1 shows the pedestrian fatalities as a percentage of total fatalities. Between 1991 and 2006, Portugal (comparing with the other European countries) achieved the best results with regard to reduce its fatalities on road accidents (81%), Figures 2 and 3. Contradicting this fact, Portugal is one of the countries where this problem is more serious, according to ANSR [3], in the year 2007, 974 (correcting for 30 days with 1.14 factor) people lost its lives in Portuguese roads and 3116 suffer

severe injuries, that represents a slight increase in statistics, comparing to 2006. Pedestrian impacts represent 16% of those fatalities, more specifically, 157 fatal injuries (with correction factor) and 619 pedestrians severely injured. 64% of pedestrian fatalities and 86% of severe injuries occurred inside urban areas. The fatality reduction that Portugal achieved lead to the anticipation (in one year) of the main goal that the European Commission transport policy [4] established for 2010. In order to fulfil a more specific objective where a 60% reduction in the number of deaths of pedestrians (registered in the triennial 1998-2000) is established as a goal, the necessity of understanding the causes of road accidents becomes more important. Road accident reconstruction could answer this necessity by developing specific formulations and methodologies that are able to represent the accidents realistically.

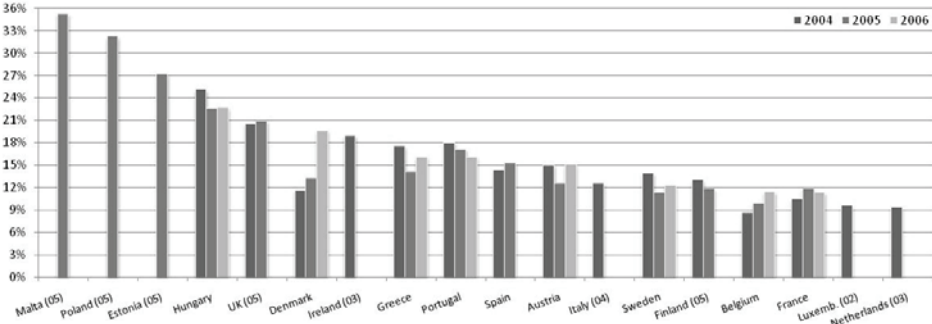


Figure 1. Pedestrian fatalities as a percentage of total fatalities: (02) data from 2002; (03) data from 2003; (04) data from 2004 and (05) data from 2005

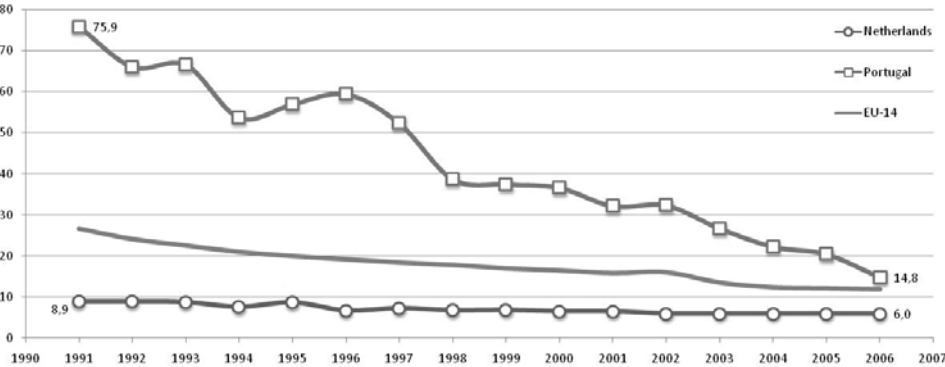


Figure 2. Fatalities per million inhabitants

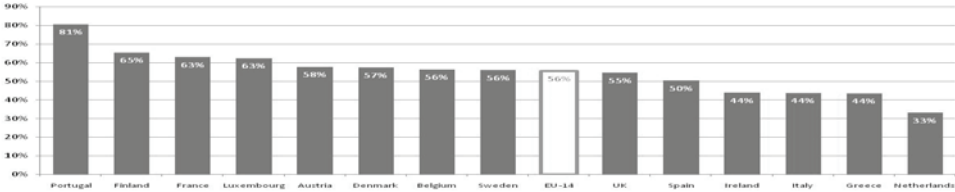


Figure 3. Pedestrian fatalities reduction, between 1991 and 2006, (EU-14)

Within the project PARA¹ the pedestrian accidents between 2004 and 2006 have been analysed providing global information about a wide range of aspects, since location, driver and pedestrian

¹ Peões, Atropelamentos e Reconstituição de Acidentes (Project Pedestrian accident reconstruction) www.dem.ist.utl.pt/acidentes/para

characteristics, weather and road conditions, among others. In addition, 50 in-depth accidents have been investigated and the data collected according the Pendant methodology. For this in-depth methodology detailed information about the accident has been collected, including injuries, vehicle damage, road conditions and road user's behaviour and actions. An accident reconstruction has been carried for each case including the determination of the speeds and driver actions, and the analysis of the contributing factors for the accident. One of the main conclusions of the PARA Project is the characterization of the typical car-to-pedestrian.

Portuguese car-to-pedestrian accident

The usual pedestrian collision occurs inside urban areas between 6 pm and 9 pm, normally on a straight road and with good weather conditions. The typical accident victim is typically an elderly male pedestrian, with 65 or more years old. In the majority of the cases, the pedestrian only suffers slight injuries and it is hit most often in places intended for crossing. The vehicle driver isn't under alcohol effect and drives a passenger car, usually speeding. Pedestrian behaviour has found to be the major cause of pedestrian accidents, but the speed of the impact vehicle represents has a primary role in about 70% of the fatalities. About 80% of the fatalities are caused by a car, but heavy trucks are overrepresented in the sample, representing about 14% of the fatalities. Motorcycles represent the remaining 6% of the fatalities.

ACCIDENT RECONSTRUCTION METHODS

Accident reconstruction involving pedestrians can be complex and, in general, requires the use of three-dimensional biomechanical models of the human body [5]. Multibody dynamics has been used in the development of these models successfully [6-12]. The commercial software that allow biomechanical analysis are very expensive, for that reason the development of vehicle and pedestrian models and its use in computational tools based in multibody [13] systems dynamics are essential, [14-16].

Depending of the accident complexity, different methodologies have been used to analyse it, from the classical analytical equations, to the use of detailed computational pedestrian models as those including in commercial software PC-Crash[®] [17] or Madymo[®] [18]. The advantages of the different approaches are compared and discussed for some of the accidents investigated. With these tools the impact speed can be determined from the projection distance with analytical tools or PC-Crash[®], but more complex tools should be used to determine speed from the injuries, what is especially important for fatal accidents. The influence of the vehicle geometry and stiffness characteristics is another aspect analysed, where the influence of the vehicle stiffness has been determined using a combined multibody-finite elements approach using Madymo[®].

Analytical Methods

Car-to-pedestrian accidents are investigated for at least half a century. Several analytical methods are developed by many authors. Eubanks and Haight [19], in addition of addressing the typical sequence of events in a car-to-pedestrian accident and the relation between the striking velocity and the pedestrian trajectory, also resume several techniques to calculate vehicle impact velocities, some of these methods are summarized by

Table 1.

Wood *et al* [20] developed an analytical method considering three phases for pedestrian collision, both for wrap and forward projections. Brach and Han [21] also had developed a throw model for frontal pedestrian collisions that takes into account the road slope.

Computational Methods

As mentioned before, the analytical methods have limitations when the accident is more complex, or when the accident data as not been correctly collected or is some important data is unavailable, or even when these methods cannot be applied due to the complexity or parameters to be determined from accident reconstruction.

Schmidt and Nagel [22] [m/s]	$V = \sqrt{\mu^2 h + 2\mu g d_c - \mu h}$	V is the striking velocity μ is the average coefficient of friction for pedestrian sliding on the ground d_c is the throw distance h is the pedestrian centre of mass's height
Stcherbatcheff [23] [m]	$d_c = \frac{v^2}{2a} + \left(\frac{3}{100} v a\right)$	a is the acceleration
Collins [24] [m]	$d_c = \frac{v\sqrt{h}}{7.97} + \frac{v^2}{254\mu}$	
Searle [25] [m/s]	$V_{min} = \sqrt{\frac{2\mu g d_c}{1 + \mu^2}}$ $V_{max} = \sqrt{2\mu g d_c}$	V_{min} is the minimum impact velocity V_{max} is the maximum impact velocity
Simms and Wood [26] [m/s]	$V = M_{cp} (A \times \sqrt{d_c} + B)$ $V = C M_{cp} (d_c - S_0)^D$	$M_{cp} = \frac{M_{car} + M_{pedestrian}}{M_{car}}$ If masses aren't know use unitary M_{cp} A,B,C,D and S_0 are experimental parameters
Northwestern University [27] [fps]	$d_f = 2\mu h - 2h \sqrt{\mu^2 - \frac{\mu d_c}{h}}$ $d_s = d_c - d_f$ $V_f = d_f \sqrt{\frac{g}{2h}}$ $V_s = \sqrt{2a d_s}$	d_f is the distance travelled by the pedestrian during fall d_s is the distance travelled by the pedestrian during slide V_s is the impact velocity at the pedestrian rest position
Eubanks (carry, fall and slide) [fps]	$V = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$	$A = (0.4 + \mu)^{-1}$ $B = \frac{d_{hood}}{V_{pedestrian} \sin\Phi} + \sqrt{\frac{h_{hood}}{16.1}}$ $C = -d_c$

Table 1. Analytical Methods to calculate vehicle striking speed on car-to-pedestrian accidents

Car-to-pedestrian collision with COSMOSMotion®

Lima *et al* [9] developed a simple pedestrian model using the CAD software Solid Works® an integrated with the add-in **COSMOSMotion**®. Only the front shape of the vehicle is modelled, even so the model has the same mass and ground height of the real vehicles. Figure 4 shows the vehicle models, being vehicle 1 a small passenger car and the vehicle 2 is an SUV. Car-to-pedestrian collision was considered frontal, in the medium line of the vehicle, and consequently, the front traversal curvature of the vehicles is neglected.

The choice of those vehicles is due to the fact that it exemplifies different impact heights on pedestrian's leg. The simulations are performed at different collision speeds: 30, 50 and 70 km/h.

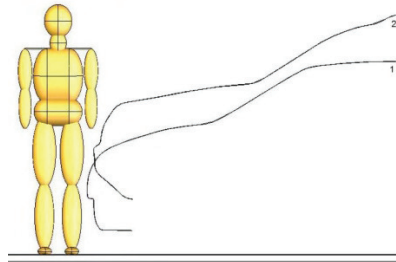


Figure 4. Vehicle front form representation: (1) small passenger car and (2) SUV.

Figures 3 and 4 shows the trajectory of the pedestrian from the impact to the rest position, for both simulations.

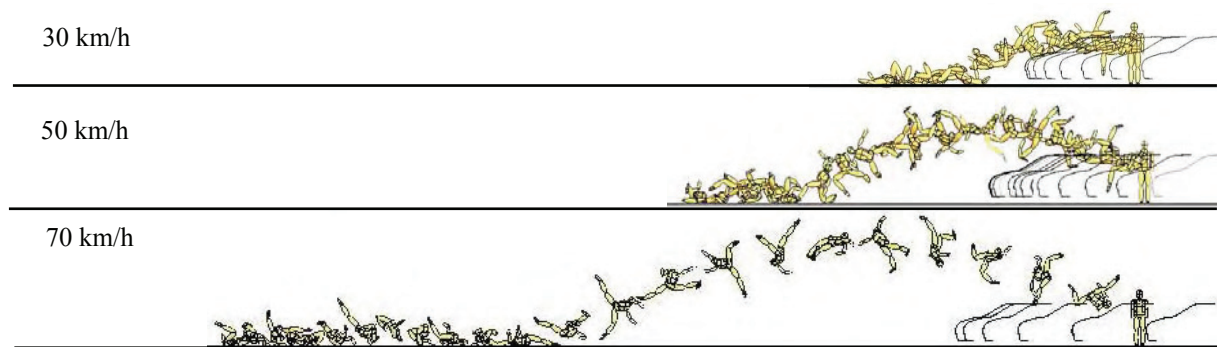


Figure 5. Small passenger car simulation

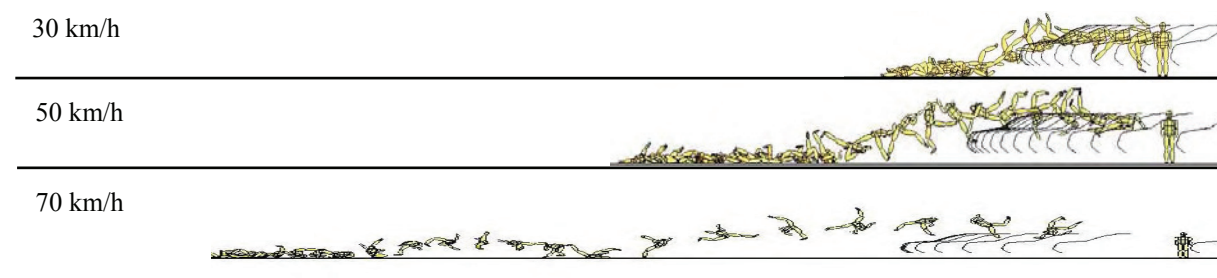


Figure 6. SUV vehicle simulation

	Impact Speed [km/h]	Projection Distance [m]		
		PC-Crash	COSMOS Motion	error [%]
Small passenger car	30	6.2	7.2	16.1
	50	14.4	13.5	6.3
	70	30.7	29.9	2.6
Off-road vehicle	30	7.9	8.6	8.9
	50	17.6	18.5	5.1
	70	28.9	33.6	16.3

Table 2. Pedestrian model results: PC-Crash[®] and COSMOSMotion[®]

As depicted on

Table 2, results obtained are suitable to determine the impact speed in a car-to-pedestrian accident reconstruction. Concerning its limitations, this model should be used in the same conditions as analytical models, having the advantages of consider pedestrian characteristics and enabling an animated simulation.

Car-to-pedestrian collision with PC-Crash[®]

With PC-Crash[®] one can reconstruct more complex accidents, using multibody dynamics formulations. This model allows simulating complex pedestrian accidents [28]. It allows to perform car-to-pedestrian accident reconstructions, for instance, the accident depicted by Figure 7, has some capabilities for accident reconstruction that are not or are difficult to include in analytical methods present above, as the pedestrian hit position or the road slope. Multibody dynamics allows determining the impact speed (45 km/h) and several biomechanical indexes that permit the correlation between them and the medical report, and then to evaluate the pedestrian hit position that in this case has been proved to be on the pedestrian crossing.



Figure 7. Car-to-pedestrian (1) real accident simulated on PC-Crash[®]

Other accident reconstruction performed with PC-Crash[®], carried out by Paula [30] shows the correlation between vehicle deformation, pedestrian thrown distance and traces of blood registered by the police. In

Figure 8 the wrap projection of the pedestrian is shown and in Figure 9 the pedestrian rest position is presented that correlates with the rest position of the body.



Figure 8. Car-to-pedestrian (2) real accident simulated on PC-Crash[®]

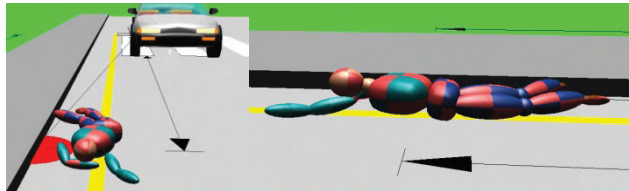


Figure 9. Car-to-pedestrian (2) pedestrian rest position

The software PC-Crash[®] can with good precision be used to determine hit position of pedestrians and impact speed of the vehicles specially for accidents involving cars and trucks.

Car-to-pedestrian collision with Madymo[®]

When the accident characteristics are too complex or what is to be evaluated requires high precision, more sophisticated models can be used. Therefore, a model that takes into account vehicle deformation and enables the rigorous determination of biomechanical indexes are necessary. One of such models is that developed by Freitas [31] and presented by Freitas *et al* [11], that uses a finite element – multibody dynamics approach implemented in Madymo[®] software. The vehicle' front has been developed using the finite elements method and is a simplification of the real vehicle, i.e., just the necessary components of the vehicle front are modelled. This method can be applied to a wide range of vehicles, known its exact shape, but for the structural characteristics such as the bonnet is not easy because, in general, this characteristics are not known.

Pedestrians' models are the anthropomorphic Pedestrian 50th percentile of Madymo[®] library, 6 YO child dummy, female and male dummies,

Figure 10. With these models there were performed car-to-pedestrian collision simulations and the results compared with PC-Crash[®], with the scenario configuration as depicted by Figure 11, the vehicle striking velocity was 40 km/h.

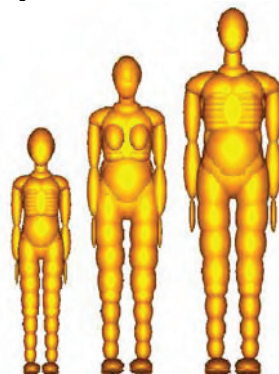


Figure 10. Madymo[®] anthropomorphic 50th percentile dummies

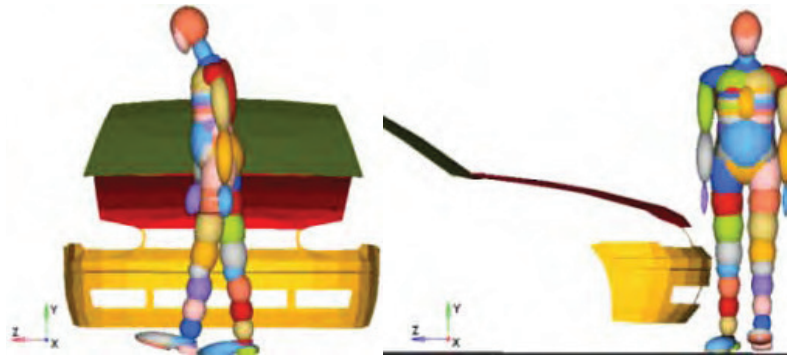


Figure 11. Madymo® car-to-pedestrian collision configuration

The results for these simulations are presented in **Fehler! Verweisquelle konnte nicht gefunden werden.**, illustrating the kinematic of the human body and the major impact zones.

Results are compared with similar simulations performed on PC-Crash® and by Simms and Wood method [26], and gathered on

Table 3. It can be observed that the projection distances obtained are shorter than that obtained with Pc-Crash, and within the limits obtained using the Simms and Wood method. The differences of the results concerning projection distance between Madymo models and Pc-Crash are coherent, because in Madymo models due to the deformation of the front components of the vehicle, the kinetic energy gathered by the pedestrian is lower and consequently the projection distances are lower.

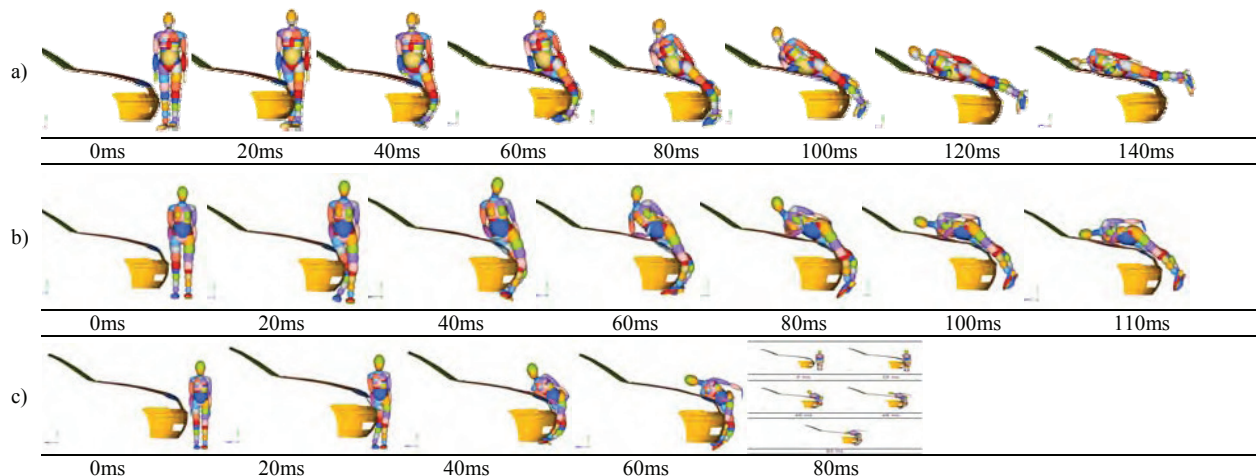


Figure 13. Madymo® car-to-pedestrian collision simulation: a) 50th percentile male dummy; b) 50th percentile female dummy and c) 50th percentile 6 YO child dummy.

Striking Velocity 40 km/h	Madymo®		PC-Crash®		Simms & Wood
	HIC	Throw Distance [m]	HIC	Throw Distance [m]	Velocity
Male	2430	10,7	1167	16,78	38,31 – 43,56
female	4741	11,56	1432	14,51	39,26 – 44,52
child	491,7	13,64	4584	17,19	40,14 – 45,30

Table 3. Car-to-pedestrian results

The details of the contact for Madymo models and Pc-Crash are presented in Figure 12.

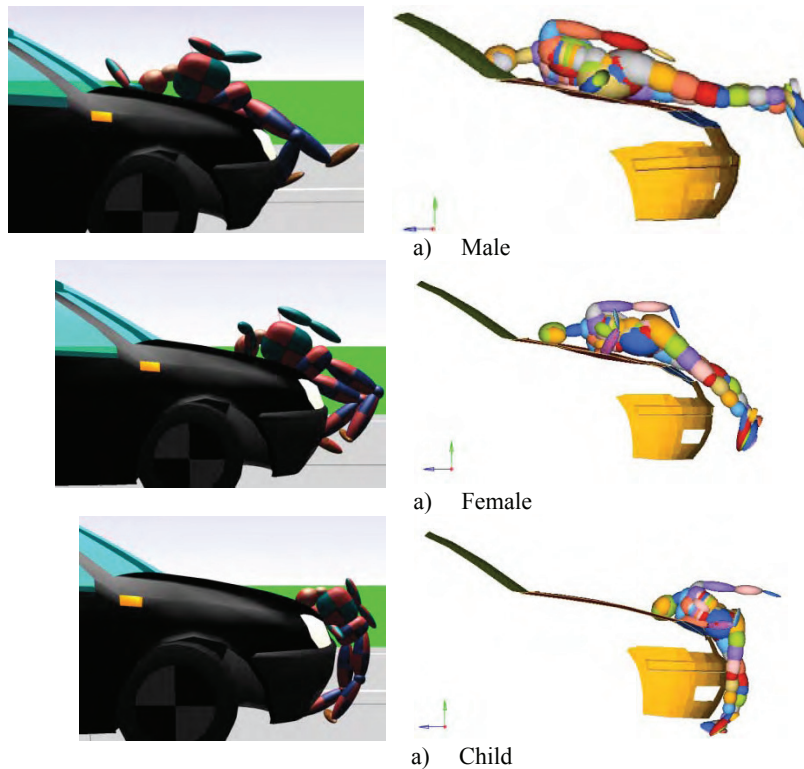


Figure 12. Illustration of the contact between the pedestrian and vehicle for *PC-Crash* (left) and *Madymo* (right).

Concerning the HIC values, with Madymo models lower values for the male and female models have been obtained, and for the child model the opposite is verified. This can be explained by two causes. One is the deformation of the vehicle and high rigidity of the vehicle near the bonnet extremity and windshield frame. For the child model the deformation of the bonnet during the head impact reduces substantially the accelerations and consequently the HIC index.

CONCLUSIONS

Pedestrian accident reconstruction can be performed with simplified models or with more complex ones, the choice that the reconstructionist must do relates with the accident complexity, the amount of information that he have and the predicted accident configuration.

Analytical methods prove to give accurate results for specific and simpler accident scenarios, mainly to determine impact speed and allow a fast way to determine a start value for the investigation. When the reconstructionist needs to solve more complex accidents, he has to use different formulations that enables the correlation between skid marks, vehicle and pedestrian rest positions, energy dissipation and evidences gathered at accident scene. In these cases, becomes mandatory that experts in accident reconstruction use software like PC-Crash[®] and/or Madymo[®]. In this work a Madymo model that includes the vehicle deformation during the impact as been presented. This model can be very useful for accident reconstructions were injury indexes have to be correlated with the injuries recorded in medical reports, or for the development and evaluation of the vehicle characteristics for pedestrian protection.

ACKNOWLEDGEMENTS

The authors thank the support granted by the Portuguese Foundation for Science and Technology (FCT), with the financing of the scholarship BD/ 26013/2005. Also the support of Allianz Portugal, DGV (Portuguese Directorate-General for Traffic) and PRP (Road Safety Prevention Institute) are gratefully acknowledged.

REFERENCES

- [1] CARE, European Road Accident Database, Road safety evolution in EU, December 2007.
- [2] Safety Net, Traffic Safety Basic Facts 2007 – Main Figures, European Road Safety Observatory (www.erso.eu). October 2007.
- [3] Road Safety Observatory, “Sinistralidade Rodoviária – Ano de 2007”, Autoridade Nacional Segurança Rodoviária (ANSR) (www.ansr.pt), Portugal, April 2008.
- [4] European Commission White Paper, European transport policy for 2010: time to decide, 2001.
- [5] J. Yang, Crash Analysis – The Pedestrian Accident Reconstruction, Chalmers University of Technology, Göteborg, Sweden, 2002.
- [6] M.T.Silva, J.C.Ambrósio, “Pedestrian Impact and Run Over Using a Multibody Simulation Tool”, International Journal of Crashworthiness, Vol. 4(3), pp. 261-271, 1999.
- [7] M.T.Silva, J.C.Ambrósio, M.S.Pereira, “Biomechanical Model with Joint Resistance for Impact Simulation”, Multibody System Dynamics, Vol. 1, pp. 65-84, 1997.
- [8] P.M.Lima, R.F.Portal, J.P. Dias, “Modelos Biomecânicos Simplificados Baseados na Dinâmica de Sistemas de Corpos Múltiplos para a Reconstituição de Acidentes com Atropelamento”. Congresso de Métodos Numéricos em Engenharia. Granada, Spain, July 4-7 2005. (in Portuguese)
- [9] P.M.Lima, R.F.Portal, J.P. Dias, “Models for Pedestrian Accident Reconstruction”. II International Conference On Computational Bioengineering. H. Rodrigues *et al.* (Eds.). Lisboa, Portugal, September 14-16, 2005.
- [10] R.F.Portal, J.P.Dias. “Multibody Models For Vehicle Accident Reconstruction”. ECCM 2006 – III European Conference on Computational Mechanics – Solids, Structures and Coupled Problems in Engineering. C.A. Mota Soares *et al.* (eds.). Lisbon, Portugal, June 5–8, 2006.
- [11] A.C.Freitas, R.F.Portal, J.P.Dias, “Simulação de atropelamentos com base na teoria dos elementos finitos e da dinâmica de corpos múltiplos para avaliação de lesões e distâncias de projecção”, CMNE/CILAMCE 2007, Page 74, Oporto, Portugal, June 13-15, 2007. (in Portuguese)
- [12] J.P.Dias, R.F.Portal, A.C.Freitas, “Causas da sinistralidade pedonal em Portugal e medidas para a sua redução”. V Congresso Rodoviário Português. Estrada 2008 – Sistemas Inteligentes, Logística e Turismo. Centro de Congressos do Estoril, Estoril, Portugal. March 12-14 2008. (in Portuguese)
- [13] P.E.Nikravesh, Computer Aided Analysis of Mechanical Systems, Prentice-Hall, Englewood Cliffs, NJ, 1988.
- [14] R.F.Portal, J.P.Dias, “Road Accident Reconstruction Based on Multibody Dynamics”. Multibody Dynamics 2007 - ECCOMAS Thematic Conference. C.I. Bottasso, P. Masarati, I. Trainelli (eds.). Milan, Italy, June 25-28 2007. Page 285.
- [15] R.F.Portal, J.P.Dias, “Modelos de Corpos Múltiplos para a Reconstituição de Acidentes Rodoviários”. Conferência Nacional de Dinâmica de Sistemas Multicorpo – DSM2007. Paulo Flores e Miguel Silva (eds.). Departamento de Engenharia Mecânica, Universidade do Minho. Guimarães, Portugal, Pages 165-172. December 6-7 2007. (in Portuguese)
- [16] R.F.Portal, J.P.Dias, “Multibody Dynamics Methodologies for Road Accidents”, 8th World Congress on Computational Mechanics (WCCM8) and 5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008). B.A. Schrefler e U. Perego (eds.). Venice, Italy. June 30 – July 5 2008.
- [17] Datentechnik, S., PC-Crash, A Simulation program for Vehicle Accidents, Operating Manual, Version 7.3, Linz, Austria, November 2005.
- [18] TNO, Madymo v6.2 Theory Manual, Delft, Netherlands, June 2004.
- [19] J.J.Eubanks, W.R.Haight, “Pedestrian Involved Traffic Collision Reconstruction Methodology”. Society of Automotive Engineer. Paper 921591, 1992.
- [20] D.P.Wood, C.K.Simms, D.G.Walsh, “Vehicle-pedestrian collisions: validated models for pedestrian impact and projection”, Proc. IMechE. Vol. 219 D: J. Automotive Engineering, 2005.
- [21] I.Han, R.Brach, “Throw model for frontal pedestrian collisions”, SAE. 2001-01-0898, 2001.
- [22] D.N.Schmidt, D.A.Nagel, “Pedestrian Impact Case Study”, Proceedings of 15th Conference Association for Automotive Medicine, 1971.
- [23] G.Sticherbatcheff *et al.*, “Simulations of Collisions between Pedestrian and Vehicles using Adult and Child Dummies”, SAE 751167, 1975.
- [24] J.C.Collins, J.L.Morris, “Highway Collision Analysis”, Thomas Publishing, 1979.
- [25] J.A.Searle A.Searle, “The trajectories of pedestrians, motorcycles, motorcyclists, etc., following a road accident”, SAE 831622, 1983.
- [26] D.P.Wood, C.K.Simms, “Confidence limits for impact speed estimation from pedestrian projection distance”, International Journal of Crashworthiness, Vol. 9(2), pp. 219-228, 2004.
- [27] L.B.Ficke, “Vehicle-Pedestrian Accident Reconstruction”, Northwestern University traffic Institute, Topic 877 and Traffic Reconstruction Vol. 2, 1990.

- [28] A. Moser, H. Steffan, H. Hoschopf and G. Kasanicky, "Validation of the PC -Crash Pedestrian Model", SAE 2000-01-0847, 2000.
- [29] T.Alves, "Análise biomecânica de lesões em reconstituições de acidentes rodoviários", Mechanical Eng. Degree Thesis, Instituto Superior Técnico, Lisbon, Portugal, November 2005. (in Portuguese)
- [30] H.Paula, "Sinistralidade pedonal: proposta de medidas preventivas e reconstituição computacional de atropelamentos", Mechanical Eng. Degree Thesis, Instituto Superior Técnico, Lisbon, Portugal, December 2005. (in Portuguese)
- [31] A.C.Freitas, "Modelos para a simulação de acidentes envolvendo peões", MSc Thesis, Instituto Superior Técnico, Lisbon, Portugal, December 2006. (in Portuguese)